School of Engineering and Science
Department of Civil & Construction Engineering

An Engineered Wetlands System for Septage Treatment in Malaysia

Valerie Siaw Wee Jong

This thesis is presented for the Degree of
Doctor of Philosophy
of
Curtin University

July 2014

Declaration

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgment has been made. This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

Valerie Siaw Wee Jong

30th June 2014

To my dearest parents, John and Michelle, and loving fiancé, Kelvin

Acknowledgements

This dissertation would have been impossible without the support and encouragement of many individuals. Foremost, I wish to extend my sincere thanks and appreciation to my supervisor, Dr Tang Fu Ee for his guidance and support throughout the period of study. I would also like to express my appreciation to the laboratory technicians of the Skylark building 1 and 2, for their technical support. I am thankful to the Associate Dean of R&D, Professor Marcus Lee for his sights, advices, and professional directions given during the course of my study. I would also like to thank Curtin University Sarawak for their financial support.

I gratefully acknowledge my uncle, Yii and his team who travelled all the way from Sibu to help me in setting up my project site. Their unremitting support in providing me with technical aids and giving me enormous encouragements, kept me going when I was at my gloomiest days during my PhD study. Earnest thanks to Uncle Huang for his assistance in maintaining my treatment system throughout the experimental period. This study would have been impossible without his help.

I am very thankful to my brother, Byron who gave me useful suggestions on my writings, and friend, Kiat for his support in the field work. To my best friend and fiancé, Kelvin, thank you for being there and taking care of me in every way possible. I'm very lucky to have you in my life. I thank my beloved mother, Michelle and my father, John who have served as a continuous source of encouragement and understanding throughout my life and studies. Thank you for standing by me through thick and thin, and for not giving up on me when I was constantly losing hope. Thank you for being proud of me all the times, even when I didn't win.

To my brother, Benjamin and the rest of my family, friends and colleagues, thank you for being so supportive and it is hard to imagine where I would have been without your understanding and support.

Abstract

A pilot-scale septage treatment system featuring two stages of subsurface Vertical Flow Engineered Wetlands (VFEWs) was designed, constructed and studied in Miri, Sarawak, Malaysia. The first stage wetlands of the system were designed to reduce majority of the pollutants from the raw septage by physical filtration and sedimentation processes, while the second stage wetlands focused on the reduction of nitrogen from the effluent besides further removal of the organic matter (OM) and particulate solids. The influences of system-related (plant presence, plant type, substrate type) and operation-related (solid loading rate, hydraulic loading rate, dosing frequency, pond and rest period) parameters on the wetland pollutants removal efficiency were investigated.

The study revealed that the overall performance of the first stage wetlands was excellent for OM, ammonia nitrogen (NH_3-N) and suspended solids (TSS) removal. Throughout the plant operation period, the majority of the contaminants were removed at the first stage with a mean relative mass reduction of at least 92% for BOD_5 and COD, 80% for NH_3-N, 81% for total nitrogen (TN), and 93% for TSS by mass, up to the solid loading rate (SLR) of 350 kg TS/m^2.yr. A high SLR of 350 kg TS/m^2.yr was still found to achieve up to a mean of 98% of OM removal and as high as 92% of NH_3-N reduction by mass at the wetlands with the presence of plants.

Planted wetlands at both stages were found to outperform their unplanted wetland counterparts in terms of NH_3-N and TSS mass reduction efficiencies. The presence of plants was shown to reduce the NH_3-N mass significantly at SLR of 250 kg TS/m^2.yr. At the second stage of the system, the NH_3-N reduction efficiency in the planted beds was also found to be constantly greater than the unplanted unit by an average of 24%. *Costus woodsonii* which is an ornamental species was also found to be an alternative to the traditional wetland indigenous reeds (*Phragmites karka*) for septage effluent treatment.

In terms of wetlands feeding strategy, the removal of OM, nitrogen and particulate solids were found to be dependent on the hydraulic loading rate (HLR). The increase of HLR from 8.75 to 17.5 cm/day impaired the overall treatment efficiency of the wetlands. The re-oxygenation capability of the wetland units was also found to be heavily affected by the dosing frequency, especially under high HLR (17.5 cm/d). The NH_3-N mass reduction was found to decrease significantly when the wetland was dosed more frequently under the same HLR. With batch feeding of wetlands with cyclic fill-pond-drain-rest regime, the extended pond:rest (P:R) period of 3:3 (days:days) showed greater removal performance for COD, BOD_5, NH_3-N, TN and TSS than the wetland fed with P:R=1:1. The study suggested that for all modes of feeding, a sufficient period of resting was found to be imperative to restore aerobic conditions within the bed and to ensure sufficient treatment of the wastewater.

The presence of palm kernel shells (PKS) was found to contribute substantially to the good nitrate elimination performance at the second stage wetlands. This study has shown that the use of PKS was effective in improving the nitrate reduction performance and subsequently the TN removal efficiency in engineered wetlands. The use of PKS which is a waste product from Malaysia's growing palm oil industry shows promise as substrate choice for engineered wetland systems to treat septage.

In terms of septage deposit dewatering and mineralisation, the study suggested that the presence of plants is beneficial in obtaining a more stable, mature and dry end-product. The planted wetlands were found to be more effective in volume reduction, and producing a septage deposit with significantly higher content of dry matter (DM) and lower content of volatile solids (VS). All planted beds had the final DM content of more than 20% in the septage deposit after 7 days of drying time, up to SLR of 350 kg TS/m^2.yr. The study also revealed that the increase of SLR decreased the overall wetland mineralisation performance.

This research project has confirmed that the two-stage VFEWs system can perform fairly well in treating septage to tertiary standards, besides effectively reducing the volume of the septage deposit and improving its quality. The relatively lower construction cost and the ease of maintenance and operation of the system have rendered this green technology favourable for implementation in both urbanised areas and also underdeveloped rural sites with small populations in Malaysia.

Publications

1. Jong, V. S. W., and F. E. Tang. 2014. "Organic Matters and Nitrogen Removal at Planted Wetlands Treating Domestic Septage with Varying Operational Strategies." *Water Science and Technology Water Science and Technology* 70 (2): 352 - 360.

2. Jong, V. S. W., and F. E. Tang. 2014. "Effects of plant presence and the use of ornamental species *Costus woodsonii* for treatment of septage in engineered wetlands." *Water Science and Technology (In review).*

3. Jong, V. S. W., and F. E. Tang. 2014. "Construction and Performance of a Pilot Vertical-Flow Engineered Wetlands (VFEWs) System for Treatment of Septage in Miri, Sarawak." *Pertanika Journal of Science and Technology* 22 (2).

4. Jong, V. S. W., and F. E. Tang. 2013. "Septage Treatment by a Two-Stage Pilot-Scale Vertical Flow Engineered Wetlands System: Effects of Plant Presence and Plant Type." *11th IWA Conference on Small Water and Wastewater Systems and Sludge Management, Harbin, China.*

5. Jong, V. S. W., and F. E. Tang. 2013. "Treatment of Septage with a Vertical Flow Engineered Wetland System." *11th IWA Conference on Small Water and Wastewater Systems and Sludge Management, Harbin, China.*

Table of Contents

List of Figures

List of Tables

List of Abbreviations

BOD_5	5-days Biochemical Oxygen Demand
C	Carbon
COD	Chemical Oxygen Demand
CST	Capillary Suction Time
DF	Dilution Factor
DM	Dry Matter
DO	Dissolved Oxygen
EC	Electric Conductivity
EFF	Effluent
HLR	Hydraulic Loading Rate
ILR	Influent Loading Rate
MRR	Mass Removal Rate
N	Nitrogen
OM	Organic Matter
ORP	Oxygen Reduction Potential
PKS	Palm Kernel Shell
PVC	Polyvinyl chloride
RE	Removal Efficiency
SLR	Solid Loading Rate
TKN	Total Kjeldahl Nitrogen
TN	Total Nitrogen
TP	Total Phosphorus
TS	Total Solids
TSS	Total Suspended Solids

VF	Vertical Flow
VFEW	Vertical Flow Engineered Wetland
VS	Volatile Solids
VSS	Volatile Suspended Solids

Chapter 1 Introduction

1.1 Background

Most major cities around the world utilise technologically sophisticated centralized wastewater treatment facilities to treat wastewater for disposal. However, such facilities are not appropriate for smaller communities (less than 2000 population equivalents), rural areas and otherwise dispersed populations (U.S. Environmental Protection Agency 2002). Thus there has been growing interest among researchers worldwide in the development and deployment of low-technology, decentralised and cost effective systems that harness natural processes to achieve equally good results for wastewater treatment in these areas. Constructed or engineered wetlands refer to a green technology designed to mimic and utilise ecological processes found in natural wetland ecosystems to remove pollutants from the wastewater loaded into the designed system. Engineered wetlands are an eco-technology that offers a treatment format with reduced technical complexity and could be operated with low or no energy demand, besides being a cost effective system in terms of construction, operation and maintenance. While the conventional treatment plants focus on wastewater treatment in larger urban regions, engineered wetland systems could be considered as an affordable and appropriate treatment method to be implemented in rural and low-density areas.

Over the past 30 years, engineered wetlands have been used in many applications, ranging from the secondary treatment of domestic, agricultural and industrial wastewaters to the tertiary treatment and polishing of stormwater and wastewater treated conventionally (Cooper 1999; Hammer 1989; Sirianuntapiboon, Kongchum and Jitvimolnimit 2006; Scholz and Lee 2005). In recent years, vertical flow engineered wetlands (VFEWs) have gained importance as a cost-effective and technically feasible approach for sludge dewatering, stabilisation and mineralization (Uggetti et al. 2011; Uggetti et al. 2009). On the wetlands, while the sludge dries by evaporation, the growing reeds derive nourishment and moisture from the sludge, both stabilizing and reducing its volume. Unlike the traditional (unplanted) sludge drying beds, engineered wetlands do not require regular removal of dried sludge. In this research project, engineered wetlands for septage treatment are suggested as an alternative technology with advantages such as having a smaller ecological footprint, ease of operation and maintenance, and an aesthetic value similar to that of natural wetlands. Removal of pollutants in engineered wetlands is based on a combination of physical, biological and chemical processes and its efficiency depends on its design and the way it is operated. To date however, limited research works on the performance of engineered wetlands have been reported, especially for septage treatment in tropical climates. This project aimed at investigating the potential of using engineered wetlands to treat domestic septage under tropical conditions in Malaysia, and understanding various factors (from system design parameters to operational practices) that contribute to the treatment performance of the system.

1.2 Implementing Engineered Wetlands System in Developing Countries

In recent years, there has been a growing interest in decentralized wastewater treatment systems because of the need for low-cost modular wastewater treatment techniques that are more economical, aesthetic and ecologically sustainable (Donnell, Privett and Behrends 2003). Often, centralized wastewater treatment systems require significant capital investment as well as substantial energy and chemical inputs for operation. These treatment systems engage more advanced collection and treatment processes to treat large quantities of wastewater. Decentralized systems on the other hand, are usually designed to operate at a smaller scale and as such, are much less capital-intensive. Decentralized wastewater management is defined as the collection, treatment and sometimes reuse of wastewater at or near the point of generation. Decentralized wastewater management systems are commonly used for treating individual onsite and small community-scale wastewater flows from dispersed facilities (Asano et al. 2007).

As a general guideline, several criteria are important in selecting the suitable types of wastewater treatment in developing countries and are listed as follows (Mara 2004):

1. Low capital, and operation and maintenance (O&M) costs;

2. Simple to operate and maintain;
3. Low or zero energy input, other than naturally available energy such as solar energy;
4. Low or zero chemicals for operation;
5. High performance, having the ability to produce an effluent of the required quality;
6. Low sludge production; and
7. Where relevant, have a low land intake.

With the above listed factors as a checklist for the selection of suitable wastewater treatment technology for suburban sites as well as small cities around in Malaysia, engineered wetlands appear to fulfil almost all the criteria above, except for the last one. However, the land intake factor may be compromised as the land cost is not high in the rural areas of developing countries.

While engineered wetlands have been successfully used in developed countries for treatment of domestic wastewater under various conditions, it is still a challenging task to incorporate this technology for wastewater treatment especially in developing countries. Despite the suitability of climate in these areas, the spread of treatment wetlands has been described as "depressingly slow" (Denny 1997). Although this eco-technology has the advantage of long term sustainability with very low costs of operation and maintenance (Randall 2003), there are several reasons for the relatively slow spread of the use of this technology in these regions as reported by Aalbers, Waste, and UWEP (1999):

- Aid programmes from industrialised countries tend to favour the more commercially valuable technologies which benefits donors;
- Experts from the developed regions are often entrenched in technologies more suitable for their own countries and are unable to transfer their conceptual thinking to the realities and cultures of the third world ; and
- Experts from developing countries have largely been educated in the ‘conventional’ technologies and have only limited access to information and knowledge on new technologies.

Moreover, although the great potential of this technology has been well-known for decades, the Malaysian local authorities (esp. in Sabah and Sarawak) still seem to be reluctant to invest additional resources such as time, space, and money not only on implementing the engineered wetlands technology, but on building and operating wastewater treatment plants. Untreated wastewater is commonly discharged into rivers and other surface waters. This is especially true in East Malaysia. It is therefore important to document the additional benefits of wastewater treatment using engineered wetlands in order to make this technology more attractive to individuals and communities. Among others, the use of industrial waste such as palm kernel shells (PKS) which is available in abundance with the rapid development of palm oil industries in Malaysia as substrate for the wetlands can be an attractive option. In this way, sustainable development is practiced with the use of this industrial by-product in the construction of the engineered wetlands technology, for treatment of wastewater and at the same time beneficially reusing this potential resource.

Besides, the engineered wetland is a technology that can inherently fit into the landscape and thus will be viewed with favour by the general public. With this advantage, another way to promote the use of this green technology is to link profitable harvestable products to the wastewater treatment operation (Zurita et al. 2011). The by-products, which include plants and biosolid from the treatment system can be used as forage, soil conditioner, fertilizer or even as cut flowers for plant species with commercial value (Koottatep, Konnerup and Brix 2009; Koottatep, Polprasert and Hadsoi 2006; Kroiss 2004; Kengne et al. 2009). Commercially valuable ornamental plants can be a good substitute to conventional wetland plants such as reeds and cattails when the replacement of these typical wetland plants with ornamental plants would not adversely deteriorate the efficiency of the wastewater treatment.

Surface water pollution by domestic wastewater has been a common issue in Malaysia, while the country has a suitable climate for the production of a vast variety of ornamental plants. Thus the implementation of this green technology in both urban and suburban areas in the country may be encouraged by incorporating floriculture/horticulture in the engineered wetlands technology, while achieving eco-friendly wastewater treatment at the same time. There has also been a growing interest in the use of this technology in other developing countries such as Thailand, Nepal, Kenya, China, Tanzania, Pakistan and Iran, where several researchers had conducted studies on the engineered wetlands technology for various wastewater applications (Haberl 1999).

1.3 Research Significance and Objectives

Contrary to wastewater, septage characteristics vary widely within and between cities, based on factors which include climate, user habits, septic tank size, design, pumping frequency, water supply characteristics, piping material, the use of water-conservation fixtures, garbage disposals and others (U.S.EPA 1999). Currently in Miri, Malaysia, faecal sludge or septage are treated at a conventional septic sludge treatment plant that started operation in May 2012. The plant was set up by the authorities at a high cost of approximately RM 20 Million. Previously, for many years before the construction of the sludge treatment plant, untreated faecal sludge or septage were dumped uncontrollably into the aquatic and terrestrial environment. Figure 1.1 (a) and (b) show one of the septage and faecal sludge dumping sites at Kuala Baram, Miri. The photos were taken during a visit to the dumping site in 2011. Loaded hauler trucks arrived at the site to dispose off the septage or faecal sludge directly into an earth trench. The environmental servicers are not required to analyse the septage before any land disposal, and no ordinances are strictly followed for safe disposal. Besides, the quantity of septage removed from septic tanks in the Miri city each year was not tracked by the authorities at the time of this research project, and thus there were no limitations on the amount of septage that was allowed to be disposed on that land.

(a)

(b)

Figure 1.1 (a) and (b) Septage and faecal sludge dumping site at Kuala Baram, Miri (screenshots of a video recorded in Feb 2011)

According to Heinss, Larmie, and Strauss (1998), treating the sludges prior to discharge or use will, in itself, make up substantial health and environmental improvements even if stringent quality standards are not met. The simplicity and scalability of the engineered wetlands technology has made it suitable for treatment of wastewater from both urbanised areas and also underdeveloped rural sites with small or disperse populations. However, the understanding of wetland treatment processes is still evolving, even though the wetland technology has been studied since 1952 (Seidel 1955: cited in Vymazal 2005) and the introduction of the earliest form of vertical flow wetlands was in the 1970's by Käthe Seidel in Germany (Vymazal and Kröpfelová 2008a). The study of septage treatment with engineered wetlands under the tropical climate is very rare and to the best of our knowledge, the use of this eco-technology to treat domestic septage has not been attempted or studied before in Malaysia. In this research project, the engineered wetlands system was studied as a suitable decentralised technology to treat domestic septage collected from households around Miri City. The aim of this project is to design, construct and assess the potential of a two-stage vertical flow wetlands for treatment of septage pumped from domestic septic tanks. The performance and efficiency of the engineered wetland-based treatment system to dewater and stabilize septic sludge and remove pollutants in the resulting effluent were investigated.

For the faecal sludge discharge into the environment, parameters such as COD or BOD_5 and NH_3-N are of prime importance. Thus in monitoring the performance of the pilot two-stage vertical flow engineered wetlands (VFEWs) system, organic matter (COD and BOD_5), nitrogen compounds (NH_3-N, NO_x-N and TN) and particle solids (TS, TSS and VSS) removal were measured as water quality indicators and descriptors of the resulting effluent. The septage treatment programme designed for this research project was developed with the intention to study different factors that were hypothesized to affect the removal of the above mentioned indices.

The specific objectives of this research project of the two-stage Vertical Flow Engineered Wetlands (VFEWs) treatment system include:

I. To design and construct a two-staged vertical flow engineered wetlands system for treatment of septage in Miri, Sarawak, Malaysia;
II. To determine the effects of plant presence and solid loading rate (SLR) on the dewatering and mineralization of raw septage deposit retained on the first stage wetlands;
III. To investigate the effects of plant presence and solid loading rate (SLR) on the removal efficiencies of organic matter and nitrogen fractions, for raw septage effluent treatment at the first stage of the system;
IV. To evaluate the effects of system-related parameters such as the presence of plants, use of an ornamental plant species and inclusion of palm kernel shells (PKS) on the removal of organic matter and nitrogen fractions, for septage effluent treatment at the second stage of the system; and
V. To assess the influence of operation-related variables such as hydraulic loading rate (HLR), period of ponding and resting (for batch-loaded wetlands), and the frequency of daily dosing on the removal of organic matter and nitrogen fractions, for septage effluent (pre-treated septage from the first stage wetlands) treatment at the second stage of the system.

The objectives of this study had been planned and implemented to improve organic matter and solids removal, besides enhancing nitrification at the first stage of the VFEWs system; while improving the overall nitrogen removal in the final system effluent using only two stages of treatment without recirculation or the inclusion of mechanical aerators and addition of external carbon source (e.g. methanol). The reduction of the total footprint and the cost of the system are also amongst the important aims of this project. Thus the use of mechanical parts in the system was minimised and the selection of materials for the wetlands construction are made based on financial sustainability, while incorporating the use of the industrial waste such as palm kernel shells as part of the wetland substrate. The use of engineered wetlands as a green technology to treat human waste helps to implement the application of the integrated life cycle management concept, which presents an opportunity to reconcile development with environmental protection.

1.4 Scope of Study

The scope of the study includes the design, building and operation of a pilot-scale two-staged Vertical Flow Engineered Wetlands system for septage treatment. This research project is an experimental parametric study, where different system and operational-related factors were investigated to determine their effects on the septage treatment performance of the wetland units. The system features such as plant presence, plant type, and substrate type were investigated and the operational parameters which include the loading rates, loading frequency and the extend of pond and rest periods were assessed. Full details of the parameters studied are presented in Section 2 of Chapters 4, 5, 6 and 7.

The treatment efficiency of the VFEWs on septage deposit dewatering and mineralisation were assessed by examining the increase in dry matter content and the reduction in volatile solids content in the septage residual layer. The “black-box” approach was employed for this study where the performance of the system in septage effluent treatment was determined by the measuring the inflow and outflow quality and quantity of the wetland units. Thus, in-depth study on the reduction of bacteria indicators (E. Coli and Faecal coliforms), pollutant removal mechanisms (adsorption, plant uptake, chemical precipitation, volatilization etc.), influence of substrate material characteristics (surface area, porosity, material sorption and leaching) and the internal hydraulics of the wetland (dynamics of the flow) are beyond the scope of this research project. The conclusions drawn from this study are specific to the design and the setup of the VFEWs system operated for approximately 12 months.

1.5 Thesis Outline

The objectives above were addressed by conducting a number of laboratory experiments on a pilot-scale vertical flow engineered wetlands system. In the following C**hapter 2,** a review of the literature on the different types of engineered wetlands and the use of this technology in the treatment of various wastewaters in different countries was presented. A variety of factors that influenced the pollutant removal performance of engineered wetlands were also discussed in this chapter.

Chapter 3 describes the materials, the experimental set-up and operational methods applied in the study. This chapter presents the project site, construction, parking order, wetlands substrate arrangement, planting, bed sizing as well as the operational regime of the system. The planting and establishments of wetland plants (*Phragmites karka)* were also reported. The chapter also documents the sampling and analysis protocols employed in this study, and the characteristics of the septage collected from households around the Miri city were discussed. The performance of the wetlands at the first stage of the VFEWs system is reported in **Chapter 4**. The effects of plant presence and solid loading rate (SLR) on the pollutant removal efficiency of the wetland beds were discussed. At this stage, the wetlands influent was raw septage and the effluent from the beds was collected for further treatment at the second stage.

Discussions on the effects of operational-related variables on pollutant removal efficiencies of the wetlands at the second stage are presented in **Chapter 5**. This chapter reports the quality of the effluent collected from wetlands which were loaded at medium and high hydraulic loading rates (HLR) at different daily dosing frequencies. The effects of extended ponding and resting periods on the pollutant removal performance of the wetlands were also discussed. Statistical analyses on the results were carried out to study the effects of the different feeding regimes on the performance of the wetlands in terms of pollutant removal efficiency. **Chapter 6** examines the effects of the system-related parameters on the wetlands performance at the second stage of the system. Comparisons between the wetland treatment efficiency were made between planted and unplanted wetlands, *Phragmites*-planted and *Costus*-planted wetlands, and the wetlands with and without inclusion of palm kernel shells (PKS) as the filter substrate.

In **Chapter 7**, the capabilities of the wetland beds in septage dewatering and mineralisation are analysed and reported. Tests were carried out on the sludge deposit that was retained on the beds' surface to study on the effects of plant presence and SLR on the efficiency of moisture and volume reduction, as well as the degradation of organic matter. The findings of the study are discussed in this chapter. **Chapter 8** is a summary of the insights obtained from this thesis. Conclusions, research opportunities and limitations, and recommendations for further research are also addressed in this chapter.

Chapter 2 Literature Review

2.1 Introduction to Wetlands

Natural ecosystem processes occurring in marshes and swamps that stimulate pollutant and nutrient removal of the receiving water have previously been studied to investigate the water treatment potential of wetlands, making use of a controlled green system (Gopal and Ghosh 2008). An engineered wetland is specially designed to replicate the processes of natural wetlands to treat wastewater, with natural and low-cost processes. Generally, wetlands can be categorised into the following types, as presented in Table 2.1.

Table 2.1 Characterisation of wetlands (Hammer 1992)

Wetland Categories	**Descriptions**
Natural wetlands	Naturally occurring wet zones which function as a transition between terrestrial and aquatic ecosystems, possessing characteristics of both environments
Created wetlands	Manmade system built in an upland area at non-wetland sites to produce or replace natural wetlands
Restored wetlands	Natural wetland subject to recovery from damages or losses to maintain or reinstate its benefits as well as the surrounding ecosystems
Constructed/Engineered (artificial) wetlands	Wetlands intentionally created from non-wetland sites for the purpose of wastewater or stormwater treatment. According to Higginsa, Hurdb, and Weilb (2000), while engineered wetlands are a more advanced form of constructed wetland, which they are essentially constructed wetlands that are specially designed or configured with added mechanisms or system aspects to remove particular contaminants from the wastewater

Reed, Crites, and Middlebrooks (1995) highlighted that an engineered wetland system is expected to provide a better performance than a natural wetland system with an equal area. The authors claimed that the process reliability of an engineered wetland system is improved since the wetland plants (macrophytes) and other important system components could be managed and manipulated in the system, compared to the naturally occurring wetlands. Being low cost and requiring low technological support, the engineered wetlands system has emerged as a potential alternative or supplementary system for treatment of municipal, agricultural, and industrial wastewater besides stormwater (Cooper et al. 1996; Vymazal et al. 1998; Haberl 1999; Kivaisi 2001). Engineered wetlands compared to natural wetlands can be built with a much greater degree of control, thus allowing the establishment of treatment facilities with more defined composition of substrate, selection of plants, and design of flow regime. Besides, the engineered wetlands are flexible and customisable in terms of site selection, bed sizing, aesthetic value and most importantly, control over the hydraulic pathways and retention time in accordance to the type of wastewater being treated. For further classification, engineered wetlands can be differentiated based on the various system features as shown in Table 2.2 below:

Table 2.2 Further classifications on the different types of engineered wetlands (Haberl 1999; Brix 1994)

Wetland Features	**Descriptions**
Life form of the dominating macrophytes	Free-floating, emergent, submerged
Water flow pattern	Vertical, horizontal
Water Level	Above soil surface: free water surface flow Below soil surface: subsurface flow
Type of configurations of the wetland cells	Hybrid systems, one-stage, multi-stages
Type of wastewater to be treated	Agricultural, industrial, slurries, etc.
Treatment level of wastewater	Primary, secondary, tertiary
Type of pre-treatment	Septic tanks, imoff tanks, mechanically or biologically pre-treated, etc.
Type of substrate	Gravel, soil, woodchips, etc.
Type of loading	Continuous, batch or intermittent loading

Subsurface wetlands are typically filled with an inert rock medium, either planted or unplanted, and are designed so that the water level is beneath the surface of the wetlands, flowing through the porous medium. The horizontal flow (HF) type of wetlands have been the most common natural treatment system since year 1969 (Cooper 1999) and have been successfully used for the treatment of wastewater for more than four decades (Kröpfelová et al. 2009). Most of these systems have been designed to treat domestic and municipal sewage, but applications such as treatment and polishing of wastewaters from agriculture, industry, septage, urban stormwater runoff and landfill leachate in HF wetlands is increasing.

Back in the 1960s, Seidel of the Max Planck Institute in Germany developed the vertical flow (VF) type wetland systems for treatment of wastewater (Seidel 1965: cited in Vymazal 2005) and decades later, Cooper et al. (1996) developed the design criteria for desired nitrification in vertical flow engineered wetlands based on oxygen demand, in accordance to their experiments and theoretical approaches. The latest generation of vertical flow engineered wetlands that have been introduced in Europe, are operated with intermittent loading regime (Haberl 1999). According to Cooper (1999), VF wetlands are more attractive than the more commonly used HF wetlands due to their much greater oxygen transfer capacity for improved nitrification, having considerably smaller surface area than HF wetlands, and their high efficiency in organic matter and pathogens removal. However, this type of wetland is particularly susceptible to substrate clogging which could potentially leads to failure of the system (Platzer and Mauch 1997). It is thus extremely important to address the wetland design and operational aspects to prevent overloading of the system and to avoid clogging.

VF subsurface wetlands are gaining popularity at present and have been very successful in France since 2000 (Molle et al. 2006). The typical engineered wetland-based treatment for domestic wastewater in France is based on two stages of vertical subsurface flow filters fed directly with raw wastewater. These vertical flow beds together with alternating phases of feed and rest are effective in maintaining the aerobic conditions within the filter bed. The retained organic deposit on the surface of the primary-stage VF wetlands, formed by the accumulation of suspended solids from the raw sewage are removed via mineralization (Molle, Prost-Boucle and Lienard 2008). Proven efficiency and application of wetlands in treating wastewater in other countries such as Ireland (Babatunde et al. 2008), Nepal (Laber, Haberl and Shrestha 1999), Italy (Masi et al.), Czech Republic (Kröpfelová et al. 2009; Vymazal 2002), USA (south Florida) (Chimney and Pietro 2006) and especially Thailand (Vymazal 2002; Kröpfelová et al. 2009) had shown that this technology can potentially be applied in tropical countries like Malaysia.

2.2 Applications of Engineered Wetlands

According to Reddy and Smith (1987), natural wetlands have been used for wastewater treatment for centuries, but often the main reason behind this wetland utilisation was disposal rather than intended treatment, as the natural wetlands are conveniently the recipients that was closer to the dumping site than the nearest waterways. However, due to the increase in environmental awareness and the wide-spread concept on eco-technologies, researchers have focused on the design and operation aspects to enhance and possibly optimise the treatment efficiencies of engineered wetlands in wastewater treatment. Nowadays engineered wetlands have been applied for the treatment of various types of wastewaters, including those from the industries, agriculture, landfills, surface runoff and etc, besides using them for sludge dewatering. During the early years of the development of subsurface engineered wetlands, almost all wetlands were used for secondary and tertiary treatment of domestic and municipal wastewater that was mechanically pre-treated, due to the issues with clogging (Langergraber et al. 2009).

2.2.1 Treatment for Various Types of Wastewater

Subsurface flow engineered wetlands are most commonly used for secondary treatment of domestic sewage. For sewage treatment in Iran, a 150 m^2 subsurface flow engineered wetland planted with *Phragmites australis* was studied for treatment of municipal wastewater (Badkoubi, Ganjidoust and Rajabu 1998). At an organic loading of 200 kg/ha.d, removal efficiencies of 86%, 90%, 89%, 34%, 56% and 99% for COD, BOD_5, TSS, TN, TP, and faecal coliform bacteria, were obtained, respectively. In China, two parallel pilot-scale integrated vertical engineered wetland systems, each with a down-flow chamber (1m×1m×1m) and an up-flow chamber (1m×1m×1 m) were built to treat domestic wastewater (Wu et al. 2013). The systems were operated for 10 months and mean removal efficiencies for COD, TN and NH_4-N was 81%, 52% and 43%, respectively at a loading rate of 125 mm/day, under the subtropical monsoon climate. A three-staged engineered wetlands system was designed to enhance organic matter removal from domestic wastewater, beyond those of one-unit systems in Turkey (Tunçsiper et al. 2009). The wetland type for the first, second and third stage was a vertical flow bed, followed by a horizontal flow unit, and the final stage was another vertical flow bed. As much as 98% of reduction was found for total suspended solids (TSS), biological oxygen demand (BOD) and chemical oxygen demand (COD) levels in the system effluent after treatment with the multi staged-system.

Agricultural non-point source pollution is considered to be one of the leading causes of watercourses pollution, especially in developing countries. These diffused sources wash away sediments and deposit pollutants from the landscape and into the receiving water bodies. Agricultural runoff containing significant amount of fertilizers and pesticides can cause serious contamination of the surface waters as well as groundwater. Studies have been carried out to understand the potential role of free water restored wetlands as filters for the nutrient discharged from agricultural areas into the ecosystems (Comin et al. 1997; Romero, Comin and Garcia 1999). In Thailand, water pollution problems have been increasing especially with wastewater from agro-industries. Kantawanichkul et al. (2003) studied the use of two engineered wetlands arranged in series (horizontal flow followed by vertical flow bed) and planted with *Scirpus grossus Linn*. to treat swine wastewater from the piggeries and found a good removal of COD, TN, NH_3-N and SS, with the elimination efficiency at 95%, 79%, 98% and 99%, respectively. The beds were operated at a hydraulic loading rate of 3 cm/d and the treated effluent was recycled at a ratio of 1:1 to optimised nitrogen removal.

Leachate from landfills and solid waste disposal sites can be a major source of surface water and groundwater pollution, and they are often difficult to handle due to variation in quality and quantity (Martin, Johnson and Moshiri 1999). Generally, landfill leachate may contain very high concentrations of dissolved organic matter and inorganic macro components with the concentrations up to a factor of 1000 to 5000 higher than concentrations found in groundwater (Kjeldsen et al. 2002). In a study carried out in Nigeria, treatment of landfill leachate with engineered wetlands was found to be effective with the effluent showing significant reductions in SS (81%), BOD_5 (86%), and NH_3-N (98%) (Aluko and Sridhar 2005). The study revealed the wetland technology as a feasible tool for the treatment of leachate before disposal, with means of preservation of the environmental quality. In another study conducted in Slovenia with two vertical flow and one of horizontal flow engineered wetlands, the effectiveness of such system as a low-cost alternative for tertiary treatment or as an independent system to treat landfill leachate was also explored and reported (Bulc 2006). The performance of the system was evaluated for 7 years and the average removal efficiency of COD, BOD_5, and NH_3-N was found to be 50%, 59%, and 51%, respectively.

2.2.2 Treatment of Sludge and Septage

Sewage sludge is defined as the sludge produced from municipal wastewater treatment plants, whereas septage refers to the combination of sludge, scum and liquid pumped from septic tanks (Metcalf and Eddy 1991). Faecal sludge (FS) denotes sludge of variable consistency collected from on-site sanitation systems, such as latrines, non-sewered public toilets, septic tanks and aqua privies (Heinss, Larmie and Strauss 1998). Septage is typically characterized by higher solids and organic content compared to domestic sewage (Koottatep et al. 2005; Teal and Peterson 1991), and its characteristics are highly variable, depending on factors such as storage duration, climatic conditions, performance of septic tanks and origin (Heinss, Larmie and Strauss 1999). Sustainable treatment options for FS is a crucial issue in developing countries, as proper disposal of the excreta that contains much more pathogens and nutrient concentrations than in domestic wastewater is essential (O.O. Cofie et al. 2006).

The US Environmental Protection Agency, USEPA stated that a well-designed septic tank will usually retain 60 to 70% of the solids, oil, and grease that enter it (U.S.EPA 1999). It is important to desludge the septic tanks at specific intervals to maintain the performance of the tanks. The disposal of septage by land application has long been reviewed as the most preferred and economical option for many local authorities in Sarawak. In some areas in Malaysia, large quantities of the septage pumped from septic tanks are disposed of unrecorded and clandestinely within the suburb and even in the urban settlement area (Ir. Teo, personal communication June 21, 2012). This unplanned and inappropriate disposal method could lead to contamination of waterways and causes marine and groundwater pollution, besides posting potential health threat to the residents.

In the majority of the cities and smaller communities in Sarawak, centralized treatment systems or sewered sanitations involve prohibitive costs. Thus, the engineered wetlands system could be proposed as a feasible option for septage treatment in those areas due to its low construction cost, simple operation and maintenance, and potential to be applied in developing countries (Seo et al. 2005). However, the treatment of septage with engineered wetlands is more complicated and different from the treatment of other domestic wastewater, as the strength of the septage contaminants are at least 10 - 100 fold stronger (O.O. Cofie et al. 2006) than those typically handled by the prevalent wetland technology for domestic wastewater treatment.

Treatment or disposal of FS has been done via several methods for the past decades. One of the commonly known methods is by using the traditional sludge drying beds, which is also known as the unplanted drying bed. On the beds, dewatering of FS is attained by both evaporation and seepage. The removal of the dried sludge deposit from the drying beds is often labour-intensive and has become a known disadvantage for the traditional drying beds technology. This sludge drying method has thus involved relatively greater capital and running costs than planted drying beds (engineered wetlands), since the retained solids need to be removed more frequently than that from the planted beds (the planted beds only require removal of sludge deposit at every 10 years). In Gaza Strip, a three-year study by Nassar, M., and Afifi (2006) showed favourable results on the effectiveness of reed-planted beds for sludge dewatering, where the beds were also reported to be economically more attractive for municipal sludge drying than the traditional sludge drying beds. The study reported that the cost of sludge treatment using reed beds was 0.60 US$/m^3 compared with 1.01 US$/m^3 for treatment using conventional unplanted drying beds.

In terms of septage dewatering, Pescod (1971) found that 5 – 15 days of septage drying time was necessary to reach a total solids content of 25% with initial solids loading rates varying from 70 to 475 kg TS/m^2.year in the yard-scale drying beds constructed in Thailand for the purpose of septage dewatering. In another study, 8 to 12 days was required to attain 40 to 70% of TS content in the dewatered FS with solid loading rates of 100 to 200 kg TS/m^2/yr on the drying beds constructed in

Ghana (Heinss, Larmie and Strauss 1998). The beds managed to remove 70 - 90%, >95%, and 40 - 60% of COD, SS and inorganic nitrogen (NH_4-N; NH_3-N), respectively from the bed effluent.

2.2.2.1 Treatment and Dewatering of Sludge Deposit

In recent years, VF engineered wetlands have gained importance as a cost-effective and technically feasible approach for sludge dewatering, stabilisation and mineralisation (Koottatep et al. 2005; Nielsen 2003). High water content in sludge imposes problems when sludge is to be further treated by co-composting, or when sludge is sent for incineration or disposal in landfill. The wetlands have been successfully used for sludge dewatering and stabilization in small cities across Europe and Asia (Cooper et al. 1996; Burgoon et al. 1997; Kengne et al. 2009; Koottatep et al. 2005). Vertical flow engineered wetlands planted with *Phragmites australis* have appeared to offer both economic and environmental advantages over the conventional method of sludge dewatering, as they do not require the use of chemical flocculants, centrifuges or belt presses (Edwards et al. 2001).

On sludge drying wetlands, the sludge is applied onto the beds, allowing the solid phase to be retained on the surface of the substrate where it undergoes humification, while the liquid phase drains out of the system for further treatment. Sludge is applied periodically at VF wetlands, where it is dewatered by percolation through the sludge and gravel layers, and via evapotranspiration and evaporation from the sludge surface (Melidis et al. 2010). The dewatering process results in the increase of dry matter content in the sludge deposit, decrease of the sludge volume and the decomposition of organic matter (Nielsen 2003). In a study conducted by Uggetti et al. (2009), moisture content of the influent sludge was found to reduce by 20% – 27%, where all the studied systems were capable of achieving similar dewatering efficiencies to those attained by conventional dewatering technologies such as centrifuges and belt-filter presses.

With slow transfer of oxygen into the sludge layer via the reed plants and their root zone, and by diffusion through the air-sludge interface, the sludge gradually becomes oxidized/mineralized (Edwards et al. 2001). Thus besides dewatering, planted VF wetlands also allow for a certain degree of sludge mineralization. Sludge mineralisation is quantified by a reduction in volatile solids (VS) content and an increased in fixed solids (FS) content (Edwards et al. 2001; Maeseneer 1997). There are several researchers that studied on the dewatering efficiency of sewage sludge using engineered wetlands (Chitzi et al. 2007; Uggetti et al. 2009; Troesch et al. 2009a), but the efficiency of septage treatment and dewatering by this eco-technology, at present, is still rarely reported.

A study carried out by Melidis et al. (2010) verified the effectiveness of the planted reed beds (VF wetlands planted with reeds) in dewatering and mineralisation of primary settled sludge. The reed beds showed an improvement in terms of total solids (TS), volatile solids (VS) and nitrogen removal, besides achieving a high sludge volume reduction up to 99.6%. Towards the end of the study period, the VS content was found to vary from 40.6% at the top layer to 35.2% at the bottom layer (Melidis et al. 2010). The results indicated a high extent of mineralization and stabilization, especially in the bottom layer. Two pilot-scale VF sludge drying beds vegetated with *Phragmites australis* were constructed in Greece to investigate the sludge dewatering capabilities of reed beds treating surplus activated sludge (SAS) collected from sewage treatment plant (Stefanakis et al. 2009). The study showed that a high septage volume reduction was observed after the reed beds treatment, with an improved quality of sludge deposit found as a result of increased dry weight content (high TS content of 96.5%) and a significant reduction in organic matter (leaving only 10% of VS (as a % of TS)). The resulting percolate has also shown to have a significant reduction in COD concentration at 96.1%.

In Staffordshire, United Kingdom, a pilot-scale reed bed system was constructed to study the dewatering of settled humus sludge produced by a Biological Aerated Filter (BAF) unit used for treatment of wastewater from the piggeries. The result of the study was reported in Edwards et al. (2001), which presented the effects of plants in treating humus sludge. The study showed that a greater dewatering efficiency was found in the planted unit compared to the unplanted one at a similar feeding rate. The sludge deposit layer at the planted reed beds was found to have a higher percentage of TS and greater reduction in the height compared to the unplanted bed.

Examinations on the cores of the final sludge deposit for both the planted and unplanted beds showed the two distinct zones, with an anaerobic black upper layer and a more oxidised lower brown layer. The unplanted control bed was found to have a had a thinner, oxidised lower layer in comparison though the differences observed between the mean VS contents in the sludge deposit was generally found to be insignificant.

2.2.2.2 Treatment of Percolate

Several studies were carried out by Koottatep Thammarat from the Asian Institute of Technology (AIT), Thailand on treatment of septage by vertical engineered wetlands (Panuvatvanich, Koottatep and Kone 2009; Koottatep et al. 2001a; Koottatep and Polprasert 1997; Koottatep et al. 2005). Koottatep et al. (2001a) indicated the wetland system as a promising and stable technology for septage treatment in tropical regions. The sand-gravel packed substrata and cattail grown engineered wetlands were found to be efficient in septage dewatering and contaminants removal, taking into design consideration the optimal solid loading rate (SLR) and septage application frequencies, as well as the percolate impounding regime. In Koottatep's studies, the planted wetlands were loaded at the solid loading rate (SLR) of 250 kg TS/m^2.yr or a constant volume of 8 m^3/week, with percolate ponding of 6 days to achieve optimum treatment efficiency (Koottatep et al. 2001a). The authors found good removal efficiencies of 80, 96 and 92% for TS, TCOD and TKN, respectively

The application of sludge on engineered wetlands is normally done by 1 - 3 partial loadings daily for a short period of time, followed by subsequent rest periods (period no loading) to prevent substrate clogging (Nielsen 2003) and plant wilting (Troesch et al. 2009a). The alternating mode of feed and rest allow for biofilm dewatering, to lose water and to increase the effective porosity of the beds, besides promoting mineralization of the sludge layer by microbial activities for the re-oxygenation of the substratum (Platzer and Mauch 1997). The duration of the wetlands idle (rest) period must be long enough for sufficient bed re-oxygenation, which is ideally twice as long as its operating time, according to O'Hogain (2003).

According to Koottatep et al. (2005), septage loading at once or twice weekly showed inconsequential effects of the feeding frequency on the system treatment performance with constant solid loading rate. However, the authors pointed out the need for percolate impounding at the wetlands fed once a week to ensure sufficient moisture for the wetland plants (cattails) which developed wilting symptoms during dry seasons. In another study conducted in Thailand, Panuvatvanich, Koottatep, and Kone (2009) revealed the effectiveness of vertical flow engineered wetlands for faecal sludge treatment using substrate with various sand depth and percolate impounding regime on nitrogen removal. It was reported that the overall TN removal (varied from 87% to 92%) increased with the sand layer depth, regardless of the percolate impounding regime (batch and permanent) where the differences in the denitrification rates observed on day 3 to day 6 during percolate impounding were not found to be significant.

In Yaounde (Cameroon), Kengne et al. (2009) evaluated the potential of vertical flow engineered wetlands planted with *Echinochloa pyramidalis* on faecal sludge dewatering and the effects of different SLRs on growth of the wetland macrophytes based on a yard-scale experimental plant. The study revealed that the system performed well for solid–liquid separation at loading rate of 100–200 kg TS/m^2/yr, with an average dry matter content of biosolid ≥30% and effluent pollutant removal efficiencies greater than 77%, 86%, 90%, 90% and 95% for ammonium nitrogen (NH_4^+), total suspended solids (TSS), total solids (TS), nitrogen total Kjeldahl (TKN) and chemical oxygen demand (COD), respectively.

2.3 Factors Influencing Wetland Treatment Efficiency

Factors affecting the performance of an engineered wetland system are generally dependent on a variety of design and operational factors relating to the system itself and the influent characteristic, as well as the way it is applied to the bed (Prochaska, Zouboulis and Eskridge 2007). System-related factors include substrate type, size and depth (Torrens et al. 2009), maturity of bed, and climate (Merlin, Pajean and Lissolo 2002). Other factors could be the presence and type of vegetation, and the system configuration. The application-related factors include the hydraulic loading rate (HLR), influent concentration, and operational regime (intermittent, batch or continuous, feeding frequency, and etc.). These application-related factors can be of great importance in determining the wetland pollutant removal efficiency, as these operational features can be manipulated or amended to improve the wetland performance even after the system has been built.

To enhance the performance of the engineered wetland-based treatment system, control of these factors is necessary as they are directly correlated to the residence time of the influent in the system, besides preventing issues with overloading. In general, a longer hydraulic retention time (HRT) allows for a longer contact period between the influent with the wetland sediments, substrate, bacteria or plants which correspondingly improves pollutant removal (Moustafa et al. 1996). Overfeeding of the wetlands could lead to serious bed clogging problem that accelerates the failure of the system.

Substrate clogging is known as the most important drawback of the engineered wetlands technology (Zhao, Zhu and Tong 2009), occurring as a result of both physical (solids retention and/or sedimentation) and biological processes (biofilm growth). In VF engineered wetlands, clogging could critically obstruct the oxygen transport and can result in a significant decline of the system’s ability to treat wastewater (Langergraber et al. 2003). It is therefore important to have a good control of the hydraulic and organic loads, and thus the oxygen renewal in the wetland substrate (Kayser and Kunst 2005). Also, appropriate management of the wetland feeding and resting periods can help to counter clogging problems and restore the beds’ infiltration capacity, as a result of microbial mineralization of the accumulated organic matter on the re-oxygenation condition of substrate (Platzer and Mauch 1997).

2.3.1 Hydraulic Loading Rates (HLR) and Solid Loading Rates (SLR)

The hydraulic loading rate (HLR) of wastewater treatment wetlands is the flow rate per unit area of the beds, typically ranging between 2.5 cm/d to 5 cm/d (Brix 1994). An increase within this range of loading rate corresponds with a decrease in the removal rates, according to Brix (1994). WPCF (1990) reported a slightly higher HLR range for subsurface wetlands with the values generally varying from 6 to 8 cm/d (Water Pollution Control Federation 1990: cited in Koottatep 2004). Kantawanichkul, Kladprasert, and Brix (2009) studied their vertical wetlands with HLR of 2, 5 and 8 cm/d for treatment of high strength wastewater under a tropical climate and found that the wetland effluent COD concentrations were independent of the loading rates, whereas on the other hand the increase in HLR significantly affected the effluent concentrations of TKN and NH_4.

In general, the performance of engineered wetlands is expected to decrease with the increase in HLR, which denotes a shorter HRT of the wastewater in the system (Mbuligwe 2004; Prochaska, Zouboulis and Eskridge 2007). Besides, the increase in HLR could also lead to possible nutrient flushing from the wetlands due to the high flow rate (Mbuligwe 2004) which will result in the increase of pollutants concentration in the wetland effluent. However, a sufficient hydraulic loading rate is still necessary to ensure a good distribution over the surface of the treatment beds, thus avoiding the occurrence of preferential flow paths through the wetland substrate.

For sludge loading, Maeseneer (1997) suggested a hydraulic loading of 1 – 1.5 m/year for aerobically stabilized sludge, while Begg, Lavigne, and Veneman (2001) adopted an average hydraulic load of 1.78 - 1.82 m/yr in their study. Septage solid loading rate (SLR) is a hydraulic measurement in terms of total solids mass applicable per square meter of the wetland surface per year (kg TS/m^2.yr) and is generally used for design of sludge treatment wetlands. SLR in the range of 30 – 80 kg TS/m^2.yr were suggested by Cooper et al. (1996) for sludge treatment in Europe, while data from several engineered wetlands system planted with reeds in the USA showed SLR ranging from 13 kg/m^2·yr to 65 kg/m^2·yr for the treatment of anaerobic digested sludge (Burgoon et al. 1997; Kim and Smith 1997). Nielsen (2003) on the other hand recommended a maximum of 50 – 60 kg dry matter/m^2.yr for treatment of sewage sludge by sludge drying reed beds in Denmark following 2 years of commissioning period.

A higher range of SLR was expected to be applicable in the tropical regions, as the warmer climate is conducive to year-round plant growth and microbial activities, which in general is advantageous for the pollutants treatment efficiency (Kaseva

2004). It was suggested by Koottatep et al. (2005) that the variations of SLR from 80 kg TS/m^2.yr up to 250 kg TS/m^2.yr did not significantly affect the overall treatment performance of the wetlands at a pilot study in Bangkok, Thailand.

2.3.2 Feeding Strategies

The availability of oxygen for the oxidation of carbon and nitrogen is the limiting factor for wastewater treatment in all engineered wetland systems according to Reed and Brown (1992). Oxygen can be transferred into the wetland media by the diluted oxygen present in the wastewater, convection due to batch loading and diffusion processes (Molle et al. 2006). In VF beds, there is generally a variety of approaches to physically promote aeration which include direct bed aeration or by intermittently flooding the units (Green et al. 1997; Laber, Perfler and Haberl 1997; von Felde and Kunst 1997). The effects of feeding and draining patterns were claimed to be significant on the hydraulic behaviour of VF engineered wetlands based on the study done by Panuvatvanich, Koottatep, and Koné (2009).

In general, VF wetlands exist in different variations according to the feeding strategies applied to the beds. A well-known method of operating VF wetlands is by intermittent feeding of the bed, which involves periodic flooding of water at the top of the wetlands. When no plants are used, this design is effectively an intermittent sand filter. After wastewater feeding, the liquid gradually drains vertically down through the bed by gravity and is discharged freely from the base. This mode enhances oxygen transfer into the wetland by allowing air to refill the bed during draining. The next dose of influent traps this air and along with aeration caused by the rapid dosing of the wetland, organic matter and ammonia nitrogen elimination can be improved (Kadlec et al. 2000). Intermittent feeding of the wetlands is operated with free drainage, and complete effluent drawing is not implemented before the next pulse of influent is introduced into the wetlands like the batch loading regime.

For intermittently-fed beds with free drainage, air convection within the wetlands is the consequence of the feeding by doses, where the wastewater introduced into the bed repeals the gas present in the wetland porous substrate, and at the same time draws in the atmospheric air when the substrate surface desaturates (Forquet et al. 2009). Nitrification can be enhanced by intermittent loading as some ammonia from the influent can be adsorbed onto the filter media during the feeding period, nitrified during the rest period and released during the following feeding interlude (Molle et al. 2006). The operation of intermittent feeding improves the redox conditions of the engineered wetlands by diffusion of oxygen through the thin water films surrounding the plant roots and substrate biofilm when exposed to the atmosphere (Jia et al. 2010).

Batch feeding of VF wetlands is operated with a downward flow pattern, where the application of wastewater is done in large batches and allows the water to percolate down through the substrate by gravity. The batch feeding regime involves rapid filling of beds to capacity, impounded for a period of time and then drained completely before being refilled in a repeating cyclical processes (Põldverea et al. 2009). The next dose is fed onto the surface of the wetland only after the bed is free of water and rested for a set period of time. In short, the batch loading consists of cycles of fill-pond-drain-rest processes. This operational method enables diffusion of oxygen from the air into the bed where oxygen was supplied by a siphon effect resulting from flooding and draining. The advantage of the batch feeding mode over continuous flow operation in wetland systems is that even at very low drain-fill frequencies, the regime ensures that the microbial populations at any given point to be exposed to decreasing organic carbon concentration, which then allows the wetland environment to be subjected to temporal redox variation (between aerobic and anoxic conditions), and therefore enhancing the BOD_5 and N removal (Stein et al. 2003). The aerobic and anaerobic conditions in wetlands are able to influence the activity of microbes for biodegradation of organic matter, nitrification and denitrification.

Experiments on the effects of different feeding regimes on nitrogen removal revealed that the system fed with batch dosed wastewater by alternating flood and drain sequence had better total nitrogen removal than the system loaded continuously (Zhang et al. 2005). Each cycle of the batch operation involved 24 hours of flooding followed by 24 hours of drying in the study by Zhang et al. (2005). The drying period functioned to improve the oxidative condition of the soil which is required for nitrifying processes that take place under aerobic conditions. Correspondingly, the NH_4^+-N removal was improved from 70% with the continuous loading regime to more than 90% with the batch loading mode, and the authors claimed that the overall total nitrogen (TN) removal rate was also enhanced due to improved nitrification (Zhang et al. 2005).

However in contradiction, Jia et al. (2010) accounted a decrease in the TN removal with wetlands operated in the sequencing fill-and-draw batch mode, with the presence of nitrate found as a predominant form of nitrogen in the effluent of batch operated systems. This was reported as a result of aeration in the system that hindered nitrate reduction. The system was operated with flood and drain (F/D) period (days) of 2/1 and 1/2 for the batch loaded wetlands. The authors found that with prolonged drying time, the ammonium removal increased and the TN removal decreased. Besides, the poor removal of TN in the system was also claimed as a result of inhibited denitrification process due to the lack of carbon source as organic substance (Jia et al. 2010; Tao and Wang 2009). A study by Burgoon, Reddy, and DeBusk (1995) also found no beneficial effects in implementing periodic draining and filling on BOD_5 and TN removal in their study on subsurface wetlands. It was claimed by the authors that the cyclic batch loading of the wetland did not show improvements on the wastewater treatment during the study period.

In terms of batch management, Molle et al. (2004) and Molle et al. (2006) reported that the batch feeding frequency and bed rest period have important impacts on wetland infiltration rates. Molle et al. (2006) discussed the important effects of the volume per batch of wastewater feeding on the hydraulic behavior of the wetland filter media, and subsequently the treatment efficiency. At the same hydraulic load of 4.8 cm/hr, the experiment was carried out with low and high batch loading frequencies, where the low batch frequency (9.5 cm/2hr) indicated less batches of greater volume and the high batch frequency (2.4cm/30min) indicated numerous small volumes of batches with shorter feeding intervals. The study revealed that the surface deposit layer on the wetland has a buffering capacity that rapidly adsorbed ammonium onto the organic matter, where the NH_4^+ was nitrified between successive batches (Molle et al. 2006). The authors found that the low batch feeding frequency with a larger volume of wastewater per application allowed better drainage, but can lead to shorter contact time with the biomass that decreases the COD removal efficiency. Molle et al. (2006) showed that a high batch loading frequency led to a reduced drainage capability and subsequently lower infiltration rate, but better water exchanges in the water column (effective volume of reaction) as a result of higher wastewater retention time within the media. However, the high dosing frequency caused lower oxygenation in the beds, and thus was a disadvantage to the NH_4^+ removal performance.

However, in another study carried out by Bancole ́, Brissaud, and Gnagne (2003), the authors found contradicting results with the study carried out by Molle et al. (2006), with greater removal of organic matter and nitrogen found with higher batch loading frequency. To date, little information is available on the performance of batch-operated engineered wetlands for real wastewater treatment, as most of the studies carried out so far have been conducted in lab conditions using artificial wastewater simulating wastewater from the sewage.

2.3.3 Wetland Plants

Wetland plants are identified as the integral part of the treatment system in engineered wetlands as plants are generally known to play important parts in the removal of pollutants from wastewater. The influence and effects of plants however, had been discussed with controversy over the years. Several authors claimed that the presence of plants in wetlands is advantageous for pollutants removal, while others discussed on the insignificant role that plants play in improving the treatment performance of engineered wetlands. Some researchers considered the proportion of nutrients uptake by plants as limited or even negligible compared to the input (Tanner 2001; Vymazal 2005; Brix 1997), but others showed that plant uptake can be an important pathway to remove nitrogen from the system (Drizo et al. 1997; Korboulewsky, Wang and Baldy 2012; Hu and Zhao).

The indirect and more important role of the plants according to Stefanakis and Tsihrintzis (2012) is to supply carbon for microbial metabolism, provide attachment sites for microorganisms on their root system and transport atmospheric oxygen into the wetland substrate through the rhizosphere. Their study showed that the presence of plants significantly improved the removal of organic matter, nitrogen and phosphorus by 6, 10 and 11%, respectively. Several other researchers also observed that plants can significantly modify the rhizosphere by exuding oxygen and carbon compounds from the roots (Morgan, Bending and White 2005; Hinsinger et al. 2003). This function of plants however, was regarded as negligible and insignificant by Kadlec and Wallace (2009) as the influent wastewater in engineered wetlands was found to provide enough organic material to negate the effects of plant exudates for enhanced pollutants breakdown in the wetlands.

One function of plants that is not controversial is their aesthetic effect, as it is a common agreement that planted subsurface wetlands are far more attractive than bare gravel. Common plants used in engineered wetlands are generally water-tolerant plants that are rooted in the soil but emerge above water surface such as reeds (*Phragmites spp.*), cattail (*Typha spp*) and bulrush (*Seirpus spp.*) (Lee, Fletcher and Sun 2009). In a pilot reed-planted bed constructed in Nasugbu, Batangas by the University of the Philippines to treat wastewater from a laundry service, comparisons between the two commonly used *Phragmites* species, i.e. *Phragmites karka* and *Phragmites australis* in terms of COD and surfactant removal was investigated (Mulingbayan 2005). This study by Mulingbayan (2005) revealed that the wetland planted with *Phragmites karka* showed better removal efficiency and consistency of the performance. The authors also stated that *Phragmites karka* was more resilient than *Phragmites australis*, but from a maintenance point of view *Phragmites karka* took up more water due to its greater aboveground biomass and may be disadvantageous if water recovery for reuse is a priority.

To increase the aesthetic value of the wetland systems, ornamental plants such as Canna and Heliconia were used in the studies by Koottatep, Konnerup, and Brix (2009), and commercial plants such as *Zantedeschia aethiopica*, *Strelitzia reginae*, *Anthurium andreanum*, *Agapanthus africanus, Canna hybrids and Hemmerocallis dumortieri* were used in another study by Zurita, Anda, and Belmont (2009) and Zurita et al. (2011). These plant species were used in engineered wetlands for wastewater treatment and their studies had revealed the potential of using these ornamentals to remove wastewater pollutants without deteriorating the efficiency of the treatment system.

2.3.4 Wetland Substrate

Substrate in the engineered wetlands is an essential component in supporting the growth of emergent plants and the attached-growth microorganisms, hydraulic conductivity and nutrient adsorption (Hoa and Koottatep 2007). Substrate in subsurface wetlands provides surface area to support microbial growth while maintaining a good hydraulic conductivity (Kadlec and Knight 1996), which is important to prevent prolonged surface ponding and substrate clogging for maximum treatment efficiency. The material of the substrate to a treatment wetland is very important in wetland planning and design, as it is the foundation for all the abiotic and biotic components present within the system (Kadlec and Knight 1996).

The conventional types of substrate used in subsurface wetlands include gravel, sand and soil. According to Gale, Reddy, and Graetz (1993) and Williams et al. (1994), substrate is the main parameter affecting nitrogen removal in the subsurface engineered wetland system. Nitrogen removal is vital in wastewater treatment as the nitrogen compounds such as ammonia can impose significant oxygen demand in the wastewater through biological nitrification and may cause eutrophication in receiving water bodies, besides being toxic to aquatic organisms (Korkusuz, Beklioğlu and Demirer 2005). Nitrogen transformation is an important microbiologically mediated treatment process and the removal of nitrogen in wetlands is achieved either by transformation into nitrogen gas, or by conversion into the form of ammonia or nitrate that could be absorbed by plants during plant assimilations.

The major removal mechanisms for total nitrogen are the microbial nitrification and denitrification processes (Korkusuz, Beklioğlu and Demirer 2005). Classic nitrification consists of a two-step oxygen driven process of ammonia oxidation to nitrite, followed by nitrite oxidation to nitrate (Cooper et al. 1996; Kadlec and Knight 1996). Classic denitrification occurs under anoxic conditions with organic carbon as electron donor and nitrate as electron acceptor (Sun and Austin 2007). According to Bachand and Horne (1999), the denitrification process is the only dominant and long term nitrate removal mechanism in engineered wetlands. The denitrification process is able to contribute up to 60 – 70% of the total nitrogen reduction, with 20 – 30% of that derived from plant uptake (Reddy and D' Angelo 1997; Spieles and Mitsch 2000).

The limitations of conventional gravel substrate in terms of nutrient removal have encouraged the use of alternative materials to replace gravels as wetland media. Previous researches had found several types of organic solids that can be used simultaneously as wetland media and carbon source to support the denitrification process. Organic substrates like maize cobs, green waste, wheat straw, soft wood and hard wood were used as external carbon sources to increase the denitification rates (Cameron and Schipper 2010). According Cameron and Schipper (2010), maize cobs were found to be an excellent carbon substrate which effectively removed nitrate. During the 23 months of experimental study, the authors found the long-term nitrate removal rate for maize cobs to be 3 – 6.5 times greater than wood media at 23.5 °C and 14 °C treatments, respectively. It was concluded in the study that the more labile carbon sources, such as maize cobs, green waste, and wheat straw provided significantly greater nitrate removal rates than wood substrate (Cameron and Schipper 2010).

Various combinations of wood materials such as sawdust (*Pinus radiata*), sawdust with soil, sawdust with sand, and medium-chip wood chippings with sand, were examined in a study by Healy, Rodgers, and Mulqueen (2006) as carbon sources in horizontal flow filters to denitrify nitrate in a synthetic wastewater. The wood chippings with sand mixture filter which was fed with 60 mg/L of NO_3-N yielded the highest nitrate removal performance, with 97% reduction of nitrate over a study period of 166 days under steady-state conditions (Healy, Rodgers and Mulqueen 2006). The study demonstrated the potential of using wood products for efficient removal of nitrate from wastewater. Other types of substrate such as plant biomass (Gersberg, Elkins and Goldman 1983), cotton burr and mulch compost (Su and Puls 2007) had also been used for wastewater treatment in subsurface wetlands at different countries in various studies.

To date, the focus on the use of gravel substrate substitute to remove nutrients is mainly on phosphorus elimination, where the research into nitrogen removal is still relatively minor. The important property of the alternative materials in terms of total nitrogen removal is primarily the ability to provide carbon feed for denitrifiers in order to reduce nitrate from nitrified influent into nitrogen gas. It is therefore crucial to select suitable materials to promote leaching of organic carbon into the system for enhanced nitrogen removal.

2.3.5 Wetland Dimensioning

There are a few guidelines available for the treatment of wastewater by engineered wetlands in various applications. In terms of wetland dimensioning, simple design models using rules of thumb providing a specific area per people equivalent as described by Wood (1995) and Kadlec and Knight (1996), regression equations by Brix (1993), the first-order k model by U.S. Environmental Protection Agency (1988) as well as the modified k-C* model by Kadlec and Knight (1996) are commonly used for prediction of wetland performance. General guidelines and maximum loading rate criteria are popular and reasonably effective for engineered wetlands design according to IWA (2000) and U.S.EPA. (2000). Therefore, the simple (*k*) and modified (*k*–*C**) first-order models are the most widely used model for predicting wetland performance and sizing of the system (IWA 2000; U.S.EPA. 2000). The first order kinetics model was preliminarily referred to with the assumptions of plug flow, minimal short-circuiting and uniformly distributed flow across the wetland. This model is normally used for purposes of preliminary sizing of new systems as well as performance evaluation of existing systems, as it does not require site specific data (Economopoulou and Tsihrintzis 2003).

Since sufficient oxygen supply is regarded as one of the main reasons of using VF wetlands for wastewater treatment and that the sizing of the wetlands is intimately related to the oxygen transfer capability of the bed, designing the VF wetlands based on oxygen transfer rate (OTR) as recommended by Platzer (1999) is also commonly referred to. According to Platzer (1999) and Cooper (1999), the most critical factor for the design of VF wetlands is total oxygen input which in terms of operational aspects of a single wetland bed, relates to the design (substrate media size and depth), wastewater strength (dissolved oxygen concentration) and frequency of loading cycles (oxygen by air flow).

For sludge treatment in engineered wetlands, Nielsen (2003) claimed that correct dimensioning, construction and operation of the beds are important as they ensure extended operational period, effective dewatering in the form of draining and evapotranspiration of water from the sludge, and a good decomposition of organic matter. Overloading during the run-in period and in the subsequent operational period are stated as other typical operational errors (Nielsen 2003). The amount of sludge to be treated, the quality of sludge, as well the climatic conditions should be considered when dimensioning engineered wetlands for sludge treatment. Typically the dimensioning of the sludge treatment wetlands is determined by the sludge areal loading rate (also known as solid loading rate, SLR) in terms of kg $TS/m^{2}\cdot yr$.

2.4 Summary

The engineered wetland has been proven by various researchers to be a natural, economically attractive, and energy efficient technology that is effective in treating various types of wastewaters, including septage. As a preferred technological system to treat polluted water, especially in developing countries, the wetlands system is carefully designed and set up in a controlled environment that mimics essential ecological functions. From previous research, the potential of engineered wetlands in wastewater treatment has been largely investigated in temperate and subtropical zones of North America and Europe, but few studies have been documented for the tropical regions of the world. The understanding of wetland treatment processes is still evolving, even though the wetland technology has been studied since 1952. Knowledge gaps such as the effects of loading mode and frequency on septage treatment efficiency, and the use of alternative materials and plant types have limited the technology’s implementation in the treatment of septage.

Due to the fact that septage exhibit greatly heterogeneous characteristics compared to domestic wastewater, a careful selection of appropriate treatment options is required, especially at the first stage of treatment where a large portion of the solids is to be removed. In Thailand, a good track record of effective septage treatment by engineered wetlands highlights the potential of adopting this green system for septage treatment in Malaysia. However, limited knowledge on this eco-technology, which has long been conceptualised as a “black-box” in terms of its treatment ability, suggests further research into the area to optimize design of the system, where the issues with clogging (especially for VFEWs) and various factors affecting the pollutant removal performance should be duly addressed and studied.

Chapter 3 Materials and Methods

3.1 Overview

A two-stage pilot-scale vertical flow engineered wetlands (VFEWs) system was designed and constructed to determine its feasibility and efficiency in septage treatment. The major focuses of this study were the various system and operation related parameters that affect the treatment efficiency of the wetlands. Detail specifications of the system and its operational practices are discussed in sections 3.2 to 3.5. Section 3.6 presents the methodologies for water quality assessment, as well as the data and statistical analyses of the study outcomes. Section 3.7 reports on the characteristics of the raw household septage used in this study.

The use of data obtained by using synthetic wastewater or sludge treatment in small-scale laboratory experiments for the design of full-scale treatment systems had been suggested as unsuitable by Kadlec and Wallace (2009). Treatment in small-scale systems are subjected to significant edge effects, and the use of relatively simple synthetic wastewater or sludge does not represent the treatment responses of real wastewater or sludge which is a lot more complex (Kadlec and Wallace 2009). Hence for this research project with pilot-scale VFEWs system, raw septage pumped by vacuum trucks from domestic septic tanks was used for treatment to eliminate the possible discrepancies of data obtained due to the use of synthetic septage. Real septage however, often has varying concentrations of constituents and the quality can differ significantly between every septic tank. The septage depends on many factors that influence its quality, which include septage storage duration, septic tank size, septic tank design and climatic condition, among others.

Septage for this research project was supplied by one of the local environmental servicers in Miri weekly and/or upon request. The septage used in this study was pumped from household septic tanks around the city that collect only toilet wastewater (excluding bathroom, laundry and kitchen load). At the time of commencement of this research project, there was no mandatory desludging ordinance set by the Miri local authority and no regulations were strictly followed for septage disposal. Generally, septage haulers would only perform their services upon request by the owner of premises.

3.2 Project Site

The experiment was set up in the grounds of Curtin University Miri, Sarawak which is located in East Malaysia, on the island of Borneo. Sarawak has an equatorial climate with hot and humid weather throughout the year. The average annual temperature falls within the range of 23 ℃ to 32 ℃, with rainy seasons occurring from November to February (Sarawak 2013). The project site is located beside the intermittent decanted extended aeration (IDEA) treatment plant in Curtin Sarawak, Miri. The system was set in an open field exposed to indirect sunlight and wind. A semitransparent overhead roof was constructed and a transparent PVC plastic sheet was installed around the perimeter of the project site to shelter the system from rainfall, as to prevent precipitation from disrupting the system and affecting the experimental output as a result of stormwater dilution.

A pilot-scale system was constructed for this research project with a two-stage integrated treatment, comprising a series of vertical flow beds and storage tanks. These outdoor filter beds were set up to simulate vertical subsurface wetlands for treatment of septage. The pilot-scale system which was constructed out in the open was preferred over the laboratory-scale system, as it was expected to better replicate the ambient environment of the nature and promote healthier growth of plants. These wetlands were allowed to have interaction with their surrounding environment (except being shaded from rain and direct sunlight) during the experimental period. The statistical replication for this research project was carried out with time blocking or sequential experiments (week as blocking factor), conducted on the same system following the acclimatization period.

3.3 System Description

The VFEWs system was designed to treat domestic septage pumped from septic tanks. The septage was transported to the project site by vacuum truck weekly or upon request. All septage was filtered through a stainless steel grid basket (Figure 3.1) upon delivery to the project site to remove garbage or any other coarse debris before storage in the septage receiving tanks. When the septage was unloaded from the truck, the truck feeder pipe was directed into a water tank fitted with the basket to screen out the unwanted materials from the incoming septage. The screened septage was then pumped up into two elevated septage storage tanks (1.5 m above ground) using a submersible pump. As shown in Figure 3.2 and Figure 3.3 below, the septage receiving tanks were positioned at the forefront of the treatment train to receive and store the septage. Two stages of treatments by vertical flow wetlands followed, with each unit built with different system aspects and operated under varying feeding regimes designed to examine the hypotheses of this research project.

Figure 3.1 Garbage strained out from the raw septage upon the truck arrival at the project site

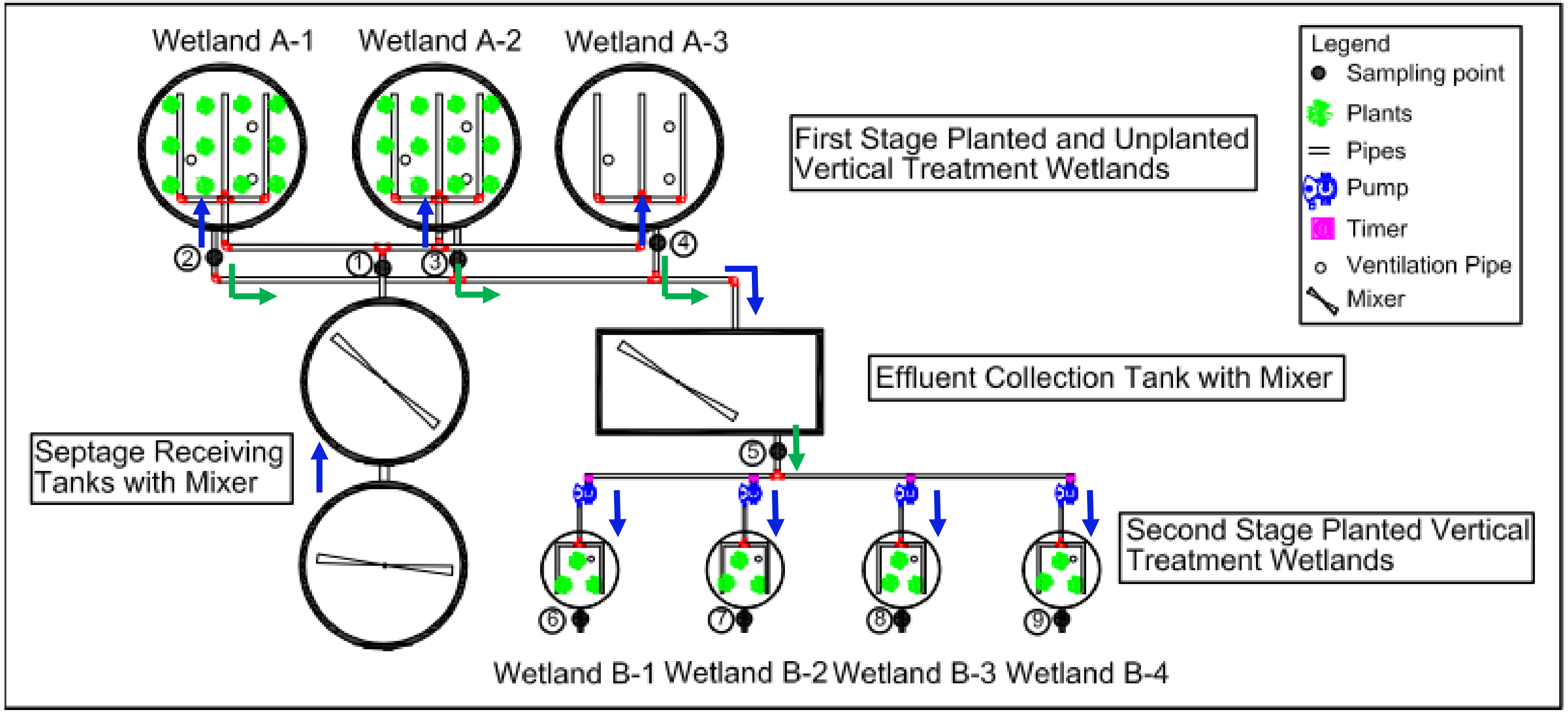


Figure 3.2 Schematic diagram of the two-stage pilot VFEWs system (plan view)

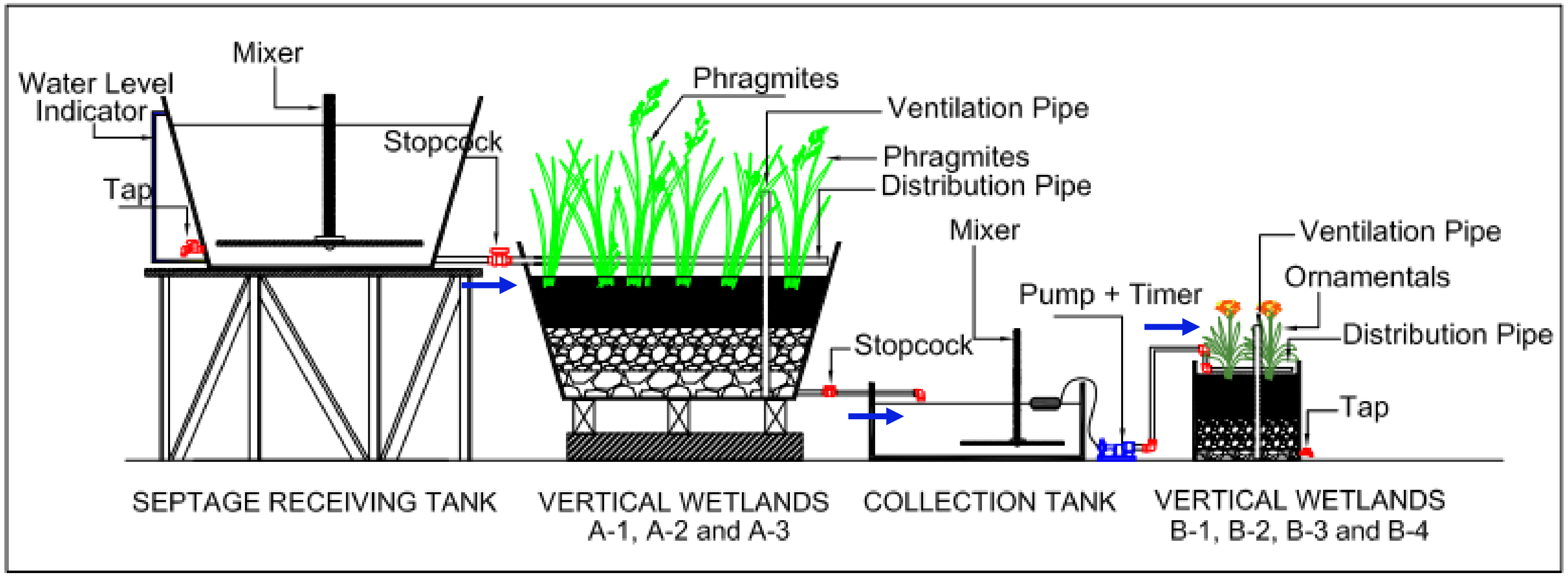


Figure 3.3 Side view of one treatment line of the VFEWs system completed with mechanical and electrical fittings

400-gallon tapered polyethylene (PE) water tanks (1.70m diameter by 1.30m in height) were used as the basin for the first stage wetlands. These wetlands had a substrate height of 0.80 m and a freeboard of 0.50 m for septage accumulation. The outflow from all the first stage wetlands was conveyed into a 200-gallon PE effluent tank for storage before the effluent was pumped into the second stage wetlands for further treatment. The second stage wetlands were built with PE cylindrical drums (0.55 m diameter and 0.90 m height) with bed height of 0.65 m and freeboard of 0.25 m. Ventilation pipes were installed into the wetlands substrate to encourage passive aeration of the beds and prevent anaerobic environment in the deeper media layers. Three and one 25 mm diameter perforated PVC pipes were inserted vertically into each wetland at the first stage and the second stage, respectively. The pipes were extended to about 0.50 m from the surface of the beds and reaching down to 0.10 m above the bottom of each wetland.

A total of three motor-driven mechanical mixers were installed in the system, one for each storage tank and collection tank to ensure homogeneous mixing of septage before feeding into the wetland beds. The motorized mixers which were mounted on the top of the tanks were supported by rigid steel frames. The feeding system of the wetlands constituted a network of 50 mm and 25 mm perforated pipes across the open surface of stage one and two wetlands, respectively for an even distribution of influent. Stopcocks and water taps were installed at designated locations in the system to direct the water flow and to obtain test samples at different stages for water quality analyses. Sampling points for the wetlands influent and effluent are shown in Figure 3.2. Holes of 10-12 mm were drilled at the bottom of the inlet pipes every 80 mm for raw septage feeding at the first stage wetlands. And for the second stage wetlands, 5 mm perforated holes were drilled at the bottom of the distribution pipes at every 50 mm.

The septage from the receiving tanks was gravity fed into the first stage wetlands on a weekly basis through the distribution network. The feedings were done manually once every week. Modified pumps and timers were incorporated into the second phase of the treatment system to control the discharge of effluent collected from the first wetlands into the subsequent vertical beds. The inlet dosing frequency and volume applied per dose for each wetland at the second stage was regulated by the electrical pumps and timers. These devices were customized and configured such that the pumps will operate at certain pre-set time interval for a specific running time per feed. Each wetland in the second stage was run by a set of individual pump and timer. All the pumps were linked to a float switch to cut off pump operation at low water level to prevent pump damage. Figure 3.4 to Figure 3.9 depict the photos of the treatment wetlands and the construction of the pilot system.

Figure 3.4 Sand and aggregates delivered to the project site for construction of wetlands

Figure 3.5 Aggregate sieving as the first round of aggregate size selection

Figure 3.6 Second round of aggregate sorting by hand picking

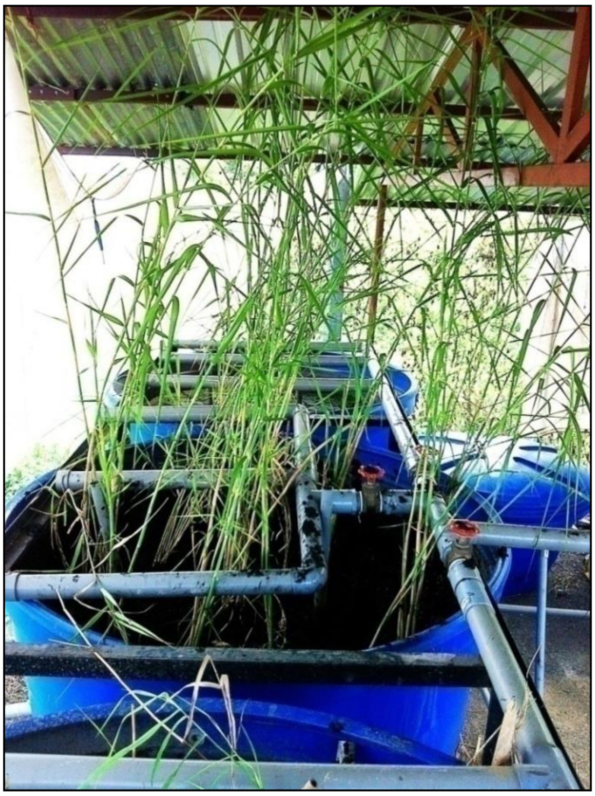


Figure 3.7 First stage of wetlands with two planted units (with *Phragmites karka*) and one unplanted unit completed with pipe network for septage distribution (Wetland A1- A3)

Figure 3.8 Second stage of wetlands planted with *Phragmites karka* completed with pipe network for septage distribution (Wetland B1-B4)

Figure 3.9 Front view of the VFEWs treatment system

3.4 Sizing of Wetlands

3.4.1 First Stage Wetlands (A1-A3)

Septage solid loading rate (SLR) is a hydraulic measurement in terms of the mass of total solids applicable per square meter of the wetland surface per year (kg TS/m^2.yr). Weekly septage loading was calculated based on the designed SLR and the total solids content as shown in Equation 1 below:

Hydraulic Load (mm/week) = $\frac{C1}{C2} \times \frac{1}{52}$ …………….................................... Equation 1

Where,

C1 = Annual sludge total solid loading rate (kg TS/m^2.yr)

C2 = Total solids (TS) content of each raw septage newly delivered (kg/L)

3.4.2 Second Stage Wetlands (B1-B4)

For the wetlands at the second stage, the area of the beds were checked against the oxygen demand and oxygen input of the wetlands as per the equation recommended by Cooper (1999) (Equation 2). Further removal of COD and nitrogen were intended at this second stage of treatment. The removals of both the organic and nitrogenous compounds are affected by the oxidation and the reduction condition in the wetlands, at which an aerobic environment will promote bacterial growth and simulate the breakdown of both carbonaceous and nitrogenous organic compounds.

Area, $A = \frac{OD}{OI\ (A)}$ ……..………..........…………………………………… Equation 2

Where,

Oxygen demand, OD (g/d) = $[0.7(COD_{in} - COD_{out})] + [4.3(NH_3\text{-}N_{in} - NH_3\text{-}N_{out})] - [0.3(2.9)(TKN_{in} - TKN_{out})]$

Oxygen input, OI (g/L) = Aeration potential of a vertical flow wetland assumed to be 50 g $O_2m^{-2}d^{-1}$ (Cooper et al. 1999)

A = Area of bed surface (m^2)

At the first stage of treatment, we made assumptions from the study carried out by Koottatep et al. (2001b) in Bangkok, Thailand on:

Raw septage characteristics: COD = 17 g/L; NH_3-N = 0.35 g/L; TKN = 1 g/L

Pollutant removal efficiency: COD = 96%; NH_3-N = 85%; TKN= 93%

And thus, producing effluent with:

COD = 0.68 g/L; NH_3-N = 0.053 g/L; TKN = 0.07 g/L

The final effluent pollutants concentration after the second stage of treatment (Standard A (Department of Environment 2009) (please see Appendix A)) was expected to be as follow:

COD = 0.12 g/L; NH_3-N = 0.01 g/L;

TKN= 0.02 g/L; (with at least 70% of removal after second stage of treatment)

Hence,

$$OD = [0.7\ (0.68 - 0.12) + 4.3\ (0.053\text{-}0.01) - 0.3\ (2.9)\ (0.07 - 0.02)]\ \text{g/L} * 21\text{L/d}$$

$$= 11.21\ \text{g/d}$$

$$A = \frac{OD}{OI} = (11.21\ \text{g/L})/(50\ \text{g}\ O^2 m^{-2} d^{-1}) = \underline{0.22}\ m^2$$

Thus, the minimum surface area for the wetlands at the second stage was set to be 0.22 m².

3.5 Wetland Substrate and Plants

Like any other ecological system, engineered wetlands are complex, living systems that evolve in response to local conditions and climate. Amongst the important parameters that are considered for successful implementation of the technology are substrate design and plant presence, besides general sizing of the wetland beds. In this research project, crushed limestone which is also known as aggregate was used as substrate in the vertical filter beds. It is a common construction material that is easily available locally. Crushed limestone is distinct from gravel (also known as sandstone or riverstone) which typically has a more rounded shape due to the natural processes of weathering and erosion at the river bed. In Sarawak, crushed limestone is relatively cheaper compared to the river gravels. Thus these crushed carbonate rocks were used to form the porous media of the VF wetlands, which acted as the main substrate of the treatment system.

Each wetland at the first stage had a bed surface area of 2.20 m^2 and the total depth of the substrate was 800 mm, with 500 mm freeboard for sludge accumulation. From bottom to top, the crushed stones filter consisted of a 200 mm layer of coarse aggregates (diameter 50 - 60 mm), a 300 mm layer of medium aggregates (diameter 30 - 45 mm), and a 300 mm layer of fine aggregates (diameter 8 - 10 mm) as shown in Figure 3.10. Each wetland at the second stage had a surface diameter of 550 mm and a total substrate height of 800 mm. The wetlands substrate comprised of (from bottom to top) medium sized crushed limestone (diameter 37.5 mm; 50 mm thick), fine aggregates (diameter 8 - 10 mm; 200 mm thick), pea gravels (diameter 3 mm;

200 mm thick), palm kernel shells (PKS) (250 mm thick) and topped with river sand (100 mm thick) as depicted in Figure 3.11.

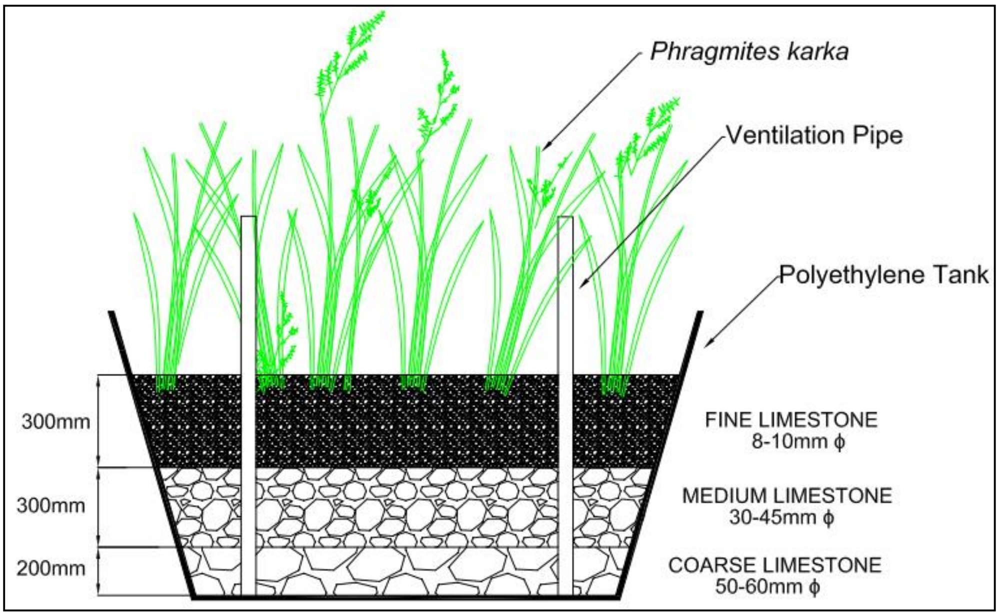


Figure 3.10 Substrate grading and layer depth for first stage wetlands

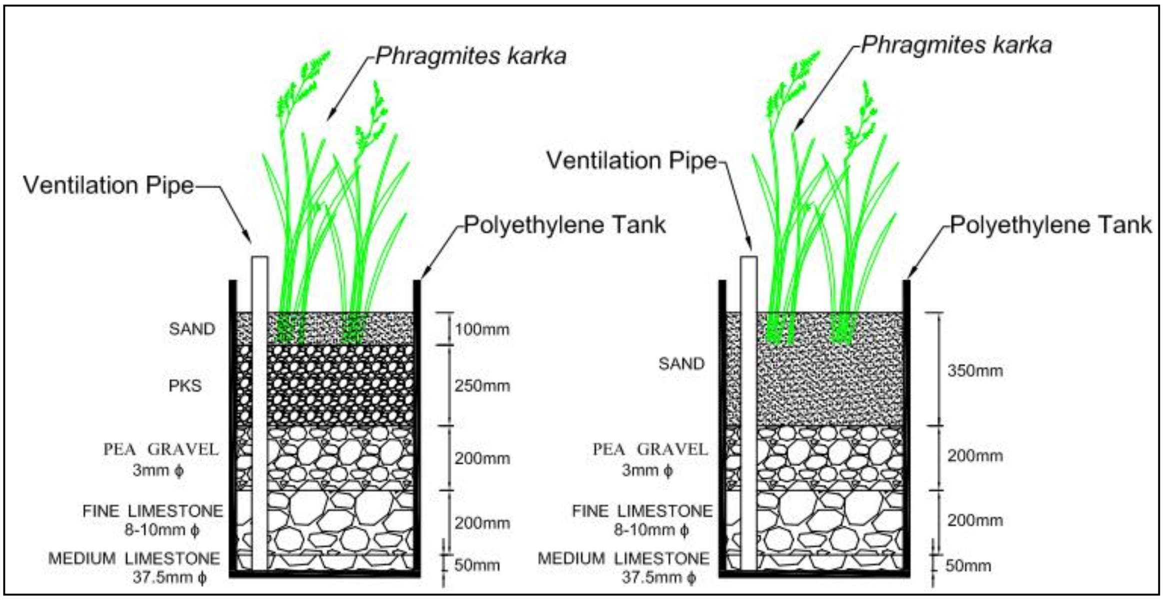


Figure 3.11 Substrate grading and layer depth for second stage wetlands (Left) with addition of PKS; (Right) without PKS

The crushed limestone was purchased directly from the local quarry and pea gravels from a local nursery. The aggregates were sieved and washed before being filled into polyethylene tanks as wetland substrate. Washed sand was added at the topmost layer to facilitate dispersion of the applied influent and to assist the growth of plants. The sand layer together with the septage deposit that was retained on the bed surface over time could assist in achieving a more uniform distribution of influent. The layers allowed initial flooding of the surface, followed by gradual seepage through the depth of the media.

As mentioned previously, PKS was added as part of the substrate in the second stage wetlands to study on its effects on the removal of pollutants from the septage influent. Malaysia is one of the world's leading countries in the palm oil industry, which subsequently leads to production of a large amount of wastes or by-products from the industry. It is estimated that 0.4 million tonnes of palm shells is created for every one million tonnes of palm oil produced (Bt Fuadi, Ibrahim and Nor Ismail 2012). PKS has high volatile and carbon contents (about 18 %w/w) (Aik and Jia 1998) and thus it could be used to supply additional carbon for the wetlands internally, as an alternative for methanol or activated carbon addition at wetlands to improve nitrate removal from the septage.

All the planted wetlands in the VFEWs system were planted with an indigenous wetland plant known as reeds or *Phragmites karka. Phragmites karka,* the common reed, is a large perennial grass of the family Poaceae. It has long rhizomes and robust, erect culms to 3 m (Dabadghao and Shankarnarayan 1973). The leaves are 15-30 cm long and nearly 2.5 cm broad, and the inflorescence is a large plume-like panicle with capillary branches and small, slender spikelets (Dabadghao and Shankarnarayan 1973).

The literature on *Phragmites* as a genus is quite extensive (Vymazal and Kröpfelová 2005; Armstrong et al. 2000; Lee and Scholz 2007; Best, Zippin and Dassen 1981; Hara, Toorn and Mook 1993; Marks, Lapin and Randall 1994) but at species level, most of the information is on *Phragmites australis*, with relatively little documentation on *Phragmites karka*. *Phragmites karka* was chosen as the wetland plant as it is widely distributed in Miri, besides having high potential productivity, deep rhizomes and root systems, and is readily cultivatable. At the second stage wetlands, *Costus Woodsonii* was planted in one of the beds to study its potential in treating wastewater. *Costus Woodsonii* which is also called the "dwarf lipstick" has bright red heads and deep green, shiny foliage on spiral stems. The plant do best in partial shade, though some thrive in full sun, others in full shade (Tropical).

In July 2011, mature reeds together with their roots were dug from the soil at the nearby river bank with a ball of field soil intact and brought to the project site. The plants were washed and the roots and rhyzomes were separated into individual shoots gently by hand. Each plant with rhizomes attached with stems of least 2 nodes was replanted individually into a plastic nursery bag filled with fine aggregates (3 - 8 mm). After the transplants, the reeds were observed to wilt and die for about a week or two possibly due to transplant shock, before new green auxiliary buds were seen growing out of the nodes. The reeds continue to grow rapidly and healthily since then. During the two months of growing period in the nursery bags, the plants were kept flooded with tap water and fed with liquid organic fertilizer fortnightly to boost plant growth.

Sieved and washed aggregates were filled into the polyethylene tanks and compacted by layers according to designed grading and depth in September 2011. The reeds were then transplanted from the nursery bags into the wetlands. After two months of growing period in the nursery bags, the reeds were rooted and the bags had to be removed with care so as to minimise the disturbance of the root ball. The reeds were planted into the wetland aggregates with the upper part of the stem exposed above the substrate and the water level, in order to maintain the growing points. The reeds were planted at approximately 0.3 m apart with a total of twelve plants per wetland at the first stage (i.e. about 6 plants/m^2), and three plants per wetland at the second stage.

Engineered wetland is essentially an ecological system, therefore some time is required for the system to establish itself before it becomes stable and the system performance to be evaluated. This is known as the acclimatization period or the commissioning period. There are varying guidelines as to the length of the acclimatization period, ranging from two to six month in the tropical climate as reported in the literature (Koottatep, Konnerup and Brix 2009; Trang et al. 2010; Koottatep et al. 2005). In order to prevent shock loading and to allow for plant acclimatization at the start of the experiment for first stage wetlands, the reeds (*Phragmites karka*) were allowed to grow for 8 weeks in the wetlands saturated with raw domestic wastewater collected from the nearby drains. The wastewater was later mixed with 25% of septage and fed twice weekly onto the wetlands, with the septage dosage increasing at 25% in a monthly step. On the 6th month, the wetland units were loaded with undiluted raw septage at the designed SLR once weekly for 4 weeks, before the commencement of sample collection for laboratory and in-situ analyses. These feeding practices are important steps to seed the wetland units with microorganisms as preparation for the subsequent treatments.

Following the acclimatization period, full operation of the system commenced on March 2012 and the study was conducted for a total of approximately 11 months. Throughout the experimental period, it was observed that the *Phragmites karka* at wetlands of both stages were infested by aphids and scale insects (Figure 3.12). Armies of ants were also spotted on the wetland beds and in the stems of the reeds. The infections of plants by aphids and scale insects, and the invasion of ants may have been encouraged by the shelter provided by the overhead roof to prevent the wetlands from rainwater and direct sunlight. The presence of ants together with aphids are known to be a mutualism relationship, with the ants farming the aphids and protecting them from predators, and in return the aphids supply the ants with sugar-rich sap (honeydew) from the plants' tissues (Delabie 2001). Allowing full sun exposure on the wetland beds by removing the roof could commonly help to resolve the problem with the insect infestation.

Figure 3.12 *Phragmites karka* planted in the wetland beds that are infested by aphids

During the early period of the experimental programme, some of the reeds experienced gradual die-off and about 40% and 60% of the reeds failed to survive in the two planted wetlands at the first stage after 3 months of operation. The limited reed survival could be attributed to the excess heat generated at the treatment site due to the lack of air circulation. The transparent PVC plastic sheets used to surround the perimeter of the project site caused heat to be trapped and accumulated within the vicinity. The plastic sheets were previously installed at the project site before the commencement of the experimental programme to prevent rainwater intrusion.

Replanting of the reeds was carried out in June 2012 to replace all plants that failed to establish. The reeds were transplanted from those grown in the plastic nursery grow bags placed alongside the wetlands as shown in Figure 3.13. These reeds were sourced from the same quarters as those planted in the wetlands and were also fed with diluted septage during the period to prepare them as back-up. Some of the PVC plastic sheets were then removed to allow for better air circulation at the site. This had clearly imposed a positive influence on the establishment of reeds with the overall survival rate at 90% after replanting. Continuous inspections had shown that the replanted reeds were suitably established after 1.5 months and the experiment programme was resumed in mid July 2012.

Figure 3.13 *Phragmites karka* planted in plastic nursery grow bags alongside the wetlands

3.6 Sampling and Analysis Protocols

Standard sampling procedures were adhered to during sample collection and the sample analyses were conducted according to the methods described in section 3.6.1. Statistical analyses on the collected data were carried out to evaluate the performance of the wetlands following the protocols presented in section 3.6.2.

3.6.1 Laboratory and In-situ Test Plan

3.6.1.1 Septage Deposit Layer

Core samples of septage deposit were retrieved using a stainless steel soil core sampler (3.8 cm diameter). The deposit samples were taken fortnightly, i.e. after every two cycles of loading using the core sampler by penetrating the entire septage deposit layer at three different points on the surface of each bed. The core samples were divided at mid-height into two segments, and both the top and bottom parts were analysed for dewatering and mineralisation efficiency. The septage deposit height was measured and the occurrence of clogging was observed as part of the assessment procedure.

Although the assessment of the hydraulic flow behaviour was not a primary aim of this research project, clogging is a common and serious operational problem in vertical flow engineered wetlands. Substrate clogging occurs when there is a physical flow restriction through the wetland filter media. Clogging leads to deterioration of the infiltration capacity at the substrate surface, besides causing occurrence of preferential flow within the substrate media due to the reduction of interstitial pore spaces between the aggregates. It is therefore essential to ensure that the system design is suitable for the intended operational regime (and vice versa) to minimise occurrence of clogging in the wetland beds. Clogging phenomena in this study was subjectively assessed based on the amount of time the septage was seen to be ponding on the surface of the wetlands. The wetland beds are reported as clogged if the infiltration time was more than 5 days.

(A) Dewatering

The physical index used to evaluate the dewatering efficiency of the wetlands on the septage deposit was the dry matter (DM) content, presented in percentage (Equation 3). Septage deposit core samples were stored in sealed containers and brought back to the lab immediately after collection for analyses. Contact time with the open air was minimized to avoid moisture loss due to evaporation before taking the wet sample weight. Core samples of the septage deposit obtained were thoroughly mixed and homogenized before each sub-sampling. Subsamples were placed in ceramic crucibles and placed in the oven for drying. Plant detritus, roots, aggregates and any coarse debris present in the core samples were removed before drying them in an oven for at least 24 hours at a temperature of 105 ℃. Larger subsamples are more representative, especially for high DM or heterogeneous samples like septage as suggested by Peters et al. (2003). Thus subsample size of at least 20g was used for analysis. Empty crucibles and crucibles with subsamples before and after oven drying were weighed and recorded to the nearest 0.001g. The subsamples were dried in the oven for 24 hours and later removed from the oven, before allowing to cool to room temperature in desiccators with active desiccants.

$$\% \text{ DM} = \frac{(W_A - W_B) x\ 100}{(W_C - W_B)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad \text{Equation 3}$$

Where,

W_A = Weight of dried septage deposit (g) + Weight of dish (g) after oven drying

W_B = Weight of empty dish (g)

W_C = Weight of septage deposit (g) + Weight of dish (g) before oven drying

(B) Mineralization

For septage deposit, the measure of organic content was used to indicate the process of septage mineralisation. The volatile solids (VS) content was the physical indice used to indicate the mineralization of the septage deposit, and the percentage of VS reduction was reported to evaluate the efficiency of the wetlands (Equation 4). VS are solids ignitable at 550 ℃ and are considered a rough measure of organic content which corresponds to the degree of septage mineralization. The drying procedures of the septage deposit core samples were carried out as per the method employed for DM testing, described previously for the assessment on septage dewatering. To do the VS test, the cooled and weighed samples together with the crucibles in the DM test were ignited in the furnace for 30 min at 550 ℃. Samples were removed from the furnace and allowed to cool in the desiccators before final weighing.

$$\% \text{ VS} = \frac{(W_A - W_B) x\ 100}{(W_C - W_B)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad \text{Equation 4}$$

Where,

W_A = Weight of oven dried septage deposit (g) + Weight of dish (g) after ignition at 550 ℃

W_B = Weight of empty dish (g)

W_C = Weight of septage deposit (g) + Weight of dish (g) before ignition at 550 ℃

3.6.1.2 Septage influent and effluent

As extensive wetlands and sample replications are costly in terms of materials, construction, operation, sampling, and laboratory testing, statistical analyses were performed based on sequential time blocking of the data obtained from the different stages and phases of experiment (operating conditions outlined in section 2 of Chapters 4 to 7). A single uniformly homogenised replicate from each sampling point (at least 2L of influent and effluent was collected and thoroughly mixed before sampling it for laboratory analyses) was retrieved once every week for lab and in-situ analyses.

Septage influent was sampled for analyses before each wetland application. Grab samples were taken from the inlet septage storage tanks, the effluent collection tank and through the tap points at the base of every wetland using pre-washed 2L high-density polyethylene (HDPE) plastic containers. Septage effluent after the first stage of wetland treatment was collected from each bed 24 hours after the raw septage was fed onto the individual wetlands. Influent for the second stage of treatment was sampled from the collection tank that was used to store all effluent discharged from the first stage wetlands. The effluent in the tank was continuously stirred by a mechanical mixer to ensure homogeneous feeding onto the subsequent wetlands via pumps.

All samples were collected in the morning around 8:00 – 9:00 am on the same day weekly or at the end of each fill-pond-drain-rest cycle (batch mode), and were transported to the laboratory within 30 minutes after in-situ testings (pH, dissolved oxygen (DO), oxygen reduction potential (ORP), electric conductivity (EC) and temperature) for analyses. The influent and effluent samples were refrigerated at 4 °C if the analyses were to be done after 2 hours. No replicate was taken during sampling unless otherwise required for testing as stated in the standard methods.

In the case of the intermittently-fed wetland, effluent samples were collected before the subsequent feeding process. Each experimental run designed to investigate different parameters for the research project lasted for at least 10 weeks and on top of that, a minimum of 2 weeks of acclimatization period was included between every switch of flow regime (e.g. switch of loading rates) or change in the system aspects (e.g. change of substrate type). It was assumed that the experiment order did not affect the results because sufficient time was allowed for all the wetland operation to stabilize after each switch to a new flow regime or each re-establishment of new system parameters.

Characterisation of influents and effluents

Total solids (TS), total suspended solids (TSS), volatile solids (VS), water temperature, pH, oxygen reduction potential (ORP), hydraulic conductivity (EC) and dissolved oxygen (DO) were the physical indices that were tested to characterise the wetland influent and effluent. Biochemical indices which include 5 days biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), ammonia nitrogen (NH_3-N), nitrite nitrogen (NO_2-N), nitrate nitrogen (NO_3-N), and total nitrogen (TN) were also tested on all the collected water samples. COD, NH_3-N, NO_3-N, NO_2-N and TN were analysed using spectrophotometer (HACH-DR2800, USA). However, the samples collected from the VFEWs system were often too concentrated for the selected testing protocol using the spectrophotometer. It was thus necessary to dilute these solutions to bring down the influent and effluent strength to the testable ranges by the DR 2800 spectrophotometer. The dilution factors (DF) were obtained by trial and error, especially for raw septage due to the wide range of septage strength. The DF was calculated based on Equation 5 below. The DF used to dilute the samples were recorded and multiplied with the readings obtained from the spectrophotometry tests to obtain the actual final concentrations.

$$\text{Dilution factor (DF)} = \frac{Sample\ volume\ (L) + Volume\ of\ dilution\ water\ (L)}{Sample\ volume\ (L)} \quad \text{.......... Equation 5}$$

The influent and effluent samples were analysed weekly to assess their bio-physicochemical properties according to the procedure manual of spectrophotometer DR 2800 (HACH 2007) (Table 3.1) or the Standard Methods for Examination of Water and Wastewater (APHA 1998) (Table 3.2). Performance in terms of percentage of pollutants removal for each wetland was calculated as delineated in section 3.6.2. In-situ testings on dissolved oxygen (DO), pH and electric conductivity

(EC) were determined using Hach Lange HQ40d Multimeter, whereas the oxygen reduction potential (ORP) was tested with an Ezdo ORP 7011 Hand Held Tester.

Table 3.1 Test methods for wetland influent and effluent analyses using HACH Spectrophotometer DR 2800 for water and wastewater testing

Constituent	Method
COD	*Method 8000 - Reactor Digestion Method
NH_3-N	Method 10031 - Salicylate Method Test 'N Tube Vials
NO_3-N	Method 10020 - Chromotropic Acid Method Test 'N Tube Vials
NO_2-N	*Method 8507 - Diazotization Method Powder Pillows
TN	Method 10072 - Persulfat Digestion Method Test 'N Tube Vials

* Denotes method accepted or approved by USEPA for water or wastewater analyses

Table 3.2 Standard test methods for examination of water and wastewater according to APHA (1998)

Constituent	Method
BOD_5	Method 5210B - 5-Day BOD Test
TS	Method 2540B - Total Solids Dried at 103-105ºC
TSS	Method 2540D - Total Suspended Solids Dried at 103-105 ℃
VSS	Method 2540E - Fixed and Volatile Solids Ignited at 550ºC

Capillary suction time (CST) of the septage was also examined for septage characterisation as this test method has been widely accepted and used for the measurement of dewaterability of sludge (Huisman and Van Kesteren 1998). CST measures the time in seconds for the interstitial water from the sludge to wet a standard area of a specific filter paper, and is measured automatically by electrodes that are turned on and off as the water passes through (Triton Electronics Ltd.). These measures were done by a Triton Electronics Ltd. 304 M apparatus (10 mm cylinder well). A high value of CST usually denotes poor filterability and dewaterability of the septage.

3.6.2 Data and Statistical Analyses

3.6.2.1 Wetland Performance

Pollutant influent loading rate (ILR) is the pollutant mass per unit surface area of the wetland per daily or weekly input, and is calculated using Equation 6. The physico-chemical compounds removal efficiencies of the wetlands were presented in terms of concentration and mass removal percentages (Equation 7 and Equation 8). The wetland performance was determined based on the concentration and mass removed for each inlet and outlet sample pairs, assuming that the inlet and outlet samples correspond to one another at each time period. Mass removal efficiency (%) and mass removal rate (g/m^2.d or g/m^2.wk) are measurements that account for the effects of evapotranspiration and water loss, taking into concern the variations in the influent volume and its corresponding outflow volume. The mean values reported for the wetland performance were calculated based on the average removal efficiencies over the specified experimental period.

Pollutant influent loading rate, ILR (g/m^2.d or g/m^2.wk) = $\frac{(\mathrm{CiVi})}{\mathrm{A} * \mathrm{I}}$ .... Equation 6

Pollutant concentration removal efficiency (%) = $\frac{(\mathrm{Ci}-\mathrm{Ce})}{\mathrm{Ci}} * 100$ .... Equation 7

Pollutant mass removal efficiency (%) = $\frac{(\mathrm{CiVi}-\mathrm{CeVe})}{\mathrm{CiVi}} * 100$ .... Equation 8

Pollutant mass removal rate, MRR (g/m^2.d or g/m^2.wk) = $\frac{(\mathrm{CiVi}-\mathrm{CeVe})}{\mathrm{A} * \mathrm{I}}$ .... Equation 9

Where,

Ci = Influent Concentration (mg/L)

Ce = Effluent Concentration (mg/L)

Vi = Influent Volume (L)

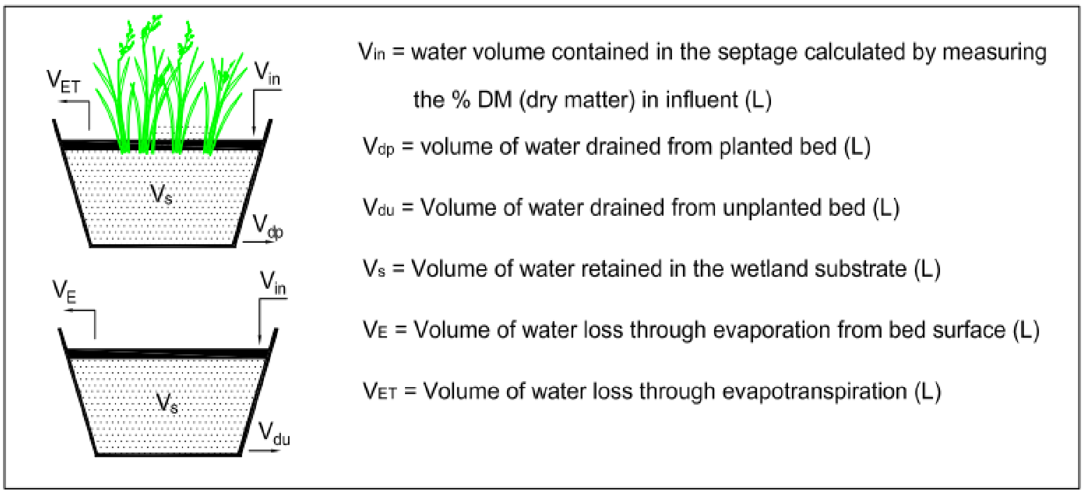
Ve = Effluent Volume (L)

A = Bed surface area (m^2)

I = Interval between wetland refilling (day or week)

(A) Measuring effluent water loss

The quantity of effluent drained out from each first stage wetlands was measured 24 hours after septage feeding using the volumetric method. At the second stage wetlands where intermittent feeding was implemented, the daily effluent volume discharged from each bed was calculated based on the drained volume measured during the interval period between two successive loadings, assuming the effluent volume released were similar throughout the day between each fed with the same dosing volume. Water loss via evaporation and evapotranspiration (ET) was estimated in accordance to the water budget in the wetland beds as illustrated in Figure 3.14, based on Equation 10 to Equation 13. Plant transpiration was calculated as the differences between the amount of water loss between the planted and unplanted beds.



V_{in} = water volume contained in the septage calculated by measuring the % DM (dry matter) in influent (L)
V_{dp} = volume of water drained from planted bed (L)
V_{du} = Volume of water drained from unplanted bed (L)
V_s = Volume of water retained in the wetland substrate (L)
V_E = Volume of water loss through evaporation from bed surface (L)
V_{ET} = Volume of water loss through evapotranspiration (L)

Figure 3.14 Water budget of the planted and unplanted first stage wetlands

At the planted beds,

$\Delta V = V_{in} - V_{dp} = V_s + V_{ET}$ …………………………………………………. Equation 10

$V_{ET} = V_{in} - V_{dp} - V_S$ ……………………………………………………………. Equation 11

At unplanted beds,

$\Delta V = V_{in} - V_{du} = V_s + V_E$ …………………………………………………….. Equation 12

$V_E = V_{in} - V_{du} - V_S$ ……………………………………………………………….. Equation 13

(B) Measuring 24 hours infiltration rate

Drainage flows were measured at the first 24 hours after loading for all first stage wetlands. The test was carried out once a week and the 24 hours infiltration rate was calculated using Equation 14.

$$Ir = \frac{Q_d * 1000}{A} \quad \text{..} \quad \text{Equation 14}$$

Where,

Ir = Infiltration rate (mm/day)

Q_d = Volume of drained water in the first 24 hours after loading (m^3)

A = Wetland surface area (m^2)

3.6.2.2 Statistical Analyses

Statistical analyses on the study results were performed using SPSS Statistics 19.0 for Windows. The major pollutants mass removal efficiencies and mass removal rates of each wetland were examined for equal variances and normality to test assumptions for a one-way analysis of variance (ANOVA). The Tukey procedure was used for multiple post hoc comparisons. Prior to all statistical tests, data were examined for normality using a Shapiro–Wilk test and for homogeneity of variances using Levene's test. If data approximated normality, no transformation was done and the differences of removal efficiencies between the wetlands were analysed with the ANOVA parametric test.

The statistical significance of the mean differences between the wetlands performance due to the influence of different system aspects and feeding regimes were determined at a confidence level of 95%. Thus, the differences were regarded as significant at $p \leq 0.05$. In the case of a violation of the ANOVA assumptions especially for normality, the data were square rooted or log transformed to achieve normal distribution before analysing the data using one-way ANOVA. Post hoc test was carried out for multiple comparisons after ANOVA, where necessary. Sample SPSS analysis output are attached in Appendix F.

Liner regression graphs were plotted to obtain the relationship between the pollutant influent loading rates (ILRs) and their subsequent mass removal rates (MRRs) for all wetland beds, in order to determine the predictability of the wetlands performance. Linear regression coefficient (r^2) was determined to assess the strength of the relationship.

3.7 Characteristics of Septage from Miri

The characteristics of raw household septage used in this study were summarized in Table 3.3. The raw septage was found to be greatly heterogeneous, reflected by the high standard deviation for the pollutant concentrations obtained. The septage delivered to the treatment site presented great variations in solids, organic carbon, nutrients and inorganic salts content. The septage was found to be biochemically stable with low BOD:COD ratio of 0.094, which indicates that most biodegradable carbon was removed during the long storage period in septic tanks. The septage used in this study had much lower CST values than those found in the literature (Vincent et al. 2011; Troesch et al. 2009b) and this indicates higher dewatering capability of the septage collected from the septic tanks around the Miri city. The septage was observed to settle well and possessed high suspended solids (TSS) content (about 80% of total solids). The raw septage was also found to be anaerobic (low DO content of 0.19 mg/L and ORP of -192 mV) and slightly acidic (mean pH of 6.91). The colour of septage often appeared to be dark black to brownish black.

Table 3.3 Physico-chemical characteristics of raw household septage in Miri

Parameter	N	Range	Mean	Std Dev
CST (s)	18	39.30 -232.94	99.95	42.52
COD (mg/L)	33	8,030 - 109,120	35,525	21,387
BOD_5 (mg/L)	33	455 - 8,740	3,341	1,826
NH_3-N (mg/L)	33	62 - 696	287	154
TKN (mg/L)	33	245 - 1,647	956	394
NO_3-N (mg/L)	33	0 - 118	24.33	22.11
TN (mg/L)	33	275 - 1,661	988	388
Org N (mg/L)	33	115 - 1,302	669	348
Temperature (°C)	33	27.20 - 30.50	29.04	0.94
EC (mS/cm)	33	0.72 - 2.36	1.45	0.38
pH	33	5.93 - 7.69	6.91	0.43
DO (mg/L)	33	0.06 - 0.86	0.19	0.18
ORP (mV)	22	(-90) - (-546)	-192.36	105.62
TS (mg/L)	33	8,000 - 150,264	42,693 (4.36 %DM)	30,359
TSS (mg/L)	33	5,200 - 119, 900	34,082	26,428
VSS (mg/L)	33	4,100 - 81,200	21,570	17,147

N = No. of samples

Table 3.4 summarizes the physico-chemical characteristics of raw septage from various regions as reported in the literature. Generally, the mean concentrations of most constituents in the Miri septage were higher than those found in the literature for other tropical sites such as Bangkok, Thailand (Koottatep et al. 2005) and Yaoundé, Cameroon (Kengne et al. 2008). The septage from Miri exhibited high concentrations of organic matter and particulate solids contents. According to the mean pollutants concentrations of the septage received during the study period (33 batches, inclusive of the septage received during the acclimatisation period), the septage may be classified as type “A” or high-strength faecal sludge that are usually collected from public toilets and bucket latrines in tropical countries (as suggested by Strauss, Larmie, and Heinss (1997) and Mara (1978)).

This could probably be related to the desludging habits of the residents in the Miri city. At the time of commencement of this research project, mandatory desludging has not been fully implemented in Miri where most residents will only call in for desludging services when they encountered problems such as septic tank overflow, backflow, odour issues or blockage. Some of the residents had even left their septic tanks un-desludged and un-serviced for over 20 years (Ir. Teo, personal communication June 21, 2012). It is fairly reasonable to assume that most of those septic tanks were not functioning at their optimum conditions, resulting in poor pollutants removal and high accumulation of sludge.

Table 3.4 Physico-chemical characteristics of raw septage from various regions

Parameter	**N**	**Thailand**[+]	**N**	**Ghana**[++]	**N**	**Cameroon**[#]	**N**	**France**[##]
CST (s)	-	N/A	-	N/A	-	N/A	-	360 ±142
COD (mg/L)	120	17,000 ±15,000[*]	-	8,400	42	31,100	-	42,000 ±13
BOD_5 (mg/L)	30	2225 ±395	-	3,700	-	N/A	-	N/A
NH_3-N (mg/L)	30	320 ±70.89	-	500	42	600	-	287 ±76
TKN (mg/L)	30	N/A	-	N/A	42	1,100	-	1,423 ±435
NO_3-N (mg/L)	30	4.81 ±1.65	-	N/A	-	N/A	-	N/A
TN (mg/L)	30	950 ±99.18	-	N/A	-	N/A	-	N/A
TP (mg/L)	30	N/A	-	N/A	-	N/A	-	517 ±438
Temperature (◦C)	30	28.67 ±1.5	-	N/A	-	N/A		N/A
EC (ms/cm)	30	N/A	-	17.27	44	2.79	-	N/A
pH	30	7.48 ±0.5	-	7.7	44	7.5	-	N/A
ORP (mV)	30	-291 ±30	-	N/A	41	-54.2	-	N/A
TS (mg/L)	30	22,420 ±7702.6	-	11,800.00	44	3.7 (% DM)	-	30,000 ±10.6
TVS (mg/L)	30	N/A	-	6,726.00	43	64.4 (% DM)	-	21,300 ±2,100
TSS (mg/L)	30	19,500 ±7,250	-	N/A	-	N/A	-	23,0300 ±8,600

N/A= Not available

N = Number of samples

* Characteristics of septage from Bangkok, Thailand (Koottatep et al. 2001b)

\+ Characteristics of septage from Bangkok, Thailand (Koottatep et al. 2005)

++ Characteristics of septage from Kumasi, Ghana (Cofie et al. 2006)

\# Characteristics of septage from Yaoundé, Cameroon (Kengne et al. 2008)

\## Characteristics of septage from Andancette, France (Vincent et al. 2011)

Chapter 4 Results and Discussions: First Stage of Treatment: Effects of Plant Presence and Solid Loading Rate on Treatment Efficiencies

4.1 Overview

Most of the experiences reported in the past decades for sludge treatment in engineered wetlands concern activated sludge, and in this research the treatment of septage using this technology was studied. The designed vertical flow engineered wetlands (VFEWs) treatment system comprised of two stages of aggregate-filled wetland beds, planted with an emergent rooted wetland vegetation known as *Phragmites karka* (reeds). In this chapter, the efficiencies of the first stage wetlands in treating raw septage are reported. The first stage wetlands were designed to reduce the majority of the total suspended solids (TSS) and the biochemical oxygen demand (BOD_5) from the raw septage by physical filtration and sedimentation processes. The effects of solid loading rate (SLR) and presence of plants on the treatment of the raw septage influent were reported and discussed in this chapter.

4.2 Operating Conditions

The septage stored in the receiving tanks was gravitationally fed once a week onto the first stage wetlands for preliminary filtration and treatment. Table 4.1 summarises the experimental schedule for the first stage wetlands that was designed to study the effects of solid loading rate (SLR) and plant presence on pollutant removal efficiencies. All the first stage wetlands were fed with the specific SLR at full load for 2 weeks before the outflow samples were collected for analyses, with the assumption that the system had stabilized and acclimatized to the flowrate by then. This was to ensure that a more consistent output on the system treatment performance can be obtained following the acclimatization period to better discern the influences of the regimes tested.

Table 4.1 Experimental plan for the first stage wetlands of the VFEWs treatment system

Objective	**Experimental Period**	**Description**	**Denotation**
Determine the effects of solid loading rate (SLR) on pollutant removal efficiency	**PERIOD I** March - May 2012 July - October 2012	100 kg TS/m^2.yr (Planted); 250 kg TS/m^2.yr (Planted)	A1-100P A1-250P
	PERIOD II October 2012- January 2013	250 kg TS/m^2.yr (Planted); 350 kg TS/m^2.yr (Planted)	A2-250P A2-350P
Study the influence of plant presence on pollutant removal efficiency	**PERIOD I** March - May 2012 July - October 2012	250 kg TS/m^2.yr (Planted); 250 kg TS/m^2.yr (Unplanted)	A1-250P A1-250UP
	PERIOD II October 2012 - January 2013	350 kg TS/m^2.yr (Planted); 350 kg TS/m^2.yr (Unplanted)	A2-350P A2-350UP

Septage was applied once weekly onto the wetlands at a volumetric rate between 54 - 1323 L/week, depending on the SLR and the septage total solids (TS) content which varied greatly with every batch of septage received. The beds were loaded with septage in one go within approximately 15 - 30 minutes, i.e. at a flowrate of around 3.6 - 44.1 L/min. Effluent of the wetlands was collected once weekly from the beds outlet 24 hours after septage loading for 8 - 10 subsequent weeks. Throughout the entire experimental period, the septage was allowed to percolate freely by gravity via the substrate layers and all the resulting filtrate was directed into an effluent collection tank for storage. The outflow of the wetlands was controlled by a stopcock and a water tap at the bottom of the wetland basins. The volume of effluent collected from each bed was measured and recorded to account for the water loss from the system.

The weekly measured and estimated raw septage and effluent volume of each bed were multiplied by the pollutant concentrations (mg/L) to calculate the daily inflow and outflow pollutant loads. Percentages of mass removed (%) and the mass removal rates (g/m^2.week) were determined to assess the performance of the beds, besides reporting the system efficiencies in terms of concentration-based removal (%). The treated effluent of each bed was collected and in-situ testings were carried out on the effluent samples almost immediately after collection. The effluent samples were collected and brought back to the laboratory after in-situ testings to undergo a series of bio-physicochemical analyses according to the methods mentioned in section

3.6.1.2. All the data collected were statistically analysed as per described in section 3.6.2.

4.3 Effects of Solid Loading Rate (SLR)

The total solids (TS) content of raw septage influent fluctuated from one batch to another with high standard deviations as discussed in Chapter 3, section 3.7. Thus the amount of septage influent applied weekly varied notably in accordance with the TS content in the septage under the respective SLR as shown in Figure 4.1. SLR of 100, 250 and 350 kg TS/m^2.yr were applied onto the planted beds to study the effects of SLR on the pollutant removal performance of the vertical wetlands. During Period I, the hydraulic loads of the bed fed with SLRs of 100 and 250 TS/m^2.yr ranged from 1.28 - 12.5 m/yr and from 3.20 - 31.25 m/yr, respectively. The average TS content in the septage received during Period II was greater and thus the volumes of septage applied onto the wetlands were generally lower than that of Period I. The hydraulic loads for the septage areal loading with 250 and 350 TS/m^2.yr were in the range of 2.33 - 22.57 m/yr and 1.66 - 16.12 m/yr, respectively at Period II.

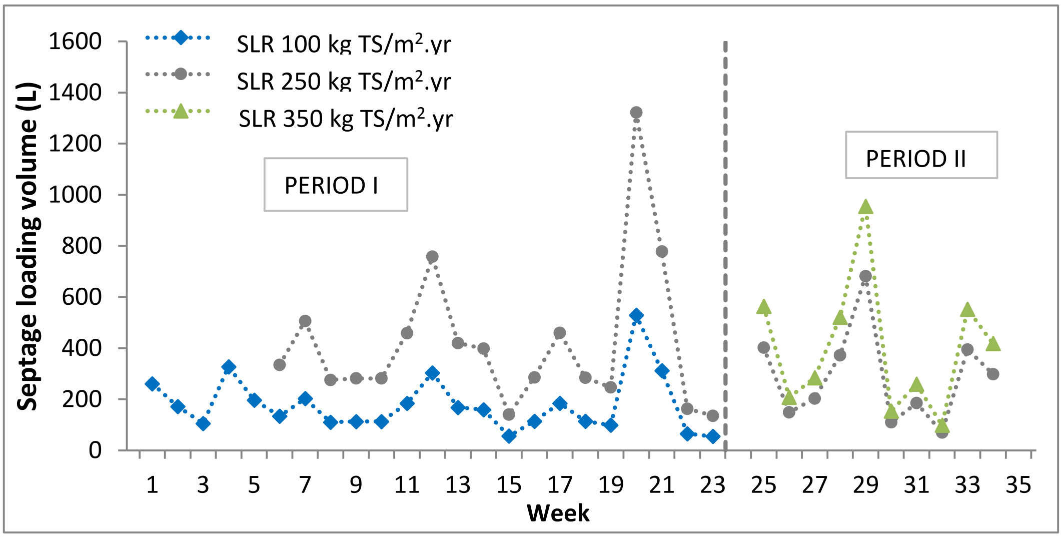
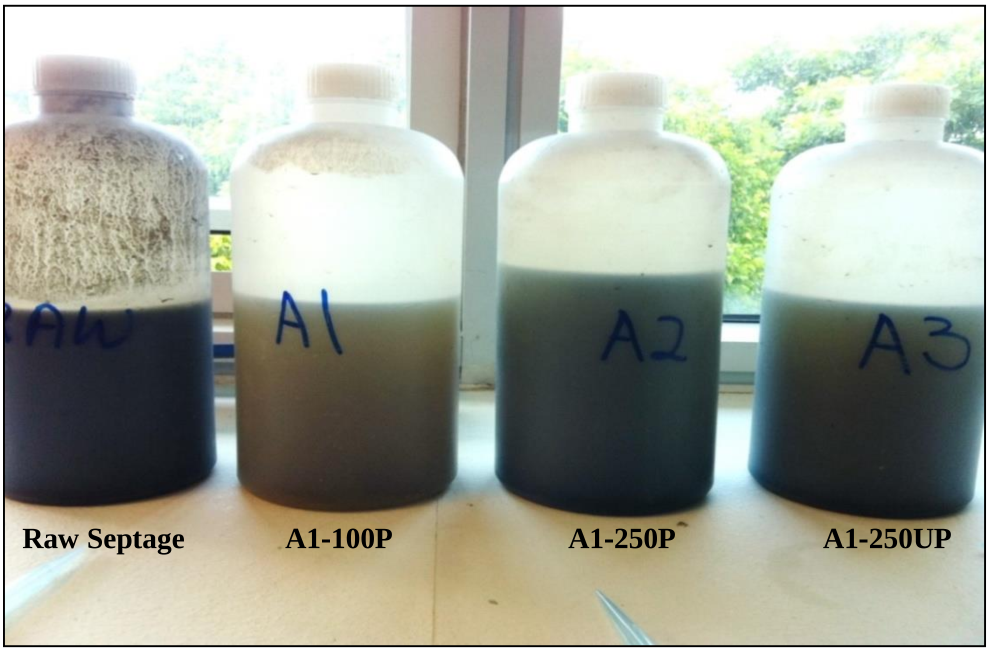


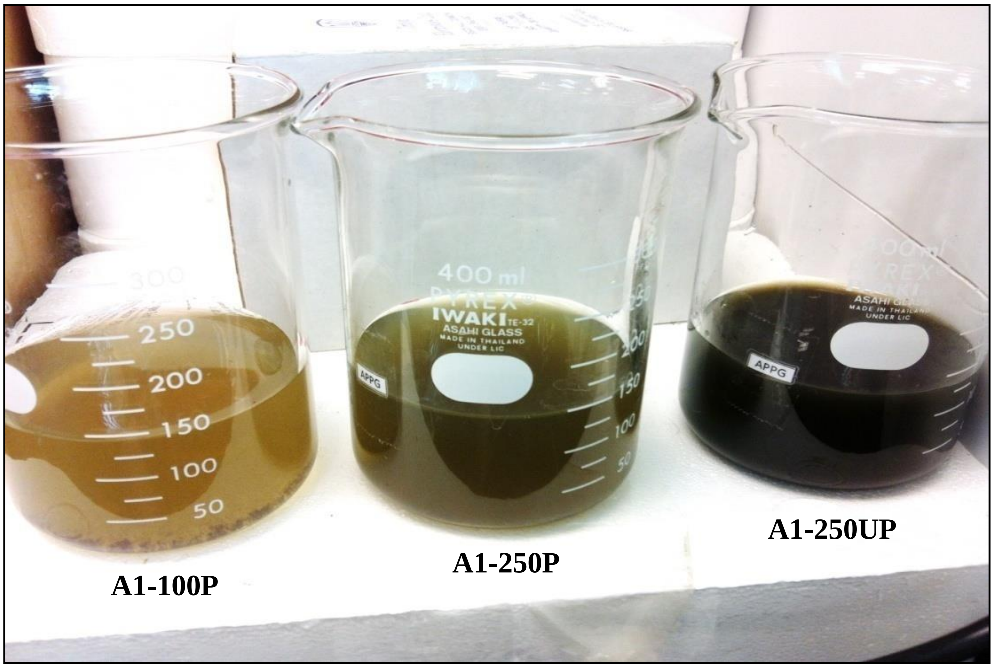
Figure 4.1 Volume of septage applied onto the first stage wetlands according to respective SLRs during the investigation period

Most often, changes in the colour and turbidity of the wetland effluent were notable by visual observation (likely due to the removal of suspended solids) as shown in Figure 4.2 (a)-(d), though this was very much dependent on the quality and the characteristics of the septage applied. The loading rate is an important factor for empirical design and operation. Prolonged overloading leads to an outer blockage (on the bed surface) and/or inner clogging of the filter substrate by reducing the active pore volume and decreasing the hydraulic conductivity of the substrate. Aeration of the wetland substrate will be restricted upon clogging and most bacterial activities will be inhibited.

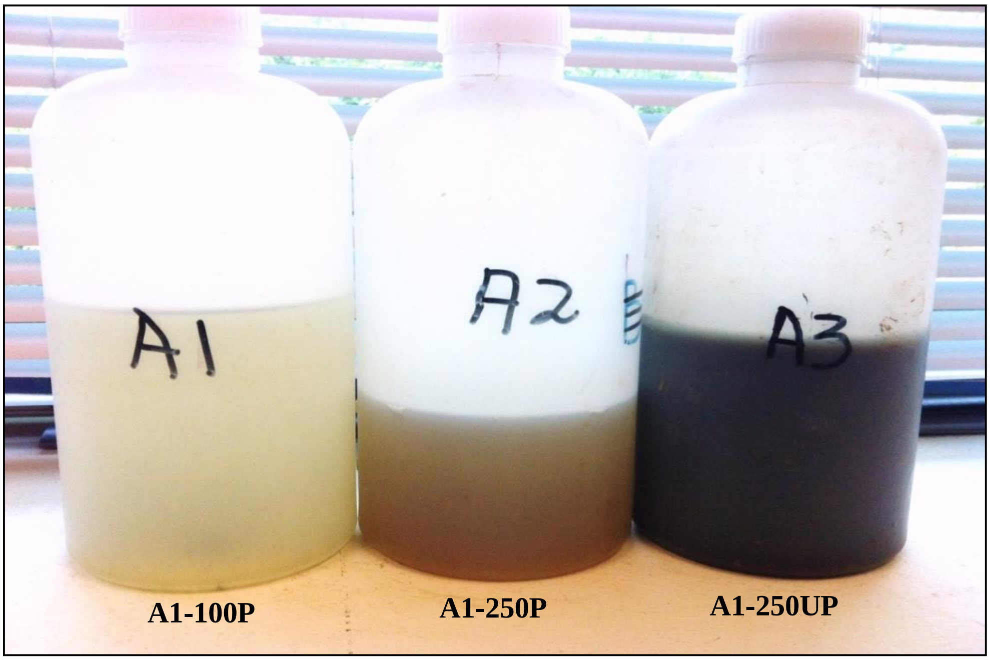
(a)



(b)



(c)



(d)

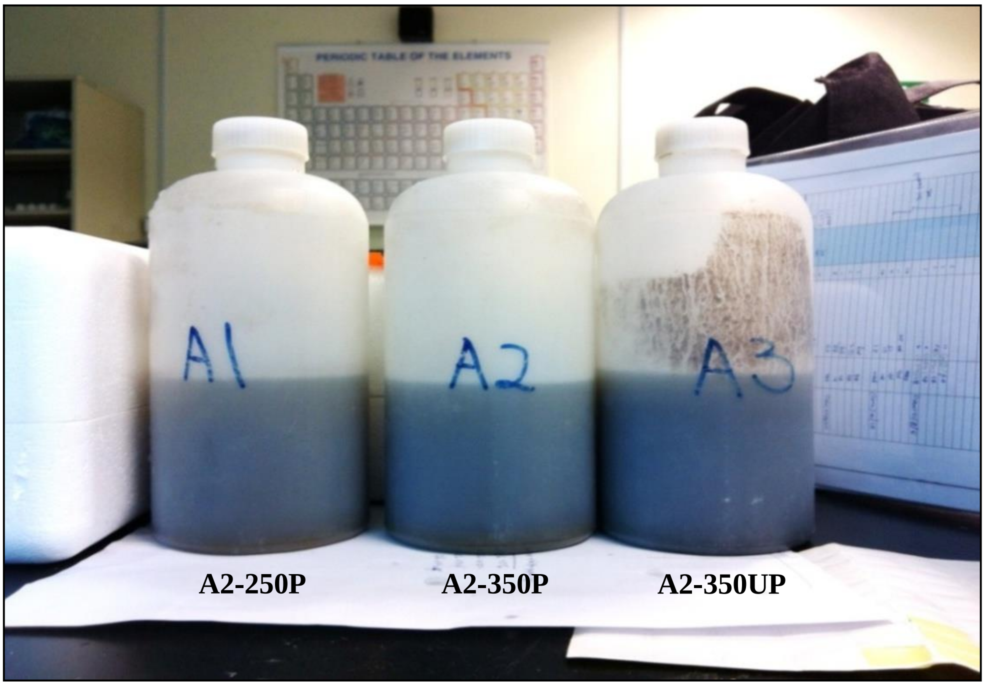


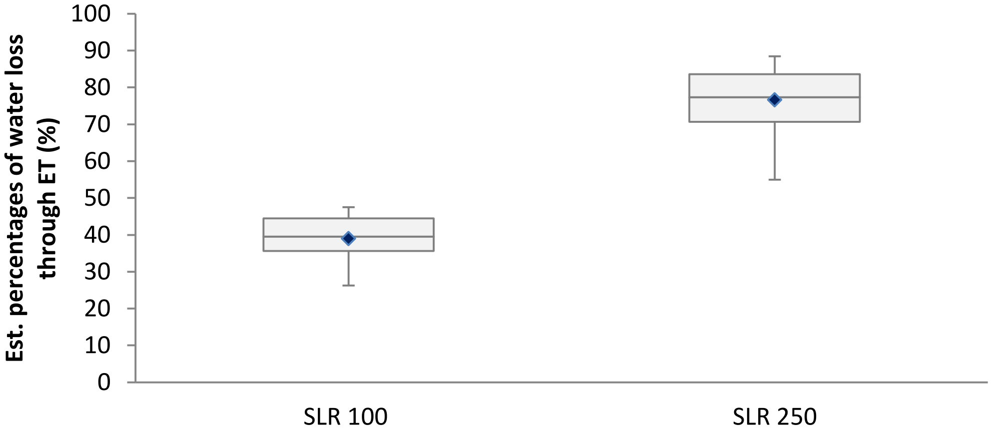
Figure 4.2 Effluent collected from the outlet of wetlands (a) - (c) A1-100P, A1-250P and A1-250UP (d) A2-250P, A2-350P and A2-350UP (left to right) with different batches of raw septage

Generally the surface of the wetlands with accumulated septage was dark brown to black in colour, and this dark colour had allowed higher absorbance of radiant heat from the sunlight that thus increased the capacity for evaporation. With regards to the volume of effluent collected from the beds fed with different SLRs, it appeared that the higher amount of water lost was associated with the higher amount of influent the bed received. The units receiving greater influent volume at higher SLRs were found to have significantly lower drained water volumes at both periods ($P<0.001$). The SLR at 250 kg TS/m^2.yr with 2.5 times higher hydraulic loads and solids content per application led to a thicker accumulated septage deposit layer compared to the wetland applied with 100 kg TS/m^2.yr. This thicker layer subsequently slowed down the water drainage to the unit base and allowed evapotranspiration (ET) to dominate over draining. This phenomena was also reported in a previous research with pilot-scale sludge drying reed beds (SDRB) in Greece, such that the units loaded at higher

SLR had more water available for evapotranspiration since the beds had remained wet for more days and allowed for higher ET rates (Stefanakis and Tsihrintzis 2011).

Figure 4.3 (a) shows the box-and-whiskers plot for the estimated percentage of water loss through ET at wetlands loaded with SLRs of 100 and 250 kg TS/m^2.yr during Period I. The plot for SLR 100 kg TS/m^2.yr shows lower and tighter quartiles than that for SLR 250 kg TS/m^2.yr, suggesting that the lower SLR led to more consistent rate of water lost via ET from the wetlands. An average of 31% and 55% of water was found to be lost through ET from wetland fed with SLRs 100 and 250 kg TS/m^2.yr, respectively and ANOVA had confirmed the significant differences between them ($P<0.001$). The difference in quartile range was more obvious in Figure 4.3 (b), when comparing the percentage of water loss between wetlands loaded with 250 and 350 kg TS/m^2.yr during Period II. Lower SLR (250 kg TS/m^2.yr) was also shown to lead to more consistent water loss via ET than the wetland fed at higher SLR (350 kg TS/m^2.yr), as illustrated by the apparently smaller quartile ranges. The mean water loss between the two beds was found to be 69% and 76% for SLRs 250 and 350 kg TS/m^2.yr, respectively and their difference was statistically significant.

(a)



(b)

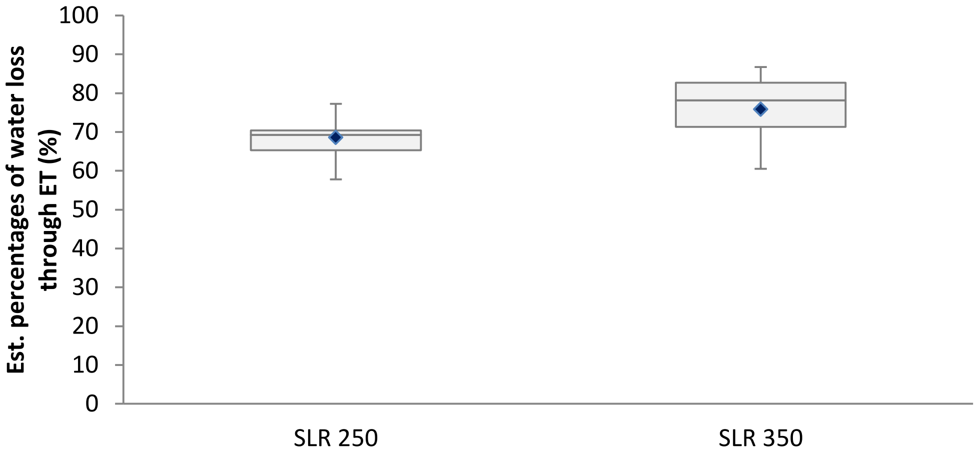


Figure 4.3 Estimated percentage of water loss (%) from the effluent of wetlands loaded with (a) SLR 100 and 250 kg TS/m^2.yr at Period I (b) SLR 250 and 350 kg TS/m^2.yr at Period II. The boxes delineate the interquartile range, above and below the median (central horizontal line), and the ‘whiskers’ show the overall range of the data. The dot inside each box represents the mean of the data.

Table 4.2 shows the ranges, average values and standard deviations of water quality parameters analysed in the raw septage and the resulting effluent after the first stage of treatment. According to the data collected, the influent and effluent temperature did not show significant variations and generally ranged between 26.2 - 30.5 ◦C. The mean pH value was often slightly acidic to slightly basic for raw septage at both periods; values ranging between 5.93 - 7.69 for Period I, and buffered near neutrality to slightly acidic with values varying between 5.81 - 7.15 for Period II.

Table 4.2 Physico-chemical parameters statistics for raw septage, effluent of wetlands A1-100P and A1-250P at Period I, and effluent of wetlands A2-250P and A2-350P at Period II

		Period I				**Period II**				
		Statistics					Statistics			
Parameter	Sampling Point	N	Range	Mean	Std Dev.	Sampling Point	N	Range	Mean	Std Dev.
Temperature (℃)	Influent	18	27.50 - 30.40	29.02	0.91	Influent	10	27.20 - 30.50	29.08	1.06
	Eff. A1-100P	18	26.70 - 30.20	28.61	1.09	Eff. A2-250P	10	26.80 - 29.50	28.62	0.76
	Eff. A1-250P	18	28.00 - 30.40	29.2	0.88	Eff. A2-350P	10	26.20 - 29.90	28.35	1
pH	Influent	18	5.93 - 7.69	6.77	0.48	Influent	10	5.81 - 7.15	6.42	0.46
	Eff. A1-100P	18	6.78 - 7.22	7.03	0.13	Eff. A2-250P	10	6.62 - 7.36	6.91	0.24
	Eff. A1-250P	18	6.71 - 7.36	7.11	0.19	Eff. A2-350P	10	6.47 - 7.61	7.13	0.32
DO (mg/L)	Influent	18	0.06 - 0.30	0.14	0.07	Influent	10	0.06 - 0.86	0.27	0.26
	Eff. A1-100P	18	0.50 - 5.57	2.17	1.32	Eff. A2-250P	10	1.61 - 6.67	3.79	1.37
	Eff. A1-250P	18	0.61 - 3.06	1.87	0.79	Eff. A2-350P	10	1.27 - 6.28	3.2	1.58
ORP (mV)	Influent	12	-100 -(- 546)			Influent	10	-90 -(- 275)		
	Eff. A1-100P	12	-156 - 466			Eff. A2-250P	10	-22 - 278		
	Eff. A1-250P	12	-178 - 211			Eff. A2-350P	10	-24 - 233		
EC (mS/cm)	Influent	18	1.04 - 2.36	1.57	0.41	Influent	10	0.72 - 1.40	1.24	0.19
	Eff. A1-100P	18	2.09 - 3.42	2.61	0.44	Eff. A2-250P	10	1.10 - 2.85	2	0.54
	Eff. A1-250P	18	1.39 - 2.47	1.98	0.33	Eff. A2-350P	10	1.36 - 2.84	1.93	0.5

N = Number of samples

Generally, the mean electric conductivity (EC) increased after treatment at the wetlands; from 1.57 mS/cm in the influent to 2.61 mS/cm and 1.98 mS/cm in the effluent of wetland A1-100P and A1-250P, respectively (Table 4.2). A similar trend was observed in Period II, with the EC increasing from 1.24 mS/cm in the raw septage to 2 mS/cm and 1.93 mS/cm in the effluent of wetland A2-250P and A2-350P, respectively. The raw septage recorded low dissolved oxygen (DO) content in Period I, with concentrations ranging from 0.06 - 0.30 mg/L. It was found that the septage presented a reduced medium with oxygen reduction potential (ORP) values deviating between -100 mV - (-546) mV (Table 4.2). The raw septage received during Period II had slightly higher average DO and ORP values, varying between 0.06 - 0.86 mg/L, and -90 - (-275) mV, respectively. Redox potential values greater than 100 mV are commonly interpreted to indicate an aerobic environment, whereas values less than -100 mV indicate an anaerobic environment (Suthersan 2002).

The ORP and DO values of the septage were found to increase significantly after the first stage of treatment under all the applied SLRs, implicating that the wetland beds were efficient in promoting aerobic treatment on the influent. The mean DO after treatment in Period I at wetland A1-100P and A1-250P was 2.17 mg/L and 1.87 mg/L, respectively; and in Period II, an average DO concentration of 3.79 mg/L and 3.20 mg/L was recovered in the effluent of wetland A2-250P and wetland A2-350P, respectively. In the case of the redox potential of the resulting effluent, ORP values obtained were found to be in the range of -156 - 466 mV for wetland A1-100P and between -178 - 211 mV for wetland A1-250P. The effluent from the bed loaded at higher SLR during Period II, i.e. wetland A2-350P was also found to have marginally lower ORP values than that of the effluent from wetland A2-250P. This has suggested that the wetlands fed with lower SLR were often more aerobic than the wetlands loaded at higher SLR, which subsequently leads to a general hypothesis which predicts more efficient treatment in the wetlands applied with lower SLR. This is because the provision of aerobic conditions in wetlands is known to be an important factor to improve the removal of most contaminants from the beds influent.

4.3.1 Particulate Solids Removal

Vertical treatment wetlands are designed to accumulate solids on the surface of the bed, forming a layer of deposit on top of the substrate that clogs the bed intentionally (Kadlec and Wallace 2009). The layer allows infiltration of the liquid portion of the applied wastewater (in this case, septage) through the overlaying deposit, before percolating down through the substrate to the bottom of the wetlands for drainage. However, vertical wetlands are designed and operated in a manner such that the surface layer is beneficial to the treatment performance without becoming detrimental to hydraulic performance (Chazarenc and Merlin 2005).

Generally, in this study the first stage wetlands provided good overall solids removal, with mean concentration removal efficiencies of about 91.5% for TS and 96.5% for TSS with SLR up to 350 kg TS/m2.yr (Table 4.3 to Table 4.5). A greater percentage of removal was accounted for in terms of mean mass removal with efficiency up to 98.1% for TS and 99.2% for TSS at wetland A2-350P (Table 4.3 and Table 4.5). This indicates good performance of the first stage wetlands in retaining particulate solids which subsequently reduced the solid content in the outflow of all beds. No major clogging phenomenon was encountered (septage infiltration was not more than 5 days at any time) during the time of operation at the VFEWs system with the septage deposit layer achieving an average dry matter (DM) content of above 20% with 7 days of drying time. The DM content was affected by the SLR applied and the dewaterability characteristic of the septage, while assisted by efficient bed draining and evapotranspiration. Further discussions on the accumulated septage layer are represented in Chapter 7.

Table 4.3 TS concentration and mass statistics for influent, and effluent of wetlands A1-100P (SLR 100) and A1-250P (SLR 250) at Period I, and wetlands A2-250P (SLR 250) and A2-350P (SLR 350) at Period II

				TS					
		Parameter		Min	Max	Std. Dev.	Mean	MRR*	RE (%)*
Period I	Concentration (mg/L)	Influent		8,000	78,000	19,981	35,299		
		Eff. A1-100P		1,200	4,800	1,102	2835		88.88
		Eff. A1-250P		1,436	16,400	3,431	3504		89.29
	Mass (g/m^2.week)	A1-100P	Inf.	1,923	1,923		1,923		
			Eff.	26.72	524.19	116	140.85	1782	92.68
		A1-250P	Inf.	4,808	4,808		4,808		
			Eff.	46.16	427.6	101	214.25	4593	95.54
Period II	Concentration (mg/L)	Influent		15,508	96,554	41,289	56,000		
		Eff. A2-250P		1,772	4,508	936	2791		92.72
		Eff. A2-350P		1,204	5,132	1,190	2966		91.53
	Mass (g/m^2.week)	A2-250P	Inf.	4,808	4,808		4,808		
			Eff.	19.59	200.81	64	106.95	4701	97.78
		A2-350P	Inf.	6,731	6,731		6,731		
			Eff.	6.04	262.9	84	128.08	6603	98.1

No. of samples, N = 18 (Period I), 10 (Period II)

MRR= Mass removal rate

RE= Removal efficiency

* Values presented as the average REs or MRRs calculated from N samples of N experimental runs

Table 4.4 TSS and VSS concentration and mass statistics for influent and effluent of wetlands A1-100P (SLR 100) and A1-250P (SLR 250)

			Period I											
			TSS						**VSS**					
	Parameter		Min	Max	Std Dev.	Mean	MRR*	RE (%)*	Min	Max	Std Dev.	Mean	MRR*	RE (%)*
Conc. (mg/L)	Inf.		5,200	60,900	14,845	24,759			4,100	29,000	7,170	14,458		
	Eff. A1-100P		35	1,810	414.76	498.40		97.72	12	870	211.37	211.25		98.5
	Eff. A1-250P		80	4,940	1,116	1442		93.6	35	1,900	522.25	657.87		95.27
Mass (g/m^2.week)	A1-100P	Inf.	433.80	1,933	459.75	1,401			342.04	1,301	298.57	857.51		
		Eff.	2.16	73.56	16.93	20.26	1,381	98.44	0.54	31.73	8.86	8.57	848.94	98.99
	A1-250P	Inf.	1,085	4,833	1,149	3,502			855.09	3,252	746.41	2,144		
		Eff.	10.68	266.83	59.62	88.79	3,413	97.31	4.26	122.60	31.99	41.19	2,103	98.02

No. of samples, N = 18

MRR= Mass removal rate

RE= Removal efficiency

* Values presented as the average REs or MRRs calculated from N samples of N experimental runs

Table 4.5 TSS and VSS concentration and mass statistics for influent and effluent wetland A2-250P (SLR 250) and A2-350P (SLR 350)

			Period II											
			TSS						**VSS**					
	Parameter		Min	Max	SD	Mean	MRR*	RE (%)*	Min	Max	SD	Mean	MRR*	RE (%)*
Concentration (mg/L)	Influent		12,600	92,250	34,530	50,863			8,300	53,640	22,400	34,371		
	Eff. A2-250P		65	1,500	545.85	768.67		97.06	30	1,280	472.14	600		96.63
	Eff. A2-350P		265	2,333	708.31	1,071		96.52	180	1,717	543.60	815.50		96.36
Mass (g/m^2.week)	A2-250P	Inf.	3,836	4,756	356.84	4,398			2,368	3,735	495.36	3,035		
		Eff.	0.90	115.09	42.98	39.33	4,358	99.08	0.42	101.09	35.32	30.98	3,004	98.95
	A2-350P	Inf.	5,370	6,658	499.58	6,156			3,315	5,229	693.50	4,248		
		Eff.	1.86	165.58	51.38	50.29	6,106	99.18	1.51	81.97	29.08	34.96	4,213	99.19

No. of samples, N = 10

MRR= Mass removal rate

RE= Removal efficiency

SD = Standard deviation

* Values presented as the average REs or MRRs calculated from N samples of N experimental runs

The mean influent TS concentration for the first experimental period (Period I) was around 35 g/L with weekly areal loading of 1.9 kg/m^2 and 4.8 kg/m^2 for wetland A1-100P and A1-250P, respectively (Table 4.3). About 96% of TS mass was removed with mean MRR of 4.6 kg/m^2.week at SLR 250 kg TS/m^2.yr. At the wetland fed with SLR 100 kg TS/m^2.yr, 92.7% of TS mass was removed with average weekly MRR of 1.8 kg/m^2 (Table 4.3). Based on the statistical analysis of the collected results, the higher septage loading rate of 250 kg TS/m^2.yr was not found to significantly affect the wetlands TS removal efficiencies ($P>0.05$). Increased SLR in Period II up to 350 kg TS/m^2.yr was also found to have no significant detrimental effect on the wetlands TS elimination efficiencies ($P>0.05$) (Table 4.3).

Mean TSS outlet concentrations varied between 35 - 1,810 mg/L for wetland A1-100P and between 80 - 4,940 mg/L for wetland A1-250P, yielding removal efficiencies from 93 - 99.8% and 81 - 99%, respectively (Appendix B1). Figure 4.4 and Figure 4.5 show the plot of influent loading rates (ILRs) and the resulting effluent mass, with the corresponding mass removal efficiencies for TSS and VSS, respectively for the wetlands in Period I. Inlet concentrations of TSS and VSS were high and were in the range of 5.2 - 61 g/L and 4.1 - 29 g/L, respectively (Table 4.4, Figure 4.4 and Figure 4.5). 98.4% of TSS and 99% of VSS mass were removed at wetland A1-100P, with no statistically important differences found between these removal performances with the reduction efficiencies at wetland A1-250P (97.3% for TSS and 98% for VSS). This implies that in terms of TSS mass elimination efficiency, the wetland performances were equally good under both the applied SLRs.

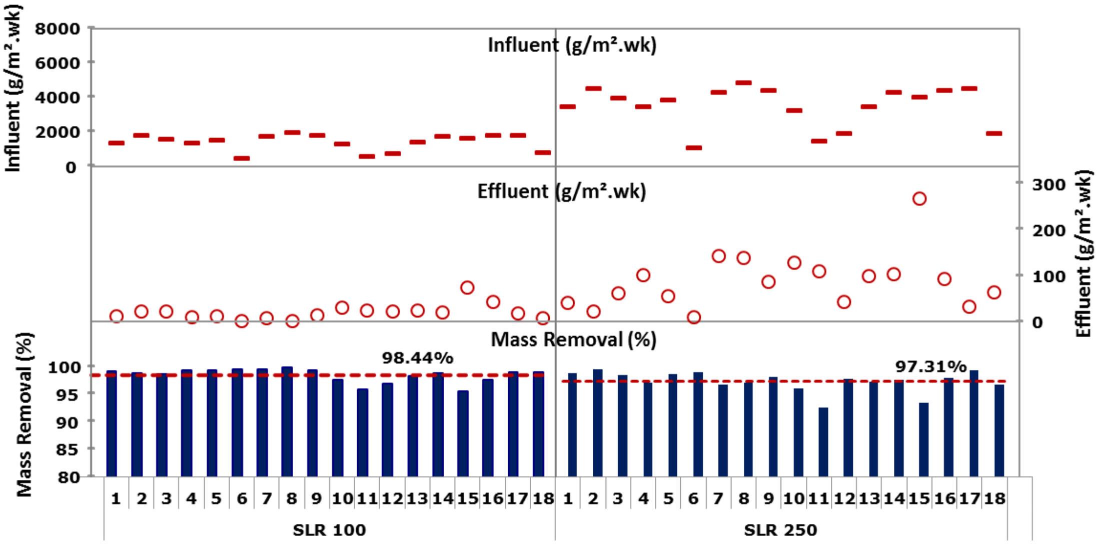


Figure 4.4 TSS influent areal loading rates and the resulting effluent loads, with the percentages (%) of mass removal for wetlands A1-100P and A1-250Pwith 18 sets of experiments

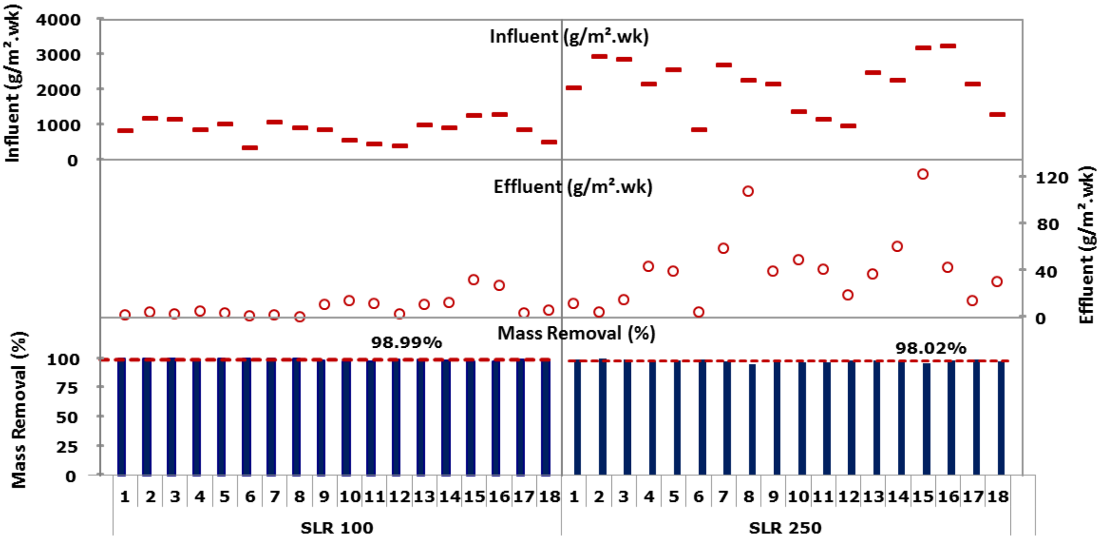


Figure 4.5 VSS influent areal loading rates and the resulting effluent loads, with the percentages (%) of mass removal for wetlands A1-100P and A1-250Pwith 18 sets of experiments

Similarly, no significant effect was found on the TSS mass removal efficiency when the SLR was increased to 350 kg TS/m^2.yr in Period II (Table 4.5). As shown in Figure 4.6 (a) and (b), the correlation between the TSS MRR with the ILR was strong (r^2>0.98) under all the applied loadings ($P<0.001$). Maximum influent TSS loading of 6.7 kg/m^2.week led to a total of 14.7 kg of SS applied onto wetland A2-350P per week, and achieving a reduction efficiency up to 99.5% with the outflow total mass out of 0.07 kg (Figure 4.6 (b) and Appendix B1). There was no discernible difference observed between the performance of wetlands A1-100P and A1-250P (Period I), and wetlands A2-250P and A2-350P (Period II) as all the regression trends showed similar fluctuations with the influent TSS loading rates during the monitoring period. MRRs were shown to increase proportionally with the ILRs and this linear regression trend indicates that the TSS MRRs could be accurately predicted by the incoming TSS loading rates under all the feeding regimes, up to SLR of 350 kg/m^2.yr. This trend of consistent treatment efficiencies of the beds showed excellent predictability of the wetlands performance capacity, which is a valuable information for wetland design.

The results showed that the VFEWs managed to maintain its treatment performance in particulate solids removal up to the SLR of 350 kg TS/m^2.yr. The influent TSS content was reduced noticeably at all wetlands in general, with the high reduction capacity of the first stage wetlands suggesting that the beds had effectively retained and removed particulate and soluble organic matter. The influent TSS and VSS loads were also found to reduce significantly after treatment at the first stage wetlands, resulting in effluent with considerably lower suspended materials and organic compounds.

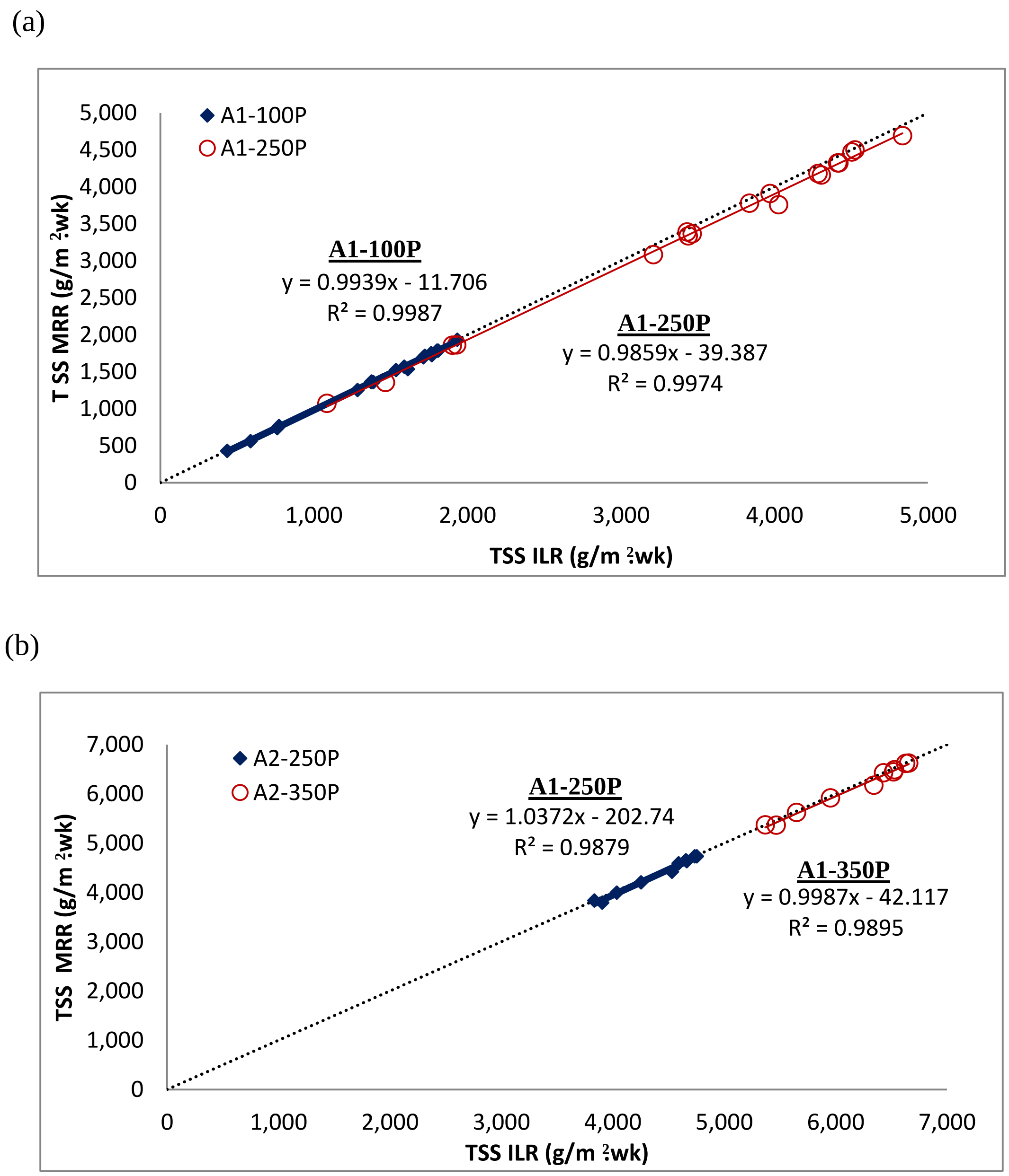


Figure 4.6 Regression graph of TSS mass removal rate (MRR) against influent loading rate (ILR) (g/m^{2}wk) for (a) wetland A1-100P and A1-250P (b) wetland A2-250P and A2-350P. The dotted line represents complete removal.

4.3.2 Organic Matter (OM) Removal

The organic pollutant removal efficiencies of the system were measured in terms of COD and BOD$_5$ reduction percentages. The inlet COD and BOD$_5$ concentrations of the wetlands varied between 8,990 - 55,180 mg/L and 894 - 8,740 mg/L, with means of 31,927 mg/L and 3,327 mg/L respectively (Table 4.6). The raw septage OM contents were found to fluctuate heavily, as the septage collected from the septic tanks was domestic in nature and highly dependent on the household usage. Effluent produced from the wetland fed with SLR 250 kg TS/m^2.yr (A1-250P) had shown greater variations in the organic matter concentrations than the effluent from the wetland loaded with SLR 100 kg TS/m^2.yr (A1-100P) (Table 4.6). The mean organic strength of the effluent from wetlands A1-100P and A1-250P were found to be 1,026 mg COD/L and 191 mg BOD/L, and 2,663 mg COD/L and 263 mg BOD/L, respectively. An average of 96% of COD was removed at wetland A1-100P, where the COD reduction efficiency was found to be lower at wetland A1-250P with 91.3% of removal performance. Increase of SLR to 250 kg TS/m^2.yr increased the influent volume and subsequently the pollutant loads applied onto the beds. This was found to deteriorate the OM treatment performance of the vertical wetlands.

Table 4.6 COD and BOD_5 concentration and mass statistics for raw septage and effluent of wetlands A1-100P (SLR 100) and A1-250P (SLR 250)

			Period I											
			COD						**BOD**					
	Parameter		Min	Max	SD.	Mean	MRR*	RE (%)*	Min	Max	SD	Mean	MRR*	RE (%)*
Concentration (mg/L)	Influent		8,990	55,180	15,081	31,927			894.00	8,740	2,109	3,327		
	Eff. A1-100P		183.33	3,180	788.14	1,026		96.04	23.40	590.00	177.22	191.33		93.86
	Eff. A1-250P		403.33	15,300	3,372	2,663		91.34	46.50	684.00	217.68	263.64		91.45
Mass ($g/m^2.wk$)	A1-100P	Influent	502.96	7,803	1,553	2,143			25.74	610.10	169.18	236.91		
		Effluent	6.24	161.83	43.85	50.40	2,092	97.28	1.05	32.74	8.77	8.40	228.51	95.97
	A1-250P	Influent	1,257	19,507	3,883	5,357			64.35	1,525	422.95	592.28		
		Effluent	25.27	398.92	110.24	160.54	5,196	96.37	2.13	70.87	19.76		571.94	96.18

No. of samples, N= 18

MRR= Mass removal rate

RE= Removal efficiency

SD = Standard deviation

* Values presented as the average REs or MRRs calculated from N samples of N experimental runs

The COD removal performance of wetland A1-250P (70.4 - 99.1%) was slightly lower than the range reported by Kengne et al. (2009) (73.4 – 99.9% reduction with SLR 200 kg TS/m^2.yr and 78 – 99.9% reduction with SLR 300 kg TS/m^2.yr). The lower OM treatment efficiency of wetland A1-250P compared to that reported by Kengne et al. (2009) was likely due to the low BOD:COD ratio of the septage used in this study. The faecal sludge used in the study by Kengne et al. (2009) were sourced from different on-site sanitation facilities, including public toilets, septic tanks and traditional pit latrines, which are often known to have high BOD:COD ratios. The colours of the sludge used were described to vary from dark colour with sludge originating from septic tanks, to yellowish with the sludge collected from public toilets or traditional pit latrines (Kengne et al. 2009), indicating the possibility of higher fractions of biodegradable matter readily available for microbial decomposition in the fresher sludge obtained from public toilets and pit latrines.

Since important difference was found in the water loss between the two beds as a result of evapotranspiration (ET), the lower COD concentration obtained from the effluent of wetland A1-100P was likely be due to the dilution effect which led to lower mass of COD retrieved per litre of effluent collected. Table 4.6 also shows the COD and BOD$_5$ statistics in terms of influent areal loading rates and the resulting effluent loads. Figure 4.7 illustrates the trend of COD mass in and mass out, and the mass removal efficiencies of wetlands A1-100P and A1-250P during Period I. The COD mass in for wetland A1-100P ranged between 1.1 - 17 kg/wk and had weekly mass removal rates (MRRs) varying between 0.49 - 7.8 kg/m^2. The mean COD mass recovered from the wetland effluent was 0.11 kg/wk with average mass reduction percentage of 97.4%.

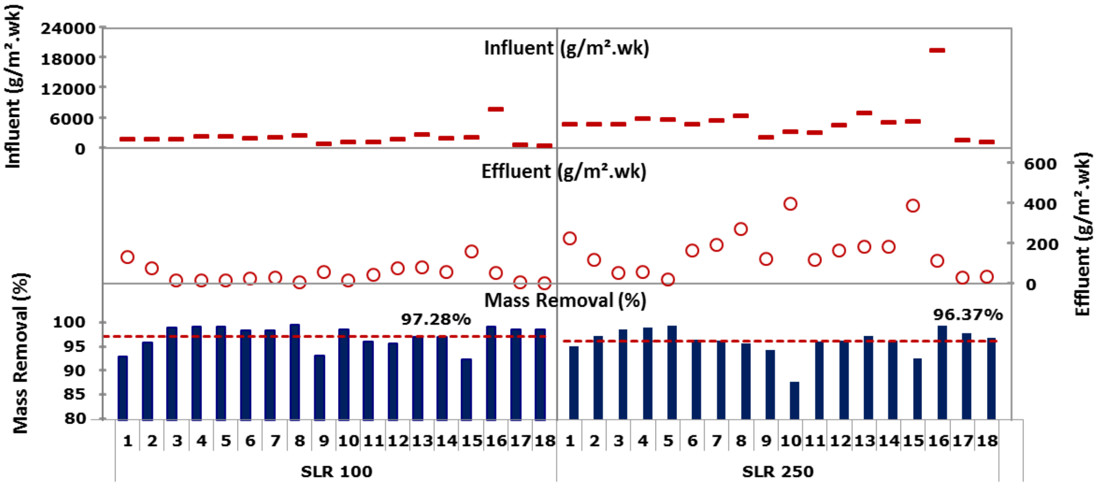


Figure 4.7 Influent COD areal loading rates and the resulting effluent loads, with the percentages (%) of mass removal for A1-100P and A1-250P at Period I with 18 sets of experiments

At wetland A1-250P, the bed produced effluent with a mean mass out of 0.35 kg/wk, at removal efficiency of 96.4%. Such difference in the COD mass removal efficiency between the wetlands however, was found to be statistically insignificant ($P>0.05$). This implies that the higher SLR did not affect the treatment performance of the wetlands in terms of the reduction of COD. As illustrated in Figure 4.8, the COD mass removal rates (MRRs) are shown to increase with the increased in the incoming COD loads. Regression lines for the two wetlands shared similar slope, suggesting that both the beds behave similarly under the applied COD loads. Likewise in terms of BOD_5 removal, no statistical difference was found between the wetlands fed with 100 kg TS/m^2.yr and 250 kg TS/m^2.yr. A total of about 88 - 99% of BOD_5 loads were reduced from the influent at both wetlands A1-100P and A1-250P, as shown in Appendix B1. The increased in SLR was not found to impair the BOD_5 treatment performance of the designed wetland beds.

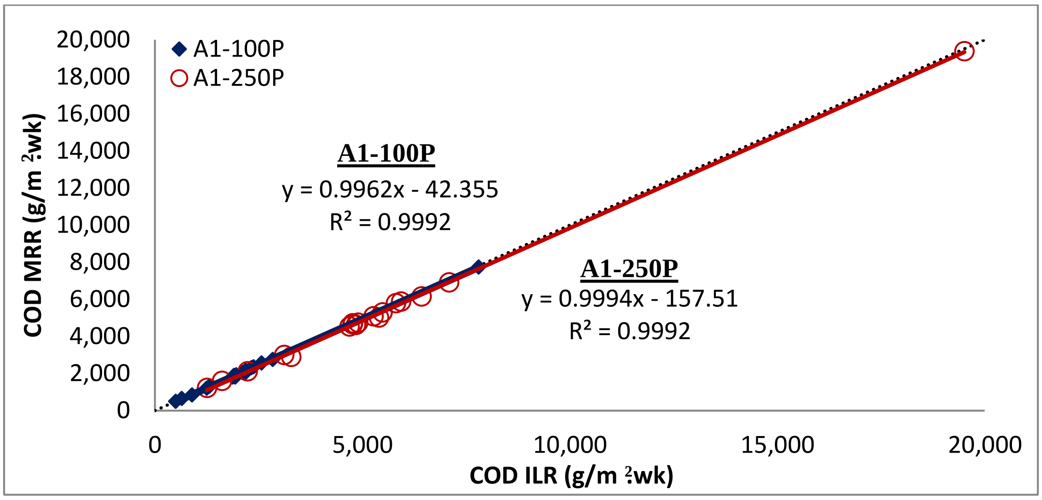


Figure 4.8 COD regression graph of mass removal rate (MRR) against influent loading rate (ILR) (g/m ²wk) for wetland A1-100P and A1-250P The dotted line represents complete removal.

As shown in Figure 4.8, it is obvious that the COD mass removal rates (MRRs) are very dependent on the influent loading rates (ILRs). It was found that the COD reduction rates of the wetlands were significantly correlated to the COD mass loading rates ($P<0.05$, $R^2>0.99$) at all applied SLRs. The positive, strong linear correlation of the organic loading rates to the reduction rates suggested no inhibitory effect of the increasing organic loading up to 20 kg COD/m^2.wk on the wetland treatment performance (Figure 4.8). The r^2(0.99) for both sets of data (wetlands A1-100P and A1-250P) were higher than those reported in the literature or those that could be calculated from the published data (Albuquerque et al. 2009; Avsara et al. 2007). The regression lines of both systems indicated equally high predictability of the wetlands performance with more than 99% of the variations in the OM mass removal rates being explainable by the strength of the incoming OM loads. A similar positive linear relationship of COD removal rates to loading rates was also reported in the literature for treatment of municipal wastewater in engineered wetlands (Poach, Hunt and Reddy 2004) and swine wastewater in marsh-pond-marsh wetlands (Jing et al. 2002).

Koottatep et al. (2001) had suggested a maximum SLR of 250 kg TS/m^2.yr and application of the septage once a week as a suitable strategy for treatment of septage with vertical wetlands in the tropics. In this research project, a maximum SLR of 350 kg TS/m^2.yr was attempted for 12 weeks (including 2 weeks of acclimatization period due to switch of SLR) with the intention to maximise land application efficiency, while investigating the effects of increased SLR on the wetland treatment performance. The same operating conditions were maintained at this second period of operation with SLR 250 kg TS/m^2.yr at wetland A2-250P and SLR 350 kg TS/m^2.yr at wetland A2-350P. Table 4.7 summarises the COD and BOD$_5$ concentration and mass statistics for the raw septage and the effluent of both wetlands. Figure 4.9 shows the trend of COD mass in and mass out, and the mass removal efficiencies of the wetlands during Period II for wetlands A2-250P and A2-350P.

The removal of the OM concentrations varied between 74 - 99% for COD and 93 - 99% for BOD$_5$ at wetland A2-350P (Appendix B1), with mean reduction of more than 93% for both indices (Table 4.7). The effluent produced at wetland loaded with SLR 350 kg TS/m^2.yr generally had higher OM concentrations than the effluent collected from the bed fed with SLR 250 kg TS/m^2.yr, but the variances were proven to be statistically unimportant ($P>0.05$). The COD mass removal efficiencies were found to average around 98% for both the wetlands A2-250P and A2-350P (Table 4.7). The reduction of BOD$_5$ was also high with a mean of more than 99% of mass removed under both applied loads. The average weekly amount of OM removed at wetlands A2-250P and A2-350P was found to be 3.8 kg COD/m^2 and 0.45 kg BOD/m^2, and 5.3 kg COD/m^2 and 0.63 kg BOD/m^2, respectively.

Table 4.7 COD and BOD_5 concentration and mass statistics for raw septage and effluent of wetlands A2-250P (SLR 250) and A2-350P (SLR 350)

			Period II											
			COD						**BOD**					
		Parameter	Min	Max	SD	Mean	MRR*	RE (%)*	Min	Max	SD	Mean	MRR*	RE (%)*
Concentration (mg/L)		Influent	8,030	109,120	29,498	42,002			455.40	8,740	1,826	3,341		
		Eff. A2-250P	240.00	1,860	490.75	721.80		95.27	8.10	54.22	76.80	76.80		97.34
		Eff. A2-350P	600.00	3,300	783.49	1,455		93.03	26.66	262.20	68.49	113.13		96.37
Mass (g/m^2.week)	A2-250P	Influent	1,469	9,126	2,044	3,826			83.32	1,341	399.69	450.89		
		Effluent	3.61	139.87	47.94	39.10	3,787	98.34	0.07	16.46	5.22	3.89	447.00	99.14
	A2-350P	Influent	2,057	12,776	2,861	5,357			116.65	1,878	559.56	631.25		
		Effluent	4.06	206.56	63.24	68.64	5,288	98.03	0.36	13.66	4.26	4.59	626.65	99.14

No. of samples, N = 10

MRR= Mass removal rate

RE= Removal efficiency

SD = Standard deviation

* Values presented as the average REs or MRRs calculated from N samples of N experimental runs

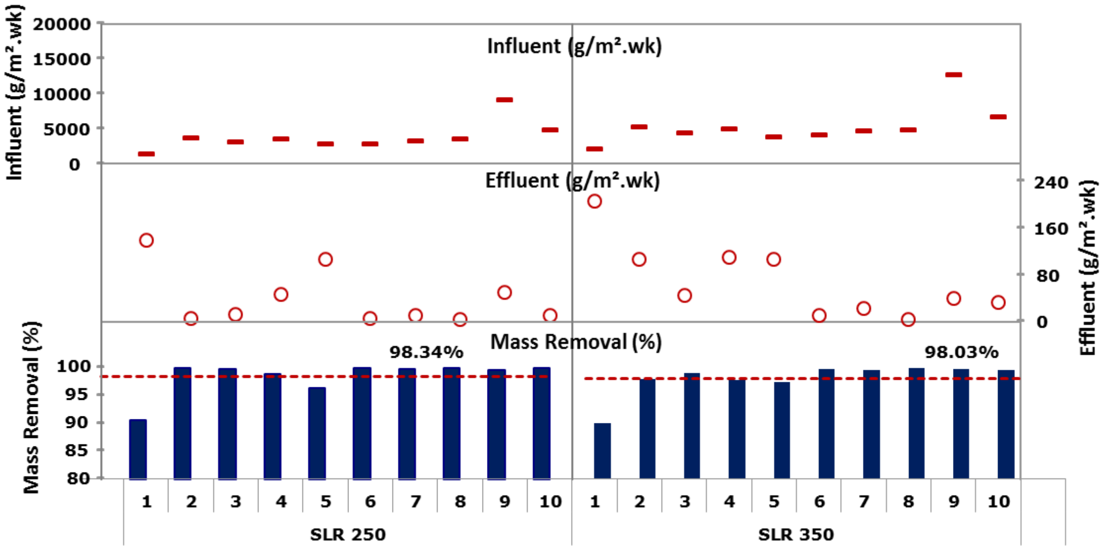


Figure 4.9 Influent COD areal loading rates and the resulting effluent loads, with the percentages (%) of mass removal for A2-250P and A2-350P at Period II with 10 sets of experiments

Statistical analysis on the data for OM removal indicated no apparent effects of SLR on the wetlands treatment efficiencies. The removal efficiency of OM was generally high up to the applied SLR of 350 kg TS/m^2.yr during the study period. COD and BOD$_5$ reduction can be partly be attributed to the combination of physical filtration and biodegradation. The first stage vertical beds achieved high suspended solids removal (as reported in the previous section 4.3.1) as a result of physical filtering by the gravel substrate, enhanced by the organic deposit layer on the wetland surface. Boutin, Lienard, and Esser (1997) claimed that this organic deposit layer remained self-managing with the action of reed stems swaying and roots growth, along with the operational regime of alternating feed and rest periods. The deposit layer is an active zone for filtration and biological degradation with the attached microorganisms, while assisting in even distribution of the influent across the wetland surface and reducing the infiltration rate for improved treatment efficiencies (Paing and Voisin 2005).

4.3.3 Nitrogen Removal

In Table 4.8, the average NH_3-N concentration of the septage influent for the wetlands was 330 ± 163 mg/L. This was in range of ammonia concentration of the Bangkok's septage as reported by Koottatep et al. (2001) (Chapter 3, Table 3.4). The resulting effluent of wetlands A1-100P and A1-250P had ammonia content varying between 14 - 147 mg/L and 15 - 139 mg/L, with mean concentration removal of 74% and 68%, respectively (Table 4.8). The wetland applied with 250 kg TS/m^2.yr produced effluent with generally higher NH_3-N concentration at lower removal efficiency than wetland loaded with SLR 100 kg TS/m^2.yr. However, no statistically significant difference was found between their treatment performances in terms of NH_3-N removal. The increased SLR did not seem to deteriorate the ammonia concentration reduction performance, although the DO contents were found to be constantly lower in the effluent of wetland A1-250P compared to wetland A1-100P, as shown in Table 4.2. These results are in agreement to the study outcome reported by Koottatep et al. (2005), such that the variations of SLR within the range of 80 - 250 kg TS/m^2.yr did not significantly affect the overall treatment performance of their pilot-scale wetlands planted with Cattail (*Typha angustifolia*). The ammonia reduction percentages obtained from this study were generally higher than the range reported by the authors at SLR 250 kg TS/m^2.yr (40 - 65% of NH_3-N removal) (Koottatep et al. 2005).

Table 4.8 Nitrogen concentration and mass statistics for raw septage and effluent of wetlands A-100P (SLR 100) and A1-250P (SLR 250)

			Period I															
			NH_3-N						**NO_3-N**				**TN**					
	Parameter		Min	Max	SD	Mean	MRR*	RE (%)*	Min	Max	SD	Mean	Min	Max	SD	Mean	MRR*	RE (%)*
Conc. (mg/L)	Inf.		153.90	695.31	163.00	327.04			0.00	35.70	9.18	14.53	372.00	1,661	388.44	1,048		
	Eff. A1-100P		14.40	147.00	30.24	74.08		73.79	0.80	79.75	18.62	15.45	90.00	282.00	67.57	199.59		79.01
	Eff. A1-250P		15.00	139.20	32.65	91.70		68.02	0.60	25.60	6.46	7.88	108.00	510.00	104.58	252.47		72.86
Mass (g/m^2.week)	A1-100P	Inf.	3.91	62.32	14.92	23.50			0.00	2.38	0.49	0.90	26.90	355.53	79.16	81.92		
		Eff.	0.51	11.14	2.77	3.71	19.80	82.88	0.04	2.57	0.69	0.66	1.51	40.93	8.69	10.04	64.62	85.94
	A1-250P	Inf.	9.79	155.79	37.31	58.76			0.00	5.95	1.22	2.25	67.24	888.82	197.89	204.80		
		Eff.	0.74	21.55	5.26	7.47	51.29	86.81	0.05	2.20	0.56	0.60	3.29	68.80	15.09	19.84	184.97	88.35

No. of samples, N = 18

MRR= Mass removal rate

RE= Removal efficiency

SD = Standard deviation

* Values presented as the average REs or MRRs calculated from N samples of N experimental runs

Figure 4.10 illustrates the influent areal loading rates for NH_3-N, corresponding effluent mass, and mass removal efficiencies for wetlands A1-100P and A1-250P. The mass statistics of the nitrogen fractions for the wetlands influent and effluent were summarised in Table 4.8. Comparing the wetland performance in terms of mass removal efficiency, the effect of SLR on ammonia reduction was found to be statistically insignificant ($P>0.05$). Greater weekly mass removal per unit area (kg/m^2.wk) at the wetland loaded with higher SLR (A1-250P) was due to the increased influent loads. Statistical analysis on the mass removal efficiencies of the two wetlands did not reveal significant difference between them, indicating that wetland A1-100P did not outperform wetland A1-250P in terms of ammonia reduction (Table 4.8).

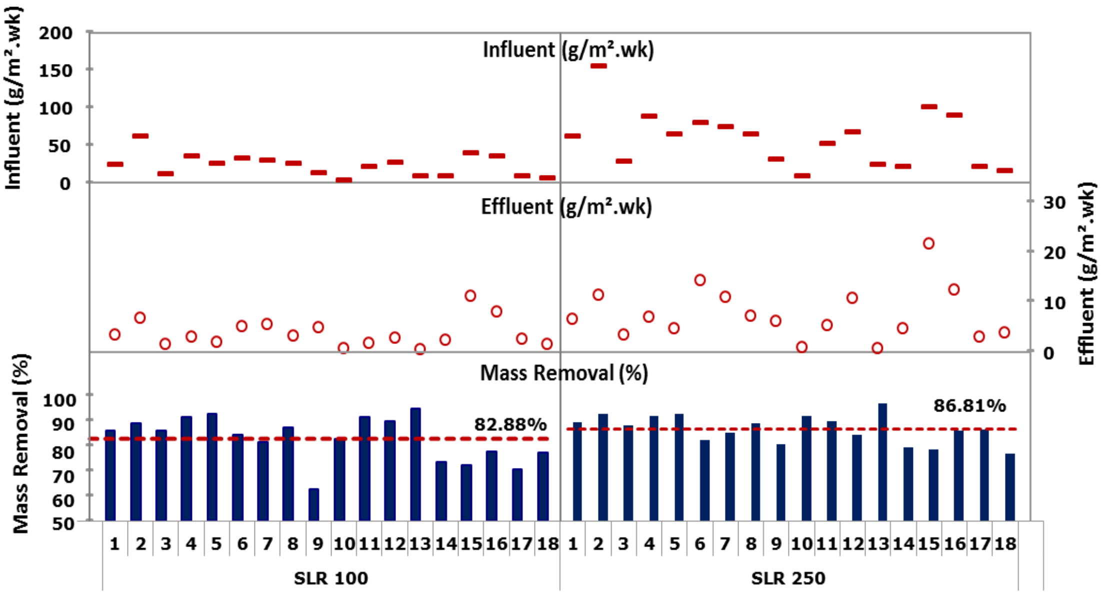


Figure 4.10 NH_3-N Influent areal loading rates and the resulting effluent loads, with the percentages (%) of mass removal for A1-100P and A1-250P with 18 sets of experiments

A regression analysis was done to predict the NH_3-N MRRs from the pollutant loading rates, and the scatter plot of the data is shown in Figure 4.11. The close fit of the points to the regression line indicates a remarkably constant areal removal rate for NH_3-N at both beds ($r^2>0.97$). The plot shows high predictability of the wetland performance with more than 97% of the variation in the NH_3-N MRRs being explainable by the strength of the incoming NH_3-N loads. The graph shows that both the wetlands had their NH_3-N MRRs directly affected by the ILRs.

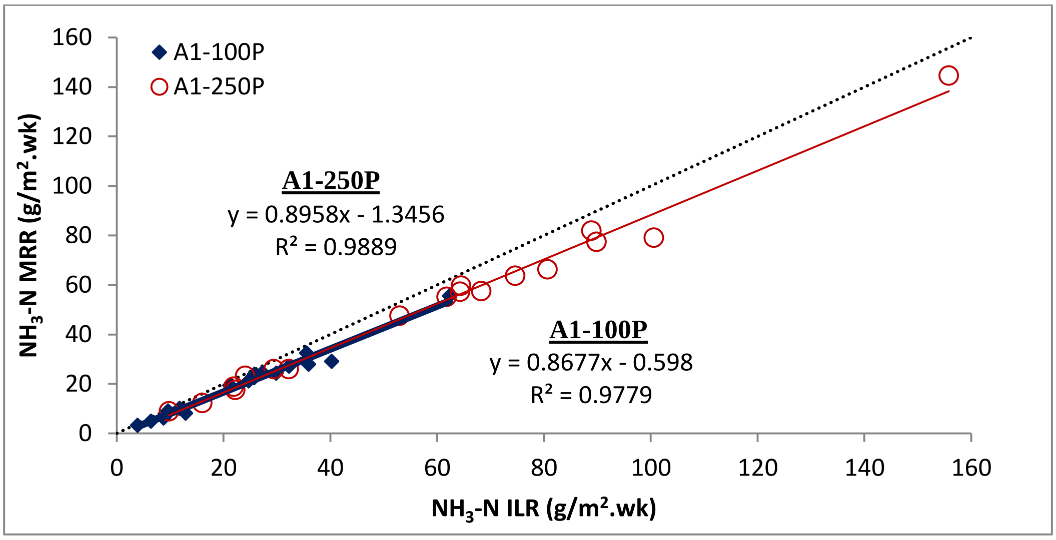


Figure 4.11 Regression graph of NH_3-N mass removal rate (MRR) against influent loading rate (ILR) (g/m ²wk) for wetland A1-100P (SLR 100) and A1-250P (SLR 250). The dotted line represents complete removal.

When the maximum SLR was increased to 350 kg TS/m^2.yr in Period II, it was interesting to find that the higher loading rates did not significantly reduce the nitrogen fractions removal efficiency of the wetlands (Table 4.9) ($P>0.05$). The study outcome revealed a slight but insignificant decrease in the NH_3-N treatment efficiency at wetland A2-350P. The differences of the NH_3-N mass reduction percentages between wetlands A2-250P and A2-360P were constantly less than 7% (Appendix B1). These differences were not found to be statistically significant.

Table 4.9 Nitrogen concentration and mass statistics for raw septage and effluent of wetlands A2-250P (SLR 250) and A2-350P (SLR 350)

			Period II															
			NH_3-N						**NO_3-N**				**TN**					
	Parameter		Min	Max	SD	Mean	MRR*	RE (%)*	Min	Max	SD	Mean	Min	Max	SD	Mean	MRR*	RE (%)*
Concentration (mg/L)	Influent		62.00	406.10	109.40	214.79			21.70	117.30	27.77	41.25	275.00	1,426	381.83	880.00		
	Eff. A2-250P		21.60	68.40	15.48	41.16		76.90	16.20	121.80	34.01	55.22	72.00	210.00	43.18	132.30		81.58
	Eff. A2-350P		31.20	94.20	19.44	55.44		68.55	1.80	67.80	28.28	26.58	108.00	216.00	37.12	153.60		78.39
Mass (g/m^2.week)	A2-250P	Inf.	10.19	65.66	16.40	23.41			1.19	8.65	2.11	4.40	38.59	255.97	64.07	98.34		
		Eff.	0.24	3.20	1.14	1.61	21.80	92.99	0.26	4.69	1.59	2.09	0.77	9.52	2.87	5.01	93.33	94.24
	A2-350P	Inf.	14.26	91.92	22.97	32.77			1.67	12.11	2.95	6.15	54.03	358.35	89.70	137.68		
		Eff.	0.20	4.84	1.37	2.20	30.57	92.49	0.01	4.19	1.66	1.37	0.60	12.39	3.59	6.15	131.54	94.69

No. of samples, N = 10

MRR= Mass removal rate

RE= Removal efficiency

SD= Standard deviation

* Values presented as the average REs or MRRs calculated from N samples of N experimental runs

Similarly in Period II, the mean DO of the effluent was significantly increased after treatment in the wetland beds. The DO concentrations ranged from 1.61 - 6.67 mg/L in wetland A2-250P and from 1.27 - 6.28 mg/L in wetland A2-350P (Table 4.2). The improved quality of the effluent after the first stage of treatment was also supported by the improved ORP values observed. Initial ORP values in the raw septage ranged between -90 - (-275) mV, and these values were increased considerably to -22 - 278 mV and -24 - 233 mV after treatment in wetlands A2-250P and A2-350P, respectively. The results suggested that treatment at the designed wetlands with feeding of once weekly promotes aerobic conditions in beds, which enhances nitrification process for the removal of ammonia.

As shown in Figure 4.12, the two regression lines for wetlands A2-250P and A2-350P have similar slopes but significantly different intercepts with the y-axis ($P<0.001$). The higher rate of mass removal was observed as the direct provenance of the higher influent loading. Both lines showed good correlation between the NH_3-N MRRs and the ILRs, implying that the oscillation of the incoming nitrogen mass was handled well by the wetlands under both loadings. The NH_3-N MRRs increased linearly up to 89 g N/m^2.wk as the incoming mass increased to 92 g N/m^2.wk (Figure 4.12). Generally, the study showed that the VFEWs can perform fairly well in terms of nitrogen reduction with SLR up to 350 kg/m^2.yr, without major issues on substrate clogging and performance deterioration due to the increased loadings.

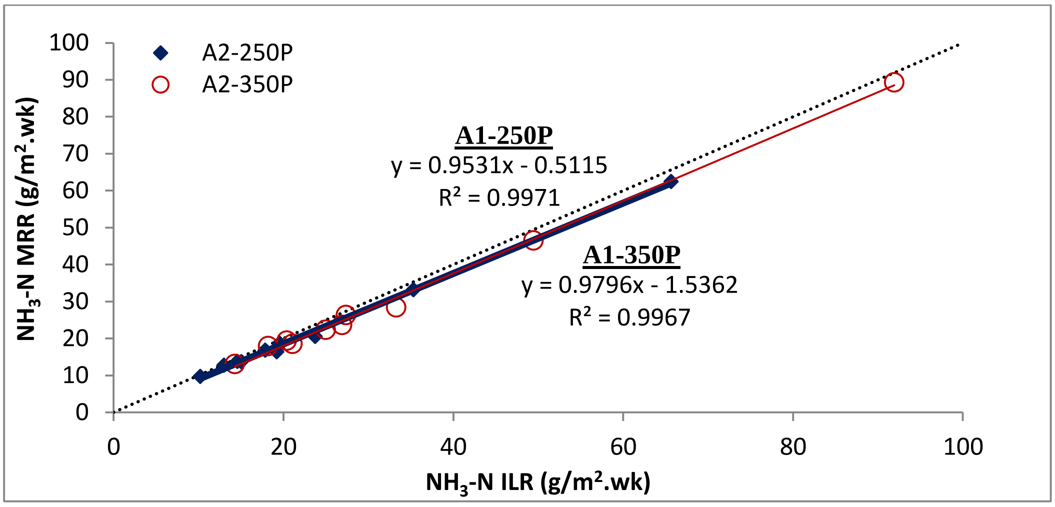


Figure 4.12 Regression graph of NH_3-N mass removal rate (MRR) against influent loading rates (ILR) (g/m ^{2}wk) for wetlands A2-250P (SLR 250) and A2-350P (SLR 350). The dotted line represents complete removal.

4.4 Effects of Plant Presence (SLRs 250 and 350 kg TS/m^2.yr)

Surface solid loading rates (SLRs) of 250 and 350 kg TS/m^2.yr were used to study the effects and significance of plant presence in the treatment of septage with vertical engineered wetlands. For the planted units, *Phragmites karka* was used as the wetland macrophytes as described in Chapter 3, section 3.5. *Phragmites* is a perennial and flood-tolerant grass with an extensive rhizome system (Figure 4.13) which can penetrate to depths of about 0.6 to 1.0 m (Haslam 1971). *Phragmites* has rigid stems with hollow internodes. This plant is known to be the most frequently used plant in subsurface flow engineered wetlands (Kadlec et al. 2000). However, according to Vymazal and Kröpfelová (2005), *Phragmites* growth is much slower compared to other emergent plants commonly used in engineered wetlands.

Figure 4.13 (Left and right) *Phragmites karka*; Roots and rhizomes; Stems

Figure 4.14 shows the volumes of influent applied onto the wetlands and their corresponding volumes of effluent collected from the base of the wetland beds. The estimated volumes collected from each bed revealed that the planted unit had produced significantly lower drained water volumes ($P<0.001$). Lower drainage rates at the planted unit can contribute to a substantial sum of physical volume loss due to relatively higher volume of septage available for loss through ET, owing to the longer retention time.

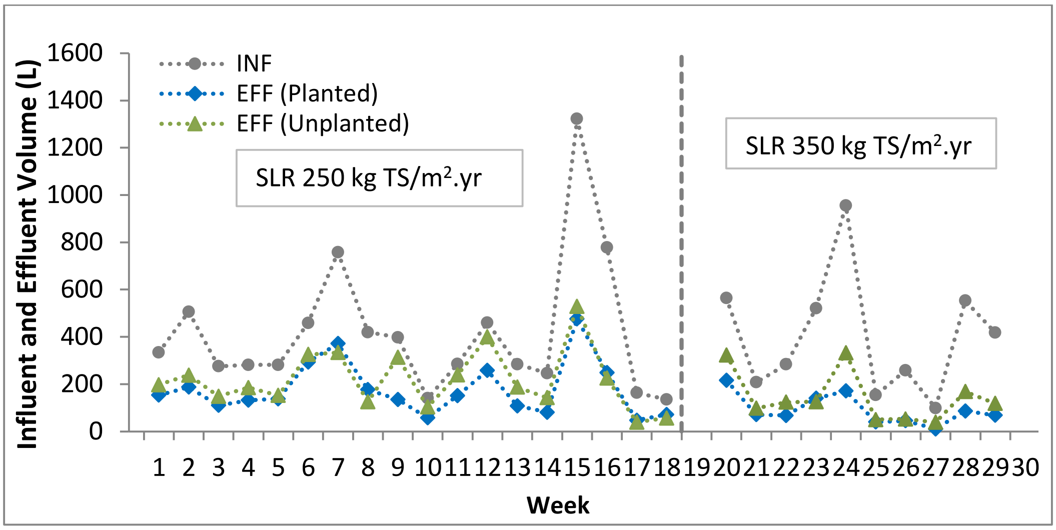


Figure 4.14 Influent and effluent volume (L) for planted and unplanted units at SLR 250 and 350 kg TS/m^2.yr

The boxes in Figure 4.15 (a) and (b) delineate the interquartile range, above and below the median (central horizontal line), and the ‘whiskers’ show the overall range of the data. The dot inside the boxes represents the mean of the data. The plots showed that the higher the amount of water lost was associated with the planted unit at both SLRs (Figure 4.15). Mean percentage of water loss for 22 weeks at planted wetland unit (A1-250P) was 55% and at the unplanted unit (A1-250UP) was 42% for the beds fed with SLR of 250 kg TS/m^2.yr. Statistical analysis has shown that the means between them was significantly different. Beds fed with SLR of 350 kg TS/m^2.yr followed a similar trend with significantly greater percentage of water loss from the planted unit (A2-350P) compared to the unplanted one (A2-350UP). Wetland A2-350P which experienced greater water loss produced 36% lesser drained volume at than wetland A2-350UP. The plots for both planted units under SLRs of 250 and 350 kg TS/m^2.yr show tighter quartiles than that for the unplanted units. This suggested that a more consistent rate of water lost via ET was found with the presence of plants.

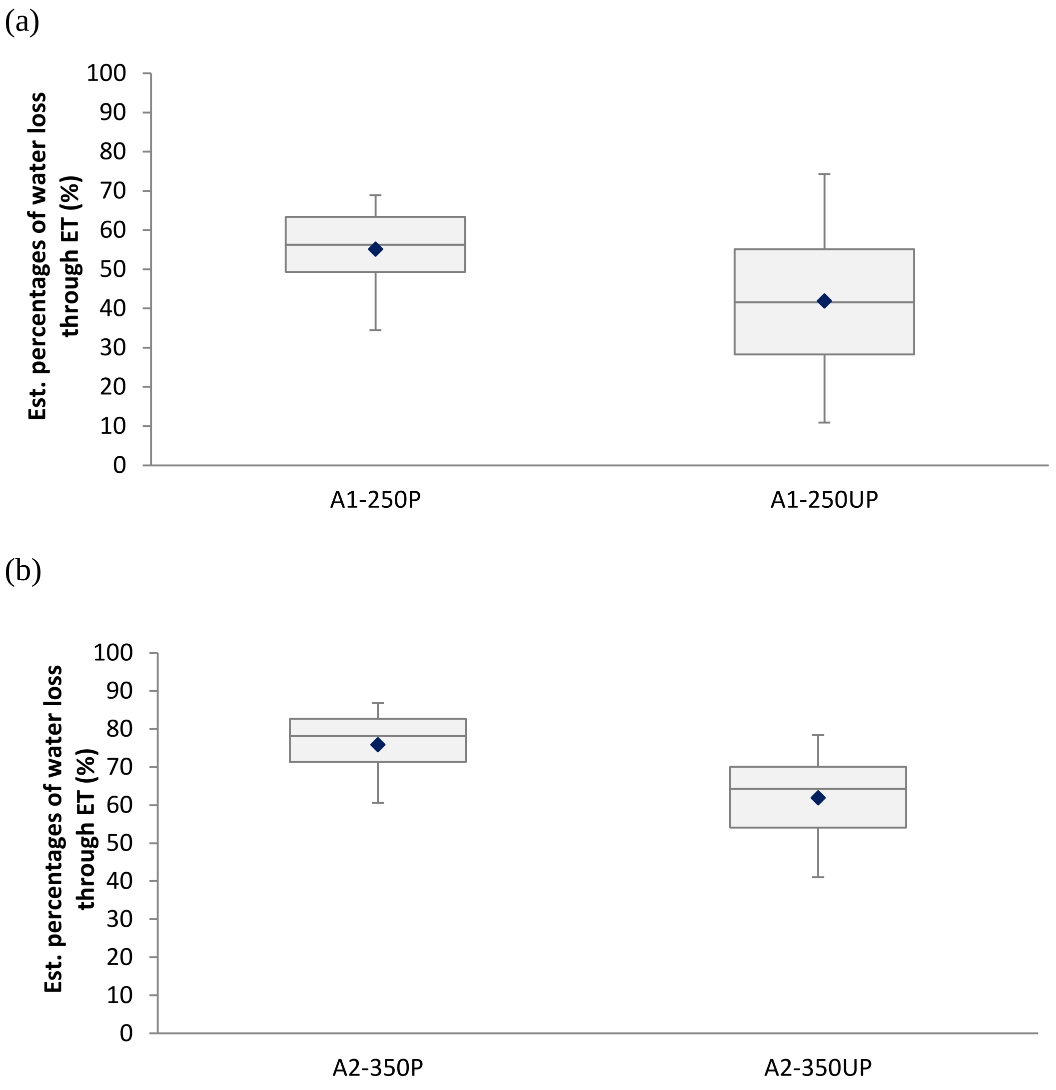


Figure 4.15 Estimated water loss from the planted and unplanted beds through evapotranspiration (%) at (a) SLR of 250 (b) SLR of 350 kg TS/m^2.yr

Dense roots network slows down the infiltration and percolation of the influent through the wetland substrate, leaving the fed septage to retain on the bed surface for an extended time and allowing evaporation and transpiration processes to prevail over drainage. The swaying of plants in the wind and the growing root system keeps channels open from the accumulated septage layer to the gravel layer, which allows drainage of the wetlands. Also, planted units with the presence of reeds consume a large amount of water for transpiration (Kadlec et al. 2000), promoting water loss through their leaf system into the atmosphere. This makes the performance comparison between the planted and unplanted units by the mass-based removal efficiency more rational than using the concentration-based reduction efficiency.

This approach was also supported by several other researchers in the field (Kantawanichkul, Kladprasert and Brix 2009; Wu et al. 2011).

At wetlands fed with SLRs of 250 and 350 kg TS/m^2.yr, the pH values were observed to increase at the outlet of both the planted and unplanted unit as reported in Table 4.10. In the present study, the pH in the effluent was found to decrease with plant presence. According to Rao et al. (2002), plants can take up significant amounts of sparingly soluble nutrients from the zone surrounding their roots with their ability to acidify the rhizosphere. The reduction of pH in the planted reactors was also due to the formation of dissolved carbon dioxide (CO_2) and carbonic acid (H_2CO_3) in water as a result of the degradation of organic compounds by aerobic organisms that lead to pH reduction in the effluent (Kyambadde et al. 2004). Besides, nutrient transformation processes such as nitrification could also lower the pH in the rhizosphere by consuming alkalinity (Bezbaruah and Zhang 2004).

With regards to the conductivity, the unplanted units produced effluent with a lower average EC value than that of the planted units (1.89 mS/cm and 1.98 mS/cm, respectively) under SLR of 250 kg TS/m^2.yr (Table 4.10). Both the effluent EC from A1-250P and A1-250UP were generally higher than the EC value of the influent. The EC of the effluent from A1-250P was about 126% of the EC of the influent septage, and 120% of the effluent of A1-250UP. A similar condition was observed in wetlands fed with SLR 350 kg TS/m^2.yr, where the unplanted bed produced effluent with a relatively lower EC than the planted one. The effluent after treatment from both beds also gave constantly higher EC values than the influent septage (Table 4.10). The increased trend of EC values in the treated effluent was also observed by Nassar et al. (2009), where the authors use reedbeds for the treatment of raw sewage sludge. The higher EC was claimed to be due to the higher amounts of ions in the bed effluent after treatment, such as increased nitrate concentration due to nitrification and higher salt concentration in accumulated sludge as a result of evaporation and transpiration in the wetlands (Nassar, Smith and Afifi 2009).

Table 4.10 Physico-chemical parameters statistics for raw septage, and effluent of wetlands A1-250P (planted) and A1-250UP (unplanted) at SLR 250 kg TS/m^2.yr, and wetlands A2-350P (planted) and A2-350UP (unplanted) at SLR 350 kg TS/m^2.yr. N is the number of samples collected and analysed for each parameter during the study period.

	SLR 250 kg TS/m^2.yr					**SLR 350 kg TS/m^2.yr**				
		Statistics					Statistics			
Parameter	Sampling Point	N	Range	Mean	Std Dev.	Sampling Point	N	Range	Mean	Std Dev.
Temperature (℃)	Influent	18	27.50 - 30.40	29.02	0.91	Influent	10	27.20 - 30.50	29.08	0.19
	Eff. Planted (A1-250P)	18	28.00 - 30.40	29.2	0.88	Planted (A2-350P)	10	26.20 - 29.90	28.35	1
	Eff. Unplanted (A1-250UP)	18	27.10 - 30.80	28.91	1.1	Unplanted (A2-350UP)	10	26.70 - 30.00	28.39	0.98
pH	Influent	18	5.93 - 7.69	6.77	0.48	Influent	10	5.81 - 7.15	6.42	0.46
	Eff. Planted (A1-250P)	18	6.71 - 7.36	7.11	0.19	Planted (A2-350P)	10	6.47 - 7.61	7.13	0.32
	Eff. Unplanted (A1-250UP)	18	6.79 - 7.58	7.18	0.23	Unplanted (A2-350UP)	10	6.79 - 7.65	7.23	0.27
DO (mg/L)	Influent	18	0.06 - 0.30	0.14	0.07	Influent	10	0.06 - 0.86	0.27	0.26
	Eff. Planted (A1-250P)	18	0.61 - 3.06	1.87	0.79	Planted (A2-350P)	10	1.27 - 6.28	3.2	1.58
	Eff. Unplanted (A1-250UP)	12	0.37 - 2.73	1.47	0.81	Unplanted (A2-350UP)	10	0.18 - 2.37	1.11	0.8
ORP (mV)	Influent	12	-100 -(- 546)	-	-	Influent	10	-90 -(- 275)	-	-
	Eff. Planted (A1-250P)	12	-178 - 211	-	-	Planted (A2-350P)	10	-24 - 233	-	-
	Eff. Unplanted (A1-250UP)	12	-254 - 139	-	-	Unplanted (A2-350UP)	10	-50 - 247	-	-
EC (mS/cm)	Influent	18	1.04 - 2.36	1.57	0.41	Influent	10	0.72 - 1.40	1.24	0.19
	Eff. Planted (A1-250P)	18	1.39 - 2.47	1.98	0.33	Planted (A2-350P)	10	1.36 - 2.84	1.93	0.5
	Eff. Unplanted (A1-250UP)	18	1.39 - 2.53	1.89	0.33	Unplanted (A2-350UP)	10	1.08 - 1.92	1.47	0.24

Referring to Table 4.10 for Period I, the raw septage was low in saturated oxygen content with a mean DO content of 0.14 ± 0.07 mg/L and ORP value of ranging between -100 - (-546) mV, indicative of the anaerobic state of the influent. Regardless of plant presence, both beds showed increased DO and ORP values in the effluent after treatment, in particular for the planted units (Table 4.10). The increased DO content in the effluent after wetland treatment suggested that both the planted and unplanted beds showed great potential for septage treatment under the operational regime. The planted bed produced effluent with higher DO content, giving values varying from 0.61 - 6.28 mg/L up to SLR of 350 kg/m^2.yr (Table 4.10). Effluent DO at the bed with absence of plants was relatively lower, with values ranging between 0.18 - 2.73 mg/L up to SLR of 350 kg/m^2.yr. The ORP which is an indicator of the redox status of a wastewater, revealed a relatively more reduced environment in the unplanted bed with the effluent ORP values ranging between -254 - 247 mV, and the effluent of the planted unit varying between -178 - 233 mV for both SLRs (Table 4.10).

4.4.1 Particulate Solids Removal

In this study, the gravel-based engineered wetlands planted with *Phragmites karka* were found to be particularly effective in reducing concentration and mass of suspended solids. The mean influent TSS concentration of 24.8 g/L was removed by 93.6% at planted wetland A1-250P, producing effluent with 1.4 g TSS/L (Table 4.11). The mean effluent TSS concentration collected from the unplanted unit was significantly higher at 2.3 g/L with 88.7% of wetland removal efficiency. The resulting effluent from all beds was observed to be less turbid and had a clearer appearance than the septage influent discernible by direct visual observation. This was attributed to the efficiency of the beds in removing suspended solids in general, regardless of plants presence.

Table 4.11 and Table 4.12 present the particulate solids mass statistics for the planted and unplanted units at SLRs of 250 and 350 kg TS/m^2.yr. Figure 4.16 shows the influent TSS areal loading rates, and the corresponding effluent mass and mass removal efficiencies for planted and unplanted beds under both SLRs. The TSS was evidently removed from the septage influent after the first stage of treatment, with significant difference found between the TSS mass in the septage influent and the resulting effluent at both SLRs ($P<0.001$), regardless of plant presence. TSS mass had been found to be removed at a greater extent by the planted unit than the unplanted one with statistical importance. The weekly influent TSS mass of 3.5 kg/m^2 was significantly reduced to 89 g/m^2 in the planted wetland A1-250P and 200 g/m^2 in the unplanted unit A1-250UP (removal of 97.3% against 93.2%). The TSS mass recovered from the effluent of the planted unit was significantly lower by an average of about 56% than that of the unplanted bed for the 22 weeks of study period. Suspended solids are principally removed by sedimentation and biofiltration processes in the wetlands (Belgiorno, De Feo and Napoli 2003). It is likely that the plant roots network with the substrate provided a more effective settling medium than aggregates alone on the unplanted beds. Filtration occurs by impaction of particles onto the roots and stems of the macrophytes or onto the gravel particles in vertical wetland systems (Vymazal 1999).

Table 4.11 TSS concentration and mass statistics for influent and effluent of planted and unplanted units at SLR 250 and 350, with the corresponding removal efficiencies (%)

			TSS					
Parameter			Min	Max	Std Dev.	Mean	MRR*	RE (%)*
SLR 250 (N=18)	Concentration (mg/L)	Influent	5,200	60,900	14,845	24,759		
		Eff. A1-250P	80.00	4,940	1,116	1,442		93.6
		Eff. A1-250UP	550.00	6,400	1,646	2,332		88.68
	Mass (g/m^2.week)	Influent	1,085	4,833	1,149	3,502		
		Eff. A1-250P	10.68	266.83	59.62	88.79	3,413	97.31
		Eff. A1-250UP	26.18	520.32	125.46	199.85	3,302	93.23
SLR 350 (N=10)	Concentration (mg/L)	Influent	12,600	92,250	34,530	50,863		
		Eff. A1-250P	265.00	2,333	708.31	1,071		96.52
		Eff. A1-250UP	1,320	7,860	1,646	2,561		94.15
	Mass (g/m^2.week)	Influent	5,371	6,658	499.58	6,156		
		Eff. A1-250P	1.86	165.58	51.38	50.29	6,106	99.18
		Eff. A1-250UP	42.12	259.76	71.79	129.65	6,026	97.86

MRR= Mass removal rate

RE= Removal efficiency

N= Number of samples

* Values presented as the average REs or MRRs calculated from N samples of N experimental runs

Table 4.12 TS and VSS concentration and mass statistics for influent and effluent of planted and unplanted units at SLR 250 and 350, with the corresponding removal efficiencies (%)

			TS						**VSS**					
Parameter			Min	Max	Std Dev.	Mean	MRR*	RE (%)*	Min	Max	Std Dev.	Mean	MRR*	RE (%)*
SLR 250 (N=18)	Conc. (mg/L)	Influent	8,000	78,000	19,981	35,299			4,100	29,000	7,170	14,458		
		Eff. A1-250P	1,436	16,400	3,431	3,504		89.29	35.00	1,900	522.25	657.87		95.27
		Eff. A1-250UP	1,896	20,800	4,311	4,664		85.49	170.00	4,800	1,222	1,449		88.99
	Mass (g/m^2.week)	Influent	4,808	4,808		4,808			855.09	3,253	746.41	2,144		
		Eff. A1-250P	46.16	427.60	101.20	214.25	4,593	95.54	4.26	122.60	31.99	41.19	2,103	98.02
		Eff. A1-250UP	47.50	1,525	331.18	423.41	4,384	91.82	12.43	409.43	104.20	124.47	2,019	93.62
SLR 350 (N=10)	Conc. (mg/L)	Influent	15,508	96,554	41,289	56,000			8,300	53,640	22,400	34,371		
		Eff. A1-250P	1,204	5,132	1,190	2,966		91.53	180.00	1,717	543.60	815.50		96.36
		Eff. A1-250UP	1,376	4,572	860.03	3,330		90.77	900.00	3,200	686.67	1,639		93.84
	Mass (g/m^2.week)	Influent	6,731	6,731		6,731			3,315	5,229	693.50	4,248		
		Eff. A1-250P	6.04	262.90	83.57	128.08	6,603	98.1	1.51	81.97	29.08	34.96	4,213	99.19
		Eff. A1-250UP	23.98	470.64	146.02	218.95	6,512	96.75	35.68	196.05	58.82	92.95	4,155	97.75

MRR= Mass removal rate

RE= Removal efficiency

N= Number of samples

* Values presented as the average REs or MRRs calculated from N samples of N experimental runs

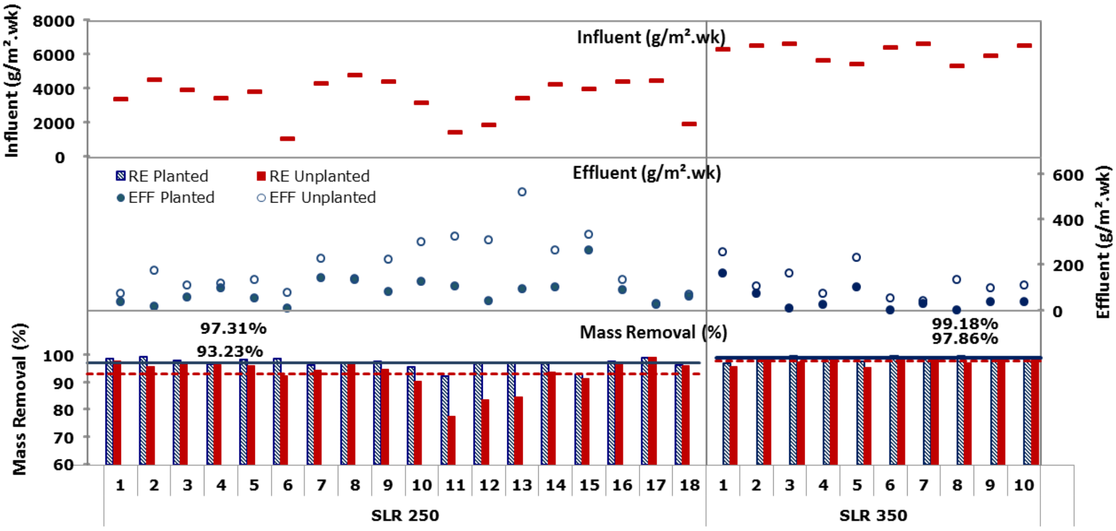


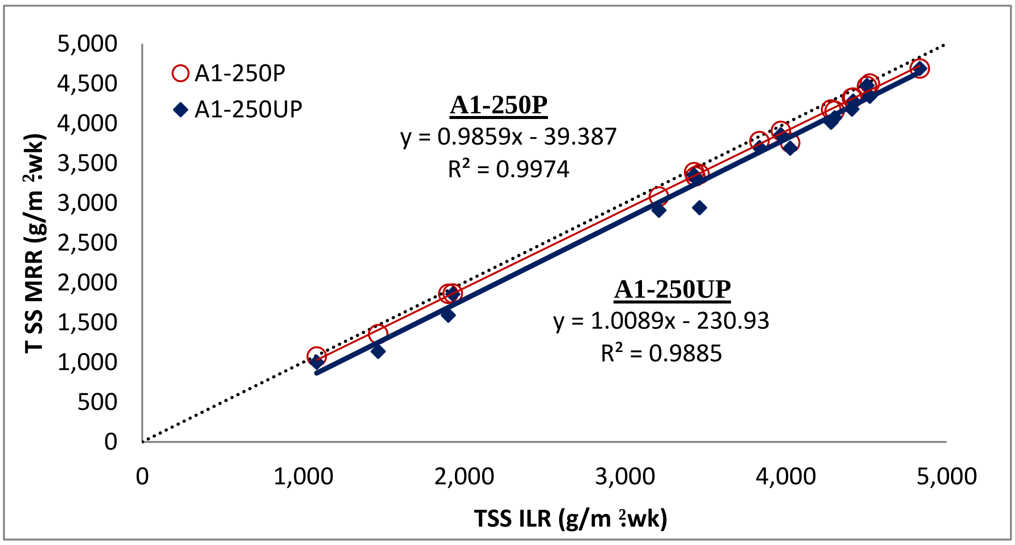
Figure 4.16 Influent TSS areal loading rates and the resulting effluent loads for planted and unplanted bed, with the percentages (%) of mass removal for each treatment (horizontal solid line indicates mean removal efficiencies for planted unit; dashed line indicates mean removal efficiencies for unplanted unit) at SLRs 250 and 350 kg TS/m^2.yr

The effects of plant presence was found to be relatively less influential in wetland loaded at a higher SLR (350 kg TS/m^2.yr), with less increase in overall mean TSS reduction efficiency at the planted unit. The increment in treatment efficiency was found to be statistically insignificant ($P>0.05$). Average MRR of TSS at the planted unit A2-350P was 6.11 kg/m^2.week, which was marginally higher than the mass removal rate at the unplanted bed A2-350UP with 6.03 kg/m^2.week (Table 4.11). Both the planted and unplanted wetlands performed equally well with maximum TSS elimination efficiency up to 99.97% in wetland A2-350P and 99.37% in wetland A2-350UP (Appendix B2).

Analysis of variance (ANOVA) showed that the relationship between the loading and removal rates was statistically important ($P<0.001$) for the parameters examined, i.e. TS, TSS and VSS. The trend of TSS removal in the wetlands are presented in Figure 4.17 (a) and (b), with the regression trendline revealing greater removal rates in the planted units over the unplanted beds. This implies that a greater amount of solids were retained in or on the beds with the help of plant roots at both SLRs. The plots showed strong linear correlation between the TSS mass applied and the mass removed, such that the highest mass eliminated was in correspondence to the highest applied loading rate. High correlation coefficients of the plots in Figure 4.17 (a) and

(b) (r^2>0.98) implied high predictability of the suspended particulate solids removal rates in accordance with the incoming solids mass. The close fit of the points to the regression line indicate a remarkably near constant areal removal rates for TSS.

(a)



(b)

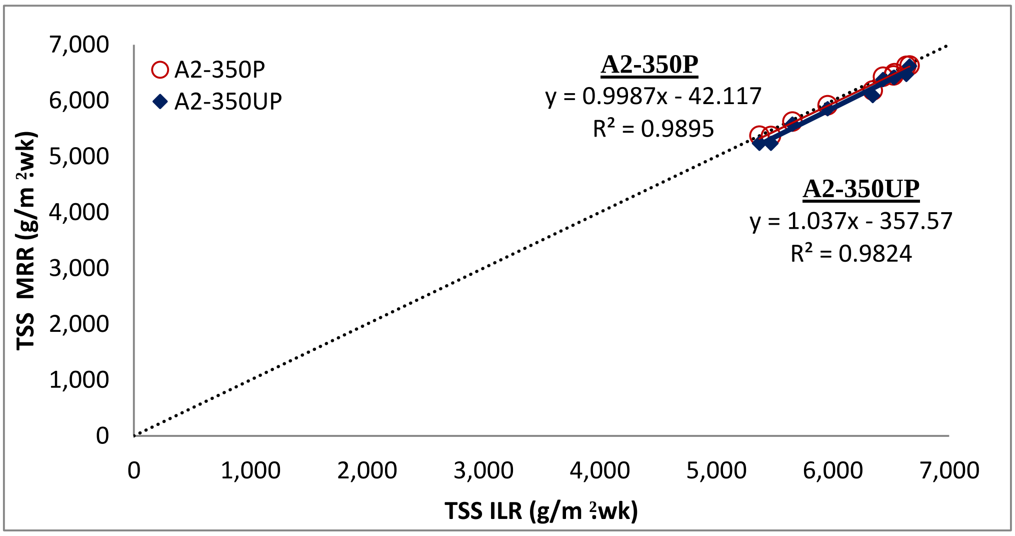


Figure 4.17 Regression graph of TSS mass removal rate (MRR) against influent loading rates (ILR) (g/m ²wk) for planted and unplanted units at (a) SLR 250 (b) SLR 350 kg TS/m^2.yr. The dotted line represents complete removal.

As shown in Table 4.12 and Figure 4.18, the removal efficiencies in terms of reduction of mass were high for TS. The planted bed produced effluent with mean TS of 0.21 kg/m^2.week while the unplanted unit discharged effluent with mean TS of

0.39 kg/m^2.week, when the wetlands were loaded at with SLR 250 kg TS/m^2.yr. The overall mean reduction percentage was 95.5% with wetland A1-250P and this was 4.8% greater than wetland A1-250UP on average. The difference was found to be statistically important. On the other hand, the effects of plant presence were insignificant for TS mass removal at the wetlands fed with SLR 350 kg TS/m^2.yr. Mean TS removal efficiency of 98.1% and 96.8% was achieved at bed A2-350P and A2-350UP respectively, where the TS mass reduction performance between the wetlands was not found to be statistically different.

The mass removal efficiency for VSS had also been found to differ greatly between the planted wetland A1-250P and unplanted wetland A1-250UP at SLR of 250 kg TS/m^2.yr (Table 4.12 and Figure 4.19). Wetland A1-250P performed significantly better in removing VSS, where the bed can eliminate VSS up to an average of 4.7% more than the unplanted A1-250UP unit. These results indicate that the rooting biomass of the planted system provided more effective filtration of the TSS mass, and contributed to the complimentary treatment of the organic portion of the TSS mass through microbial decomposition processes. Although the effect of plant presence on VSS reduction efficiency at wetlands loaded with SLR 350 kg TS/m^2.yr was not found to be statistically important, the overall VSS removal percentages were greater in the planted unit compared to the unplanted one. VSS content of the effluent produced from the planted A2-350P bed was low at 0.07 kg/week even under maximum VSS mass of 11.50 kg/week (Figure 4.19 and Appendix B2).

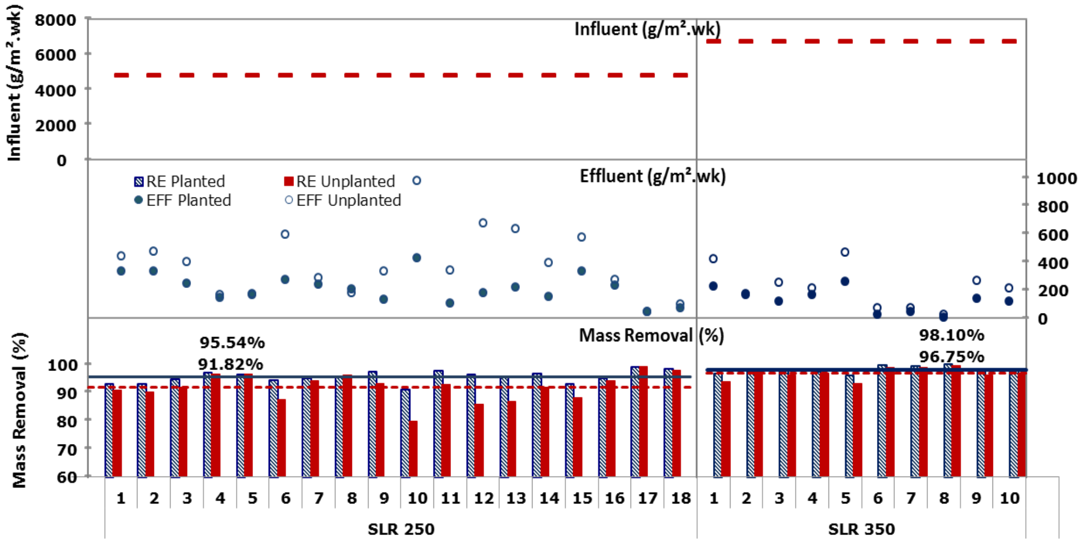


Figure 4.18 Influent TS areal loading rates and the resulting effluent loads for planted and unplanted bed, with the percentages (%) of mass removal for each treatment at SLR 250 and 350 kg TS/m^2.yr (horizontal solid line indicates mean removal efficiencies for planted unit; dashed line indicates mean removal efficiencies for unplanted unit)

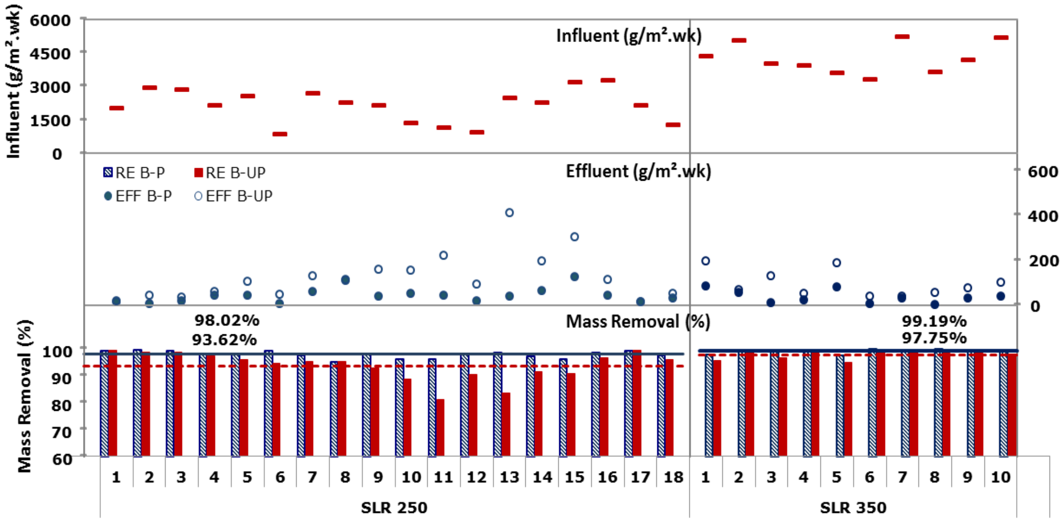


Figure 4.19 Influent VSS areal loading rates and the resulting effluent loads for planted and unplanted bed, with the percentages (%) of mass removal for each treatment at SLR 250 and 350 kg TS/m^2.yr (horizontal solid line indicates mean removal efficiencies for planted unit; dashed line indicates mean removal efficiencies for unplanted unit)

4.4.2 Organic Matter Removal

In Table 4.13, the concentrations of the organic matter (OM) indices (COD and BOD_5) are presented for the septage influent and the treated effluent from planted and unplanted units under SLRs of 250 and 350 kg TS/m^2.yr. Generally both the wetlands provided high OM removal efficiency, with the percentage of reduction exceeding 86% and 90% on the average for COD and BOD_5, respectively for the vertical wetlands regardless of plant presence (Table 4.13). Comparisons between the effluent produced by the planted and unplanted beds showed greater OM elimination performance in the planted units, based on the wetlands removal efficiency throughout the study period. The effluent from the unplanted wetland at both SLRs showed greater fluctuations in the OM concentrations and loads than that of the effluent from planted unit with the higher standard deviations obtained.

At SLR of 250 kg TS/m^2.yr, the average COD and BOD_5 concentration reduction for A1-250P unit was 91.3% and 91.5%, respectively; and for A1-250UP was 86% and 90.6%, respectively. Figure 4.20 depicts the influent COD areal loading rates, and the corresponding effluent mass and mass removal efficiencies for the planted and unplanted beds under the SLRs of 250 and 350 kg TS/m^2.yr. The planted unit had been found to outperform the unplanted one with statistical significance (by ANOVA at 95% confidence level), with an average difference of 4.5% between the COD mass removal efficiency of wetland A1-250P and A1-250UP. Weekly mass of 160 g COD/m^2 and 20 g BOD/m^2 was recovered in the effluent of wetland A1-250P, and 368 g COD/m^2 and 27 g BOD/m^2 in the effluent of wetland A1-250UP. The significant difference found between the COD removal efficiency of the wetlands suggested that the plants provided an important practical benefit towards the wetland system performance with respect to organic matter elimination. Other studies comparing planted and unplanted beds have also shown important difference in the COD removal efficiency between the beds (Korboulewsky, Wang and Baldy 2012; Wang et al. 2001; Wang et al. 2009).

Table 4.13 COD and BOD$_5$ concentration and mass statistics for influent and effluent of planted and unplanted units at SLR 250 and 350

			COD						**BOD$_5$**					
Parameter			Min	Max	Std Dev.	Mean	MRR*	RE (%)*	Min	Max	Std Dev.	Mean	MRR*	RE (%)*
SLR 250 (N=18)	Concentration (mg/L)	Influent	8,990	55,180	15,081	31,927			894.00	8,740	2,109	3,327		
		Eff. A1-250P	403.33	15,300	3,372	2,663		91.34	46.50	684.00	217.68	263.64		91.45
		Eff. A1-250UP	1,705	17,340	3,842	4,266		86.13	66.60	912.00	253.50	296.41		90.61
	Mass (g/m^2.week)	Influent	1,257	19,507	3,883	5,357			64.35	1,525	422.95	592.28		
		Eff. A1-250P	25.27	398.92	110.24	160.54	5,196	96.37	2.13	70.87	19.76	20.34	571.94	96.18
		Eff. A1-250UP	38.34	829.26	248.14	368.45	4,989	91.86	1.90	72.72	22.11	27.46	564.82	94.69
SLR 350 (N=10)	Concentration (mg/L)	Influent	8,030	109,120	29,498	42,002			455.40	8,740	1,826	3,341		
		Eff. A2-350P	600.00	3,300	783.49	1,455		93.03	26.66	262.20	68.49	113.13		96.37
		Eff. A2-350UP	2,040	6,120	2,826	2,826		88.93	28.95	459.60	117.63	225.23		93.44
	Mass (g/m^2.week)	Influent	2,057	12,776	2,861	5,357			116.65	1,877	559.56	631.25		
		Eff. A2-350P	4.06	206.56	63.24	68.64	5,288	98.03	0.36	13.66	4.26	4.59	626.65	99.14
		Eff. A3-350UP	36.59	370.53	122.79	176.33	5,181	95.49	3.78	53.38	15.52	14.47	616.77	97.71

MRR= Mass removal rate

RE= Removal efficiency

N= Number of samples

* Values presented as the average REs or MRRs calculated from N samples of N experimental runs

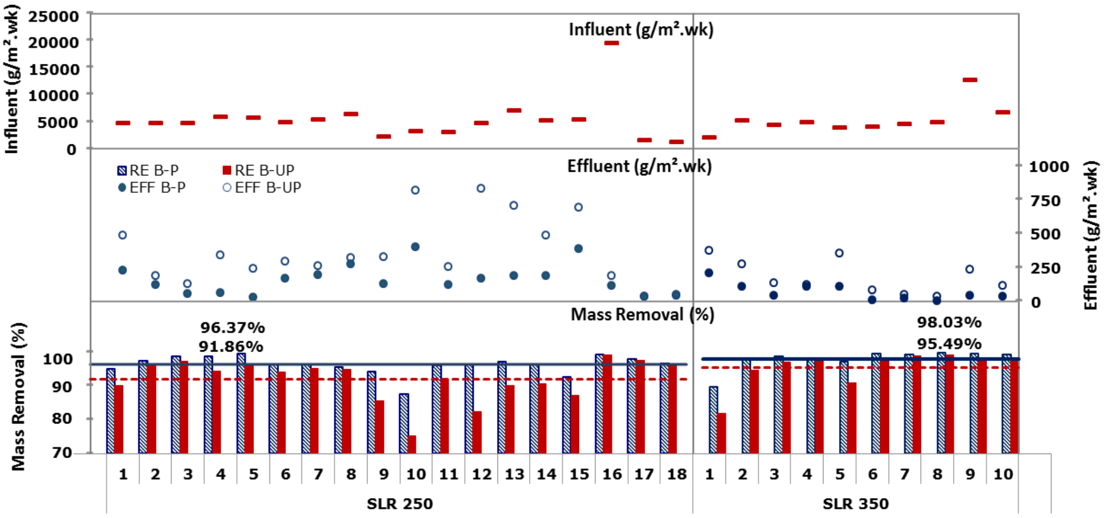


Figure 4.20 Influent COD areal loading rates and the resulting effluent loads for planted and unplanted bed, with the percentages (%) of mass removal for each treatment at SLR 250 and 350 kg TS/m^2.yr (horizontal solid line indicates mean removal efficiencies for planted unit; dashed line indicates mean removal efficiencies for unplanted unit)

The planted wetlands were expected to operate in a more oxidizing condition, where subsequent clear improvement was found in organic mass removal with greater DO concentration recovered in the effluent of the planted bed (Figure 4.5). The study revealed that the effects of plants in primary treatment were significant in reducing COD concentration and mass from the septage as the pollutant was mainly removed by physical filtration mechanism and through sedimentation. The wide range in removal efficiencies observed was mostly due to the septage influent quality, especially the form of pollutants (soluble or particulate forms). As shown in Figure 4.21, it is evident that a majority of the organic pollutant was present in particulate form with the COD mass out of the wetlands following a close correlation with the TSS mass out of the beds at SLR of 250 kg TS/m^2.yr.

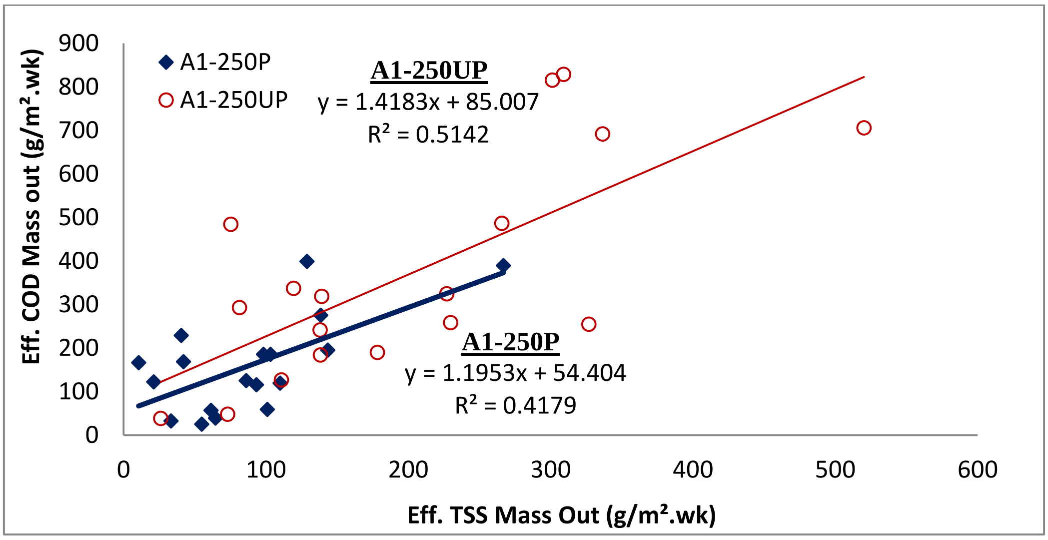


Figure 4.21 Scatter plot of COD against TSS mass recovered in the effluent of A1-250P and A1-250UP

Higher COD removal efficiencies in wetland A1-250P suggested that plants roots network could be a better settling medium for the particulate matter than aggregate substrate alone. The conjecture can be justified with the planted bed that allowed better filtration of suspended solids, as it produced effluent with 56% less TSS mass out compared to the effluent from the unplanted bed (as previously discussed in section 4.4.1), explaining the higher removal of COD in the planted unit. The particulate form of OM can be easily filtered out by the substrate itself (explaining the high removal efficiencies in unplanted unit), and the result from this study suggested even better performance when the aggregate-based beds were complimented with presence of roots network.

COD removal efficiency for the planted and unplanted wetlands loaded with SLR of 350 kg TS/m^2.yr was found to differ by an average 2.5%, where both the beds had provided excellent treatment on OM in general (Table 4.13). The COD mass out was similar for the two beds. The planted unit A1-350P produced effluent with organic mass out between 9 - 454 g of COD per week at an average removal percentage of 98%. COD removal at the unplanted bed A1-350UP was lower at 95.5%, producing effluent with 80 - 815 g of COD weekly. Unlike the results with SLR 250 kg TS/m^2.yr, the planted wetlands did not show a higher removal than the unplanted beds in terms of the overall COD mass removal efficiency. The plant presence seemed to have little influence on the COD treatment performance at SLR 350 kg

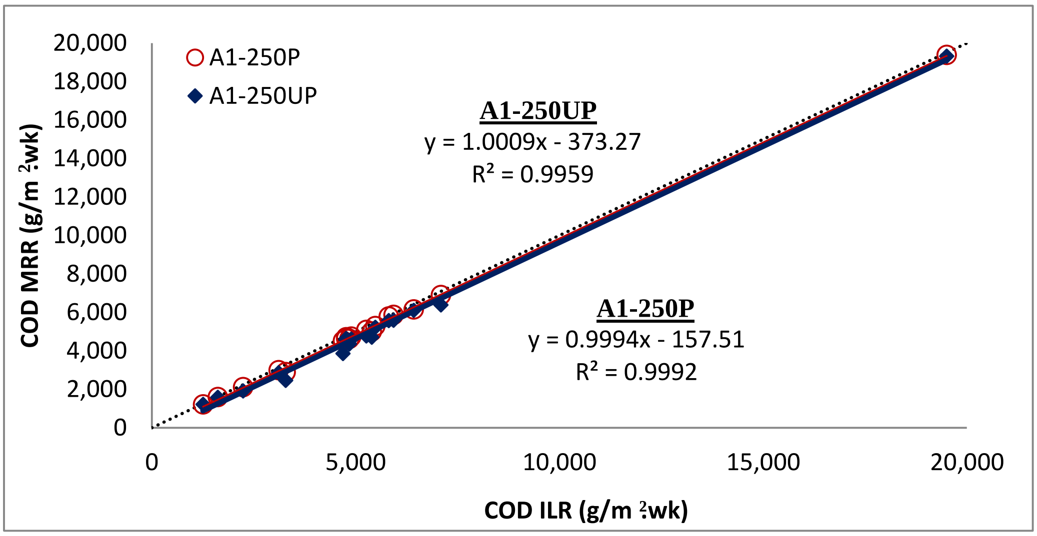
TS/m^2.yr with no statistical differences found between the two wetlands (ANOVA, P>0.05).

Nonetheless, statistical analysis on BOD_5 mass removal efficiency indicated that the planted unit significantly outperformed the unplanted one (P<0.001). This result is in agreement with the research outcome recorded by Dunbabin, Pokorny, and Bowmer (1988) and Reddy, D'Angelo, and DeBusk (1989), such that the BOD_5 removal from wastewater was discovered in the root-zone of wetland plants where higher DO concentration was reported, indicating a more oxidised microenvironment near the rhizophere that stimulates pollutant degradations. The significantly greater BOD_5 removal of the planted wetland A2-350P could also be related to the slightly higher BOD:COD ratio of the septage received in the second period (Period II for SLR 350 kg TS/m^2.yr) compared to the first period (Period I for SLR 250 kg TS/m^2.yr) with ratio of 0.14 against 0.11, which suggested a relatively higher biodegradability of the septage in Period II.

As presented in Table 4.10, the average pH of the septage delivered to the project site during Period II was slightly more acidic than the septage received during Period I. This also explains the higher ratio of biodegradability (BOD:COD) that indicates the treatability of the raw septage using the engineered wetlands which is ultimately a type of bioreactor. The microorganism colonies residing on the plants rhizosphere facilitated the decomposition of the available biodegradable organic matter in the liquid fraction of the raw septage that percolated through the septage deposit layer and the rhizosphere. It is suggested that this extra treatment was absent in the unplanted unit. Generally, the higher rate of septage accumulation at the wetlands fed with SLR 350 kg TS/m^2.yr was claimed to aid the overall reduction of suspended solids (TSS) and COD in the wetlands, with or without presence of plants. This explains the insignificant differences found between the two wetlands in terms of COD and TSS removal.

The trend of increasing OM removal with increasing loading rates has been reported in other studies (Calheiros, Rangel and Castro 2007; Mbuligwe 2005). The wetland performance is thus commonly summarised by regression equations and first-order models (Kadlec et al. 2000). In this study, the mass removal rate of COD and BOD_5 of the planted units was constantly observed to be slightly greater than the unplanted units. The MRRs of the OM indices were increasing proportionally with increasing ILRs for both beds as shown in Figure 4.22 (a) and (b). A good correlation was observed between the MRRs and the incoming loads for OM compounds ($r^2>0.99$), which signifies the important effect of the COD ILRs in affecting its mass removal rates. The slope of the linear regression trendlines indicates that a satisfactory response to changes in incoming mass was observed for both beds. A statistically significant linear dependence of the mean of the COD MRRs on ILRs was detected ($P<0.001$) for the planted and unplanted wetlands loaded under both SLRs. The trend was found to be similar with BOD_5 removal with high regression coefficients (positive and very close to 1) for both planted and unplanted beds under all the applied SLRs (Appendix E).

(a)



(b)

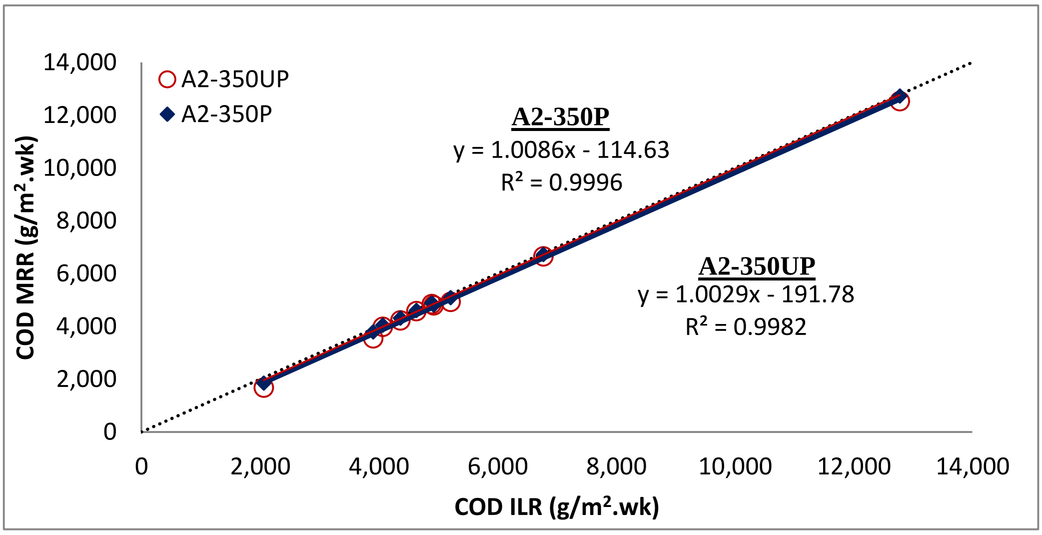


Figure 4.22 Regression graph of COD mass removal rate (MRR) against influent loading rate (ILR) (g/m ²wk) for planted and unplanted units at (a) SLR 250 (b) SLR 350 kg TS/m^2.yr. The dotted line represents complete removal.

4.4.3 Nitrogen Removal

Initial influent concentration of ammonium was high (154 - 695 mg /L) with large standard deviations (163 mg/L) as shown in Table 4.14. The concentration removal efficiencies of ammonia were observed to be higher in the planted wetlands. Planted wetlands A1-250P and A2-350P also presented greater MRRs, resulting in significantly higher ammonia mass removal efficiencies in these units compared to the unplanted wetlands (Table 4.14). The data set indicates that the planted units under both SLRs (250 and 350 kg TS/m^2.yr) outperformed the unplanted ones with mean NH_3-N concentration removal percentage of 68% at A1-250P and 68.6% at A2-350P, against the NH_3-N reduction efficiency at the unplanted units which was lower at 63.3% at A1-250UP and 55.7% at A2-350UP. The comparisons between the planted units and the unplanted ones had demonstrated the importance of plant presence in N fractions removal.

Figure 4.23 depicts the influent NH_3-N areal loading rates, and the corresponding effluent loads and mass removal efficiencies for planted and unplanted beds under SLRs of 250 and 350 kg TS/m^2.yr. Effluent collected from the planted wetland A1-250P had an ammonia concentration of 91.7 mg N/L with a weekly mass out of 16.4 g. In wetland A2-350P, 55.4 mg/L or 4.8 g/week of NH_3-N was recovered in the effluent collected.

Table 4.14 Nitrogen concentration and mass statistics for influent and effluent of planted and unplanted units at SLR 250 and 350 kg TS/m^2.yr , with the corresponding removal efficiencies (%)

			NH_3-N						NO_3-N				TN					
Parameter			Min	Max	SD	Mean	MRR*	RE(%)*	Min	Max	SD	Mean	Min	Max	SD	Mean	MRR*	RE(%)*
SLR 250 (N=18)	Conc. (mg/L)	Influent	153.90	695.31	163.00	327.04			0.00	35.70	9.18	14.53	372.00	1,661	388.44	1,048		
		Eff. A1-250P	15.00	139.20	32.65	91.70		68.02	0.60	25.60	6.46	7.88	108.00	510.00	104.58	252.47		72.86
		Eff. A1-250UP	61.20	140.76	21.88	99.88		63.3	0.40	20.00	5.76	8.08	168.00	651.00	140.53	320.62		66.52
	Mass (g/m^2.wk)	Influent	9.79	155.79	37.31	58.76			0.00	5.95	1.22	2.25	67.24	888.82	197.89	204.80		
		Eff. A1-250P	0.74	21.55	5.26	7.47	51.29	86.81	0.05	2.20	0.56	0.60	3.29	68.80	15.09	19.84	184.97	88.35
		Eff. A1-250UP	2.25	27.12	6.53	9.98	48.78	79.86	0.02	2.18	0.67	0.76	6.39	66.35	14.94	28.56	176.25	80.79
SLR 350 (N=10)	Conc. (mg/L)	Influent	62.00	406.10	109.40	214.79			21.70	117.30	27.77	41.25	275.00	1,426	381.83	880.00		
		Eff. A2-350P	31.20	94.20	19.44	55.44		68.55	1.80	67.80	28.28	26.58	108.00	216.00	37.12	153.60		78.39
		Eff. A2-350UP	44.40	132.00	28.28	81.18		55.66	0.60	38.40	14.05	12.48	150.00	336.00	59.56	227.40		70.09
	Mass (g/m^2.wk)	Influent	14.26	91.92	22.97	32.77			1.67	12.11	2.95	6.15	54.03	358.35	89.70	137.68		
		Eff. A2-350P	0.20	4.84	1.37	2.20	30.57	92.49	0.01	4.19	1.66	1.37	0.60	12.39	3.59	6.15	131.54	94.69
		Eff. A2-350UP	1.52	8.56	2.70	4.65	28.12	84.46	0.01	5.65	1.71	1.08	3.66	24.47	7.43	13.41	124.27	88.66

MRR= Mass removal rate

RE= Removal efficiency

SD = Standard deviation

N = Number of samples

* Values presented as the average REs or MRRs calculated from N samples of N experimental runs

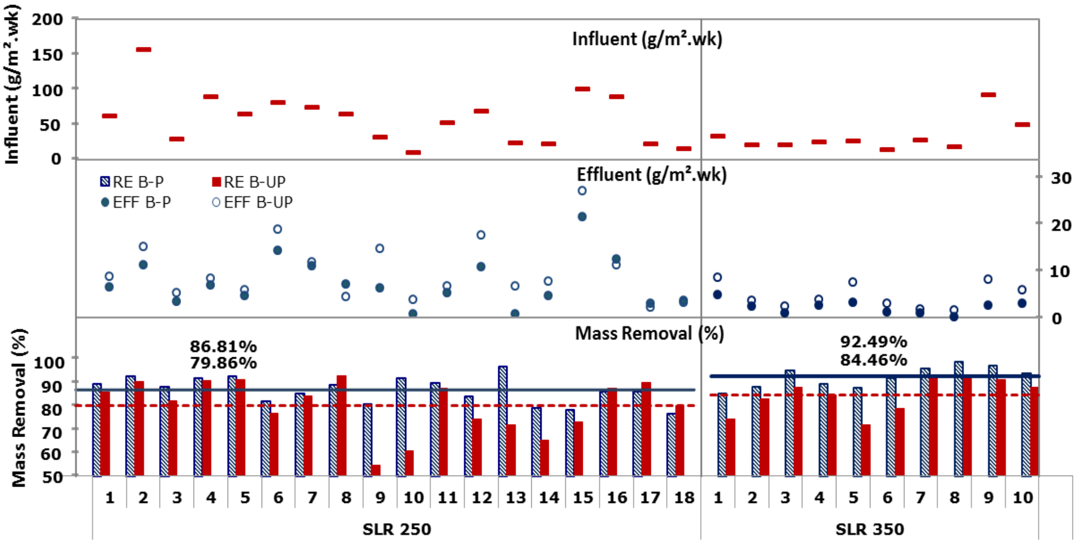


Figure 4.23 Influent NH_3-N areal loading rates and the resulting effluent loads for planted and unplanted bed, with the percentages (%) of mass removal for each treatment at SLR 250 and 350 kg TS/m^2.yr (horizontal solid line indicates mean removal efficiencies for planted unit; dashed line indicates mean removal efficiencies for unplanted unit)

The NH_3-N removal efficiency of the planted bed A1-250P appeared to be lower than that observed by Koottatep et.al (2001b) in their study for treatment of septage in vertical engineered wetlands with SLR 250 kg TS/m^2.yr in Bangkok. An average removal efficiency of 85% was obtained from their study, with 46 mg/L of NH_4 recovered in the wetland effluent (Koottatep et al. 2001b). The less effective ammonia elimination in the A1-250P unit could be due to the higher COD concentration found in the Miri's septage (mean of 31,927 mg COD/L against 17,000 mg COD/L in Koottatep's study), which could consequentially limit nitrification process and subsequently restrict the ammonia removal potential. Organic carbon availability could promote heterotrophic bacteria growth, which directly compete with autotrophic nitrifying bacteria for both oxygen and surface area. The heterotrophic bacteria are generally known to outcompete nitrifying bacteria for oxygen (Vymazal et al. 1998) and in mass.

The raw septage used in this pilot study also contained higher concentration of TSS, ranging from 5,200 - 60,900 mg/L with mean of 24,758 mg/L (as discussed previously in section 4.4.1); against 1,000 - 44,000 mg/L of TSS with mean of 15,000 mg/L in Koottatep's study. Greater particle solids retention on the surface of the beds allowed for ET to prevail over draining, thus consequentially causing greater water loss and increased the pollutant concentration readings in the effluent. For a better comparison, determination of SLR using the suspended solids (TSS) content are suggested over the use of total solids (TS) content to control the septage loading on the wetlands. This is because the measurement of SLR in terms of TSS disregards the dissolved salts content for loading, as it accounts only for the suspended particles that are present in the septage for application onto the wetlands.

Engineered wetlands are usually efficient in reducing organic compounds as delineated by high COD elimination efficiency, but the corresponding removal efficiency for nitrogen are often low (Vymazal 2007). The performance improvement by the planted units had already been reported, but often with no statistically significant differences found for both OM and ammonia removal (Tietz et al. 2008; Keffala and Ghrabi 2005; Brix 1997; Chung et al. 2008). Based on the removal efficiency of NH_3-N in the present study, it was found that the presence of plants had important influence on the NH_3-N treatments. The presence of plants was shown to significantly reduce NH_3-N mass with 86.8% of removal at a mean MRR of 51.3 g/m^2.week at SLR 250 kg TS/m^2.yr (Table 4.14). The superiority of the treatment performance at the planted unit over the unplanted one was also demonstrated in beds loaded with higher SLR of 350 kg TS/m^2.yr. The presence of plants in wetland A2-350P improved the NH_3-N removal efficiency by a mean of 9.5%, with the beneficial contributions of plants enhancing ammonia elimination from the septage influent (Table 4.14). This significance of plant presence is in agreement to the findings by Stefanakis and Tsihrintzis (2012) for treatment of synthetic wastewater in pilot-scale vertical wetlands. Planted beds were found by the authors to be superior in the removal of nitrogen by 10%, with significantly lower NH_3-N mass recovered in the effluent.

The planted wetlands A1-250P and A2-350P in this study had an average of 25.2% and 52.7% lesser NH_3-N mass recovered in their treated effluent, respectively compared to the effluent from their unplanted counterparts (Table 4.14). The higher NH_3-N removal efficiency for the planted beds was probably due to the prevalence of a more oxygenated environment in the wetland units. The mean DO concentrations in the effluent of the planted beds under both SLRs were found to be higher than the unplanted ones, with the ORP values also patently showing a more aerobic microenvironment with the presence of vegetation (Table 4.10). As reported in the literature, higher interstitial redox potential was recorded for the planted wetlands over the unplanted wetlands in several comparative studies (Tanner et al. 1999; Dunbabin, Pokorny and Bowmer 1988). Williams et al. (1994) also reported on the higher densities and activity of nitrifiers found in biofilm associated with wetland plant roots and rhizomes than in the gravel media, which directly supported the statements on the importance of plants in ammonia reduction in treatment wetlands.

As discussed in section 3.5, *Phragmites karka* planted in the system showed signs of wilting towards the end of Period I, probably due to lack of ventilation at the site. After regrowing of the plants prior to the recommencement of the experiments in Period II, the *Phragmites* in the system showed a healthy growth rate throughout the rest of the study period (June 2012 - January 2013). The *Phragmites* after replanting were not found to be sensitive towards the raw anaerobic septage which had low redox potential and high ammonia content. The reeds grew well in the beds and their presence had shown to aid NH_3-N removal from the septage. Electric conductivity (EC) of the treated effluent from both the planted and unplanted units were generally higher than that of the raw septage. This could be attributed to the nitrification process that occurred in the vertical wetland units which led to the increase of nitrate content in the effluent, contributing to higher EC. Besides, evaporation and transpiration from the system increased the salt concentration in accumulated septage that was retained on the beds surface. As such, every time when a subsequent batch of septage was applied onto the wetlands, part of the accumulated salts in the septage deposit would leached out from the beds through the drained water, thus increasing the EC of the percolate.

Plants play an indirect role in pollutant removal through microbial activity which is known to be the major factor in affecting the treatment efficiencies of wetlands. It is well recognised that plants have extensive oxygen transport systems to transfer the oxygen from the atmosphere to the roots to cope with soil anaerobiosis around the root zone, and stimulate aerobic degradation of organic matter for contaminants removal (Delaune, Pezeshki and Pardue 1990). The plants transport oxygen to their root system that harbours bacteria that treat the influent. Besides, the roots network also increases surface area for attachment and provides food sources for the microbial populations known as biofilm.

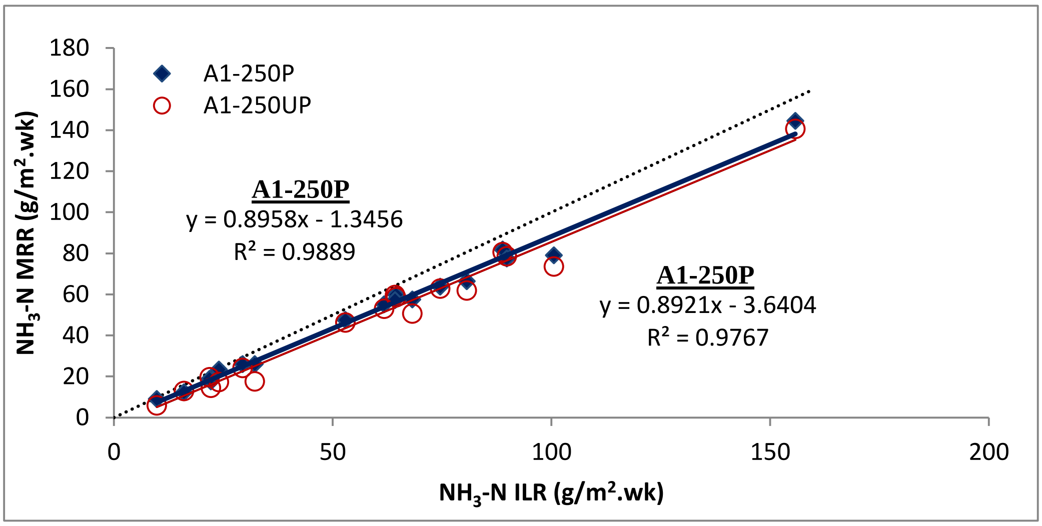
Nitrification process is very dependent on the metabolic activity of nitrifying bacteria present in the biofilm. During the first stage of treatment, nitrification rates were most likely limited by both oxygen and nitrifiers availability. The raw septage influent itself is anaerobic (DO = 0.06 - 0.3 mg/L (Table 4.10)), and does not support large populations of nitrifiers. It is suggested that the greater performance in ammonia removal in the planted unit was due to the improved aeration provided by the plant roots and their colonization by nitrifying bacteria that subsequently elevated ammonia elimination efficiencies, in which this condition was deficient in the unplanted unit.

Overall total nitrogen (TN) removal was quite satisfactory, considering that the units are the first treatment stage of the pilot system. It was found that the difference in treatment efficiency between the planted and unplanted units was generally insignificant for TN. The TN concentration removal was 72.9% for planted unit A1-250P and 66.5% for the unplanted unit A1-250UP; and 78.4% for planted wetland A2-350P and 70% for unplanted wetland A2-350UP (Table 4.14). Generally, the nitrogen mass removal efficiency was higher in the planted unit by 9.4%, with an average removal of 185 g N/m^2.week at SLR 250 kg TS/m^2.yr, and by 6.8% with an average removal of 131.5 g N/m^2.week at SLR 350 kg TS/m^2.yr. These differences between the beds however, were not significant as per statistical analysis by ANOVA for both SLRs ($P>0.05$).

Generally the wetland plants provide measurable improvement on nitrogen removal, primarily via enhancement of the nitrification-denitrification processes be it directly or indirectly, and promoting transformation into gaseous forms (Tanner 2001). Complete N removal by denitrification was limited by a higher DO concentration in the substrate of the planted unit; and by an insufficient supply of nitrate in the unplanted unit. Nitrate removal was also found to be efficient in the planted wetlands under the two applied loading rates, which poses the possibility of simultaneous biological nutrient removal with coupled nitrification–denitrification processes occurring in the planted wetlands. This was supported by the redox heterogeneity in the wetland beds, with both aerobic (near root zone) and anoxic microsites (microsites further away from the roots network) present in the system.

Figure 4.24 (a) and (b) reflect the relationship between the NH_3-N ILRs with the MRRs of the planted and unplanted systems. Statistical analysis on the data has shown that the two regression lines in the scatter plots are parallel with significantly different intercepts ($P<0.001$). The chart suggested a similarly strong positive correlation between the NH_3-N influent mass and its removal rate for both systems, with the planted unit generally outperformed the unplanted one with greater MRRs observed (Figure 4.24). The close fit of the points to all the regression lines ($r^2>0.97$) indicated a remarkably near constant areal removal rates for the NH_3-N species. The areal removal rates for the planted beds were consistently high, indicating a near complete areal removal rates. The dependency was found to be slightly stronger for the planted units compared to the unplanted beds for both SLRs, with relatively greater slope obtained from the regression lines. The correlation was similar to the findings by Dzakpasu et al. (2011) on the treatment of domestic wastewater in integrated constructed wetlands in Ireland, with a significant linear relationship found between the NH_3-N areal loading and removal rates with $r^2 = 0.99$.

(a)



(b)

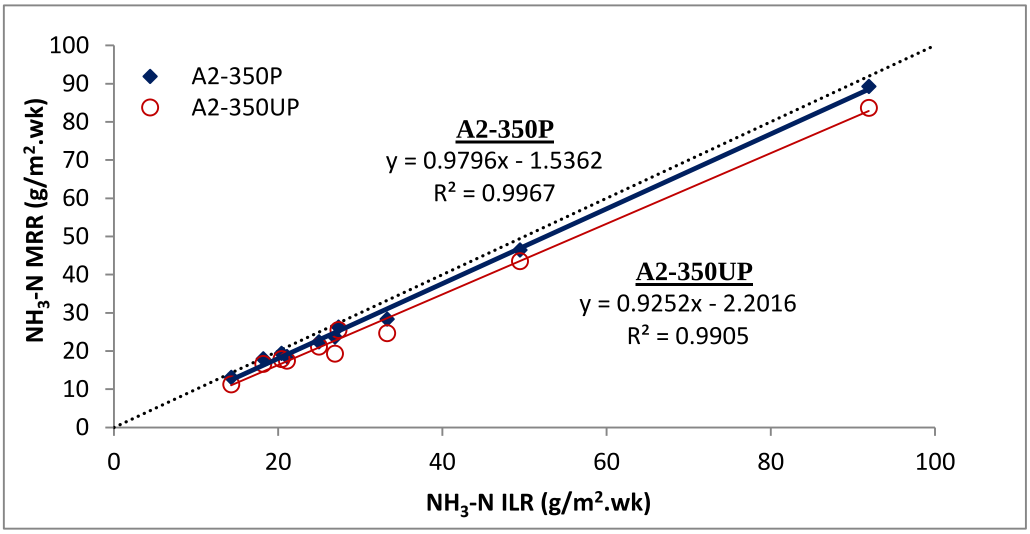


Figure 4.24 Regression graph of NH_3-N mass removal rate (MRR) against influent loading rate (ILR) (g/m².wk) for planted and unplanted units at (a) SLR 250 (b) SLR 350 kg TS/m^2.yr. The dotted line represents complete removal.

4.5 Summary

The overall performance of the first stage wetlands in the VFEWs system was very good in organic matter (OM), ammonia nitrogen (NH_3-N) and suspended solids (TSS) removal. In general, the quality of septage influent was significantly improved after the first stage of treatment, indicating that the wetland beds were efficient in retaining pollutants and promoting aerobic treatments on the wastewater. The DO content and the ORP status of the anaerobic septage was considerably improved from 0.06 - 0.86 mg/L to 0.5 - 6.67 mg/L and from (-90) - (-546) mV to (-156) - 466 mV respectively, depending on the applied solid loading rates (SLRs) up to 350 kg TS/m^2.yr and the presence of plants. The presence of the organic deposit layer formed by solids retention on the surface of the beds was found to assist in evenly distributing the septage onto the wetlands and lowering the infiltration rates for improved treatment efficiencies.

During Period I of the study, the lowest applied SLR of 100 kg TS/m^2.yr had mass reduction efficiencies of 97.3% for COD, 82.9% for NH_3-N and 98.5% for TSS. Increased SLR to 250 kg TS/m^2.yr did not significantly deteriorate the treatment performance of the wetlands with only marginally lower removal of COD and TSS found in beds fed at the higher loading rate. Further increment of SLR from 250 to 350 kg TS/m^2.yr during Period II was also found to have no significant effect on the wetlands pollutants removal efficiencies. At SLR of 350 kg TS/m^2.yr, as much as 98% and 99% of COD and TSS mass was removed respectively, while a total of 92.5% of NH_3-N mass was eliminated from the raw septage influent.

The results also confirmed that the plants played an important role in pollutants removal, with the planted systems yielding better performance than the unplanted systems for elimination of most constituents of interest, up to the SLR of 250 kg TS/m^2.yr. The planted unit had been found to outperform the unplanted one, with an average difference of 4.5% between the COD mass removal efficiency at the planted and unplanted wetlands with SLR of 250 kg TS/m^2.yr. The presence of plants was also shown to significantly reduce NH_3-N mass at 86.8% with a mean mass removal rate of 51.3 g/m^2.week at SLR 250 kg TS/m^2.yr, proving the beneficial contribution of plants in promoting ammonia removal from the raw septage. Although the performance of the unplanted wetlands was generally inferior to the planted ones, the treatment efficiency was still considered satisfactory. The majority of the organic pollutants in the raw septage were present in particulate form, and thus the high reduction efficiency of the influent OM and solids content were primarily attributed by physical filtration on the gravel bed, enhanced by the plant rooting system.

Plants were found to affect the hydrological mass balance of the wetlands system considerably, as the water loss in the planted system was observed to be significantly greater than the unplanted system as a result of evapotranspiration. At SLR of 250 and 350 kg TS/m^2.yr, the mean percentage of water loss for 22 weeks at the planted unit was 55% and 76%, and at the unplanted unit was 42% and 62%, respectively. This makes the approach of comparing the treatment performance between the planted and unplanted units by the mass-based removal efficiency more rational than by the concentration-based reduction efficiency. The study outcomes also suggested high predictability of the pollutants removal rates according to the incoming pollutant mass at the first stage wetlands, with remarkably near constant areal removal rates for almost all the tested pollutants up to SLR of 350 kg TS/m^2.yr at both planted and unplanted units.

Chapter 5 Results and Discussions: Second Stage of Treatment: Effects of Operational-related Strategies on Treatment Efficiencies

5.1 Overview

A wetland is a highly complex ecosystem that requires multi-disciplinary inputs for its design and operation. As with any wastewater treatment system, the principle elements of the engineered system design are hydraulics and mass loading rates. The operational regime for engineered wetlands is one of the imperative aspects that affects the system performance in terms of pollutant removal, besides ensuring the durability of the system for long term operation. The most important operating factors include feeding mode (how the influent wastewater is applied), hydraulic loading rates (HLRs), bed resting time and retention time. Hydraulic strategies on how the feeding and draining of the wetland beds are implemented can affect the overall behaviour and efficiency of the system. By selecting a suitable mode of operation in vertical flow systems, an effective system can be designed, operated and maintained to ensure successful implementation of the technology. In this study at the second stage of the VFEWs system, the wetlands influent was dosed intermittently or in batches. This second line of treatment wetlands were introduced with the pre-treated septage collected from the first stage wetlands, to allow further treatment on the effluent before final discharge into the environment.

5.2 Operating Conditions

10 sets of data were collected for each experimental run which lasted for twelve weeks, including 2 weeks of stabilization period. Table 5.1 describes the setup of each wetland at the second stage and the operational strategies implemented on each wetland bed. The effects of the application regimes on wetland performance are reported in the following sections. Substrate thickness, grading and arrangement are as described in section 3.5. All the wetlands were operated in either intermittent

(with free drainage and no prolonged resting) or batch (fill-pond-drain-rest) mode. Intermittent feeding was implemented on a daily basis with several numbers of flushing onto the wetland beds at specific time intervals. This mode of operation allowed free drainage of effluent with no obligatory ponding, where the wastewater percolates vertically downwards by gravity through the substrate layers.

Table 5.1 Details of parametric studies to examine effects of hydraulic loading rates (HLRs), dosing frequency and feeding mode on pre-treated septage treatment at the second stage wetlands

Parameter	Feeding Mode		HLR (cm/d)		Dosing frequency		P:R (days:day)	Wetland Denotation
	Intermittent	Batch	8.75	17.5	4x	8x		
HLR	✓		✓			✓		B-MM
	✓			✓		✓		B-HH
Dosing Frequency	✓		✓		✓			B-MM (4x)
	✓		✓			✓		B-MM (8x)
	✓			✓	✓			B-HH (4x)
	✓			✓		✓		B-HH (8x)
Pond:Rest Period		✓					1:1	B-PR1
		✓					2:2	B-PR2
		✓					3:3	B-PR3

*All wetlands are planted with *Phragmites karka* and the substrate medium consisted of aggregates, PKS and topped with sand
*B-MM denotes wetlands fed at medium HLR of 8.75 cm/d; B-HH denotes wetlands fed with high HLR or 17.5 cm/d
*B-PR denotes wetlands fed in batches with fill-pond-drain-rest cycle

The batch feeding approach was carried out by sequential batch loading with transient flooding onto the bed surface. Application of the hydraulic load was done in one-go without hydraulic fractioning of the influent (single feeding per batch at full volume) and the effluent was left ponded in the wetland for a period of time before allowing it to be drained out from the wetlands. Subsequent bed resting followed, with the wetlands being left idle (rested) for an extended time period. The batch loading with sequencing fill-pond-drain-rest mode was examined with different periods of wetland ponding (P) and resting (R) at P:R (days:days) of 1:1, 2:2 and 3:3.; where P:R=1:1 was subjected to one day flooding and one day resting, for instance. The wetlands were thus fed once every 2, 4 and 6 days for each cycle. The volume of influent applied per batch was 21 litres with constant hydraulic load of 0.088 m^3/m^2/batch.

To evaluate the performance of the wetlands, influent and effluent samples were collected once a week and analysed for their organic matter, nitrogen and particulate solids compounds, besides monitoring the pH, DO, EC, ORP and temperature changes. The influent was sampled before the pre-treated septage was pumped into the wetlands and the effluent samples were collected from the outlet of each unit at the end of each loading cycle. Sampling and analysis protocols are as presented in section 3.6. The effects of different pond and rest (P:R) period under the batch loading mode reported under section 5.5 were investigated by comparing each group of treatment (P:R of 1:1, 2:2 and 3:3) using post hoc test after ANOVA. Post hoc means separation tests performed using Tukey's (HSD) test when ANOVAs were found to be significant (as described in section 3.6.2.2).

5.3 Effects of hydraulic loading rate (HLR)

Hydraulic loading rate (HLR) is an important design aspect to minimise the possibility of overfeeding and occurrence of clogging that deteriorate the treatment performance of the wetlands. It is necessary to establish an appropriate range of hydraulic flows to allow the maximum designed flow to be accommodated while still allowing good pollutant elimination efficiency. The HLRs reported in the literature varied greatly. Brix and Arias (2005) recommended HLR of 5 – 6 cm/d for VFEWs in Denmark. Mitterer-Reichmann (2002) reported an average HLR of 2.7 cm/d for 5.5 m^2/PE, for 200 vertical flow systems in Austria. Prochaska et al. (2007) presented higher HLR (0.08 – 0.17 m/d) and organic loading rates (OLR) (20 – 40 g BOD_5/m^2 d) in pilot-scale VFEWs in N. Greece. Langergraber et al. (2007) reported that no clogging was observed in vertical wetlands with less than 10 cm/d of HLR applied onto the beds. In this study, the effects of HLR were studied at the second stage of the VFEWs system for treatment of pre-treated septage with intermittent feeding (8 times daily) at medium and high HLR of 8.75 cm/d (B-MM) and 17.5 cm/d (B-HH), respectively.

Throughout the monitoring period, fluctuations observed for the performance of the wetlands were found to be affected by the applied hydraulic loads. Physico-chemical parameters statistics for influent and effluent of the wetlands were shown in Table 5.2. The pre-treated septage influent was slightly alkaline with pH ranging between 7.58 - 8.02 at a mean temperature of 27.7 ℃. The mean EC value was clearly higher in the effluent of wetland B-MM than the effluent in wetland B-HH, indicating the presence of higher amount of free ions in the effluent under lower HLR.

Table 5.2 Physico-chemical parameters statistics for influent and effluent of wetland B-MM and B-HH. N is the number of samples collected and analysed for each parameter during the study period.

Parameter	Sampling Point	Statistics			
		N	Range	Mean	Std Dev.
Temperature (℃)	Influent	10	26.10 - 29.90	27.74	1.27
	Eff. B-MM	10	28.60 - 33.00	30.04	1.36
	Eff. B-HH	10	28.20 - 33.10	30.27	1.59
pH	Influent	10	7.58 - 8.02	7.81	0.14
	Eff. B-MM	10	6.64 - 7.18	6.87	0.17
	Eff. B-HH	10	6.70 - 7.23	6.94	0.19
DO (mg/L)	Influent	10	0.41 - 4.69	2.26	1.73
	Eff. B-MM	10	3.56 - 7.14	4.89	1.12
	Eff. B-HH	10	0.69 - 2.08	1.26	0.43
ORP (mV)	Influent	10	-109 - 310		
	Eff. B-MM	10	125 - 310		
	Eff. B-HH	10	-241 - 175		
EC (mS/cm)	Influent	10	1.02 - 2.75	1.72	0.71
	Eff. B-MM	10	1.31 - 2.49	1.73	0.48
	Eff. B-HH	10	1.30 - 2.37	1.66	0.42

Since the commencement of the experiment, the wetland with high HLR of 17.5 cm/d had produced effluent with relatively lower quality than that at the wetland loaded with medium HLR of 8.75 cm/d. At the second week of operation, notable colour difference between the effluent of wetlands B-MM and B-HH was recorded (Figure 5.1), possibly due to the increased flow rate and the occurrence of minor clogging that induced flow short circuiting which deteriorated the overall removal efficiency of suspended solids and other pollutants. In addition to that, more obvious deviations in ORP readings and DO concentrations were also observed in the effluent between the two wetlands, indicating a more reduced micro-environment in the wetland loaded at higher HLR.

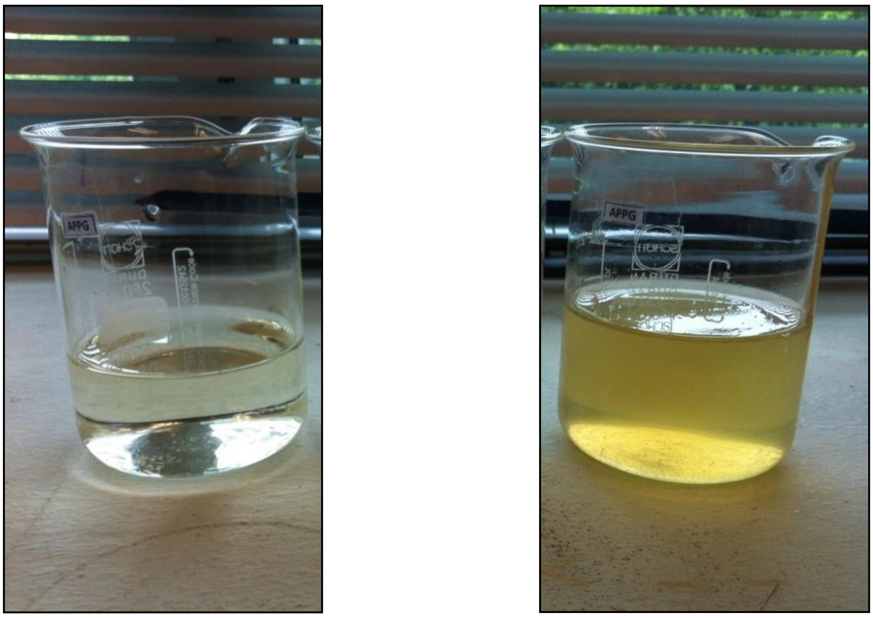


Figure 5.1 Effluent collected after 2 weeks of operation at (Left) wetland B-MM; (Right) wetland B-HH

5.3.1 Organic Matter (OM) Removal

Under the two HLRs (8.75 cm/d and 17.5 cm/d), great fluctuation in the wastewater compositions was observed, typical of the septage characteristic, which allowed for the wide range of OM mass loadings to be applied into the systems (Table 5.3). The wetlands treatment performance at the two HLRs of 8.75 and 17.5 cm/d were compared. The removal of OM had been found to be HLR dependent. At lower HLR which corresponds with longer hydraulic retention time (HRT), higher pollutant removal efficiencies were obtained. The results as shown in Table 5.3 indicate that the increase of HLR from 8.75 to 17.5 cm/day clearly impaired the overall level of treatment in the wetland unit. The effluent concentration and mass statistics showed that wetland B-HH (HLR 17.5 cm/d) significantly underperformed its wetland counterpart B-MM (HLR 8.75 cm/d) in the removal of OM.

.

Table 5.3 OM indices concentration and mass statistics for the influent (pre-treated septage) and the resulting bed effluent of wetlands B-MM (8.75 cm/d) and B-HH (17.5 cm/d). Corresponding bed performances are reported in terms of pollutant removal efficiencies (%). Standard deviation for means given in parenthesis to indicate range.

	Concentration (mg/L)		RE (%)*	Mass (g/m$_2$.d)		Removal	
	IN	OUT		IN	OUT	g/m^{2}d *	RE (%)*
COD							
Medium HLR 8.75 cm/d (B-MM)	2,224.00 (±834.24)	105.00 (±50.33)	94.28	194.60 (±73.00)	7.33 (±3.58)	187.27	95.44
High HLR 17.5 cm/d (B-HH)	2,224.00 (±834.24)	183.33 (±52.92)	90.11	389.20 (±145.99)	27.41 (±7.50)	361.79	91.58
BOD							
Medium HLR 8.75 cm/d (B-MM)	182.70 (±351.60)	3.30 (±2.29)	98.63	21.18 (±5.23)	0.23 (±0.17)	20.95	98.91
High HLR 17.5 cm/d (B-HH)	182.70 (±351.60)	23.82 (±10.42)	89.69	42.36 (±10.46)	3.52 (±1.43)	38.83	91.25

No. of samples, N = 10

MRR= Mass removal rate

RE= Removal efficiency

* Values presented as the average REs or MRRs calculated from N samples of N experimental runs

Figure 5.2 shows the influent COD areal loading rates and the resulting effluent loads for wetlands B-MM and B-HH, with the percentages (%) of mass removal for each treatment. At HLR 8.75 cm/d, wetland B-MM was fed with 195 ± 73 g/m^2.d of COD and the loading rate was increased by 2 fold at wetland B-HH which was fed at HLR of 17.5 cm/d, with the same batches of influent (Table 5.3 and Figure 5.2). The removal efficiency of COD dropped significantly with the increase of HLR in the studied wetlands. For instance, the COD elimination efficiency decreased from 95.4% at 8.75 cm/day in wetland B-MM to 91.6% at 17.5 cm/day in wetland B-HH. In terms of BOD$_5$ reduction, significant difference was also found between the mass removal efficiency of wetlands B-MM and B-HH whereby the increase in HLR deteriorated the performance of the bed by a mean of 7.8%. Elimination of BOD$_5$ is both a physical and biochemical process. Physical settling and filtration of organic particles happens as the water flows through the wetland media and the dissolved compounds are subjected to decomposition and mineralisation by the microorganism attached to the plant rhizomes and the substrate (Reed, Crites and Middlebrooks 1995).

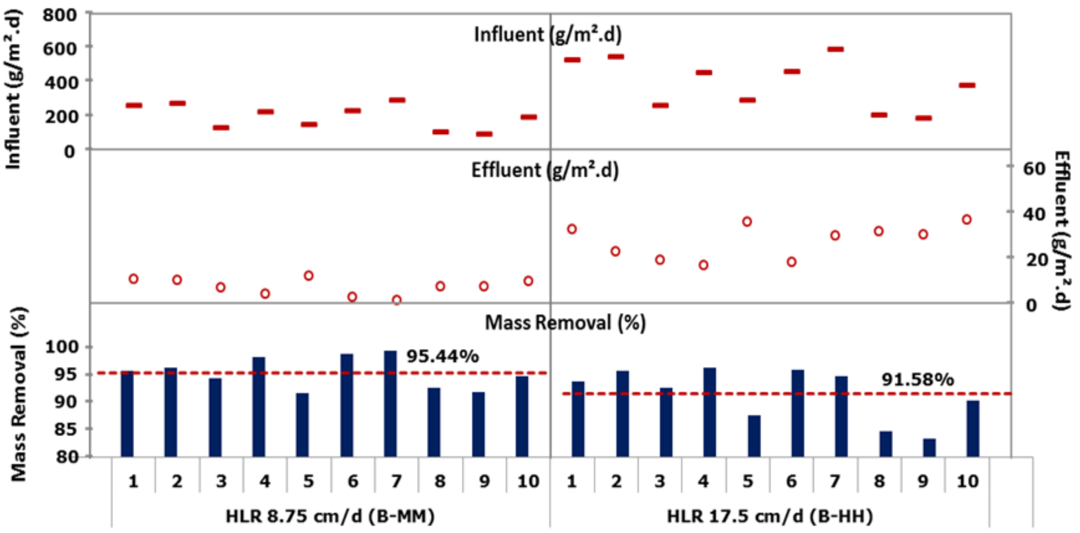


Figure 5.2 Influent COD areal loading rates and the resulting effluent loads for wetland B-MM and B-HH, with the percentages (%) of mass removal for each treatment (horizontal line indicates mean removal efficiencies for the wetland units)

Both the wetland beds (B-MM and B-HH) were loaded intermittently with frequent flushing of influent at 8 times daily, 7 days a week up to 12 weeks of operation. With two times more solids and organic matter loadings onto the bed at wetland B-HH, more rapid build-up of surface deposit was expected. As shown in Figure 5.3, a decrease of wetland B-HH outflow rates were observed, due to the occurrence of gradual bed clogging with the operational time. Surface deposit and interstitial pore clogging could have hindered infiltration and reduced permeability of the wetlands, which subsequently decreased the rate of re-oxygenation of the substrate. Reduced performance of the wetland led to lower elimination rate of OM and sufficient bed resting was suggested to restore the filterabilty and permeability of the vertical bed. However, according to Ruppe (2005) once filter clogging has occurred, failures can occur more rapidly than the initial clogging event (after bed resting), if the bed is continuously operated under the same loading that caused the clogging. The presence of desiccated deposit particulate matter contained in the pore space is expected to be a significant factor in subsequent clogging events (Ruppe 2005).

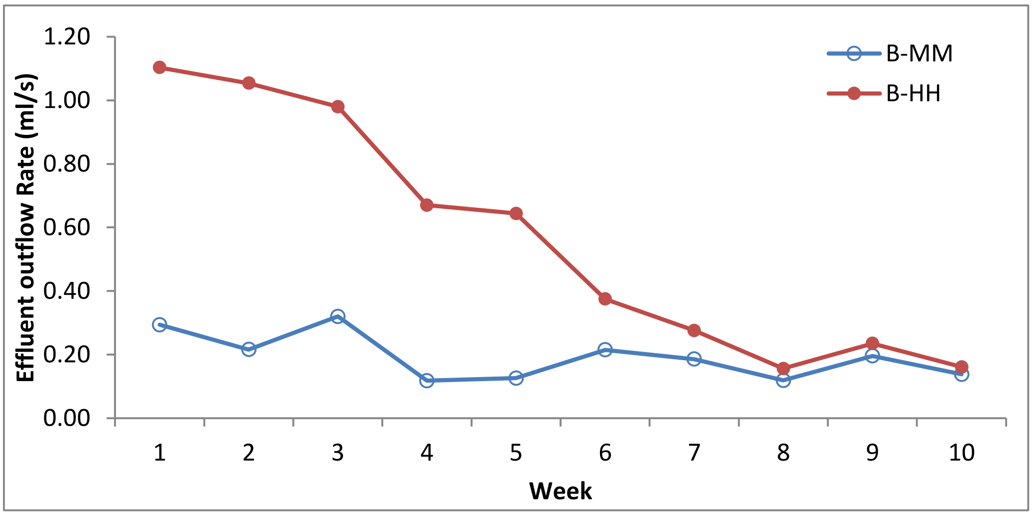


Figure 5.3 Weekly outflow rates for wetland effluent under medium and high HLR

The areal mass removal rates (MRRs) for COD in the study were clearly shown to be affected by the influent loading rates (ILRs) as shown in Figure 5.4. The close fit of the points to the regression lines recorded a remarkably constant areal removal rates for COD at both wetlands. All the data points lay close to the line representing complete removal, especially for effluent of wetland B-MM.

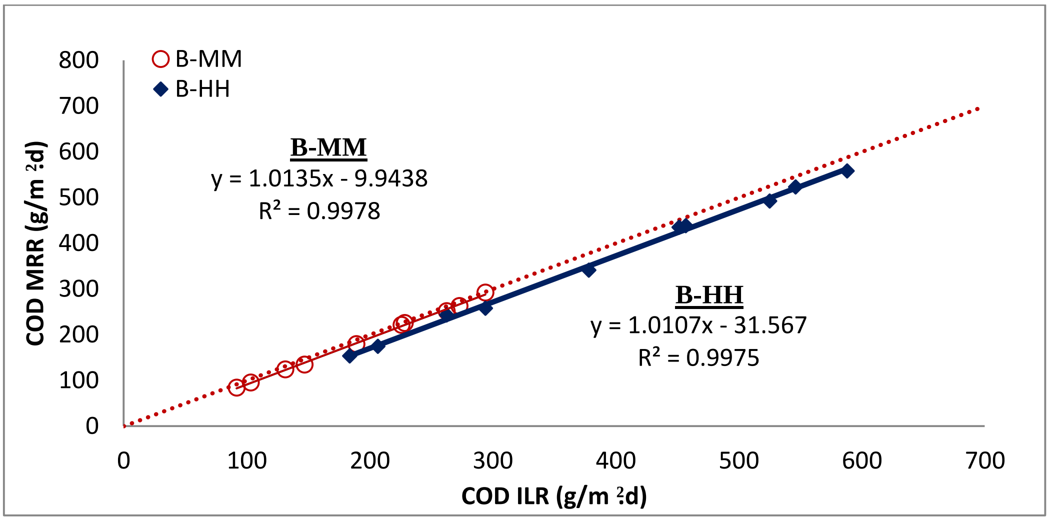


Figure 5.4 Regression graph of COD mass removal rate (MRR) against influent loading rate (ILR) (g/m ²d) for B-MM and B-HH. The dotted line represents complete removal.

5.3.2 Nitrogen Removal

Table 5.4 summarises the concentration and mass statistics for various nitrogen fractions in the wetlands influent and effluent, together with the pollutant removal efficiencies of wetlands B-MM and B-HH. Figure 5.5 depicts the wetland performance for NH_3-N removal at wetlands B-MM and B-HH during the study period. The study outcome revealed that the ammonia removal was more sensitive to the change of HLR compared to COD and TSS (TSS removal is discussed in the following section). At high HLR (17.5 cm/d), the effluent NH_3-N concentration removal was significantly less than that at medium HLR (8.75 cm/d) ($P<0.001$); where the influent NH_3-N concentration was reduced to 15 mg/L at wetland B-HH, compared to effluent concentration of 0.83 mg/L recovered from the effluent of wetland B-MM.

Table 5.4 Nitrogen indices concentration and mass statistics for the influent (pre-treated septage) and the resulting bed effluent of wetlands B-MM (8.75 cm/d) and B-HH (17.5 cm/d). Corresponding bed performances are reported in terms of pollutant removal efficiencies (%). Standard deviation for means given in parenthesis to indicate range.

	Concentration (mg/L)		RE (%)*	Mass (g/m$_2$.d)		Removal	
	IN	OUT		IN	OUT	g/m^2.d *	RE (%)*
(NH$_3$-N							
Medium HLR 8.75 cm/d (B-MM)	55.25 (±24.44)	0.83 (±0.61)	98.14	4.83 (±2.14)	0.06 (±0.04)	4.78	98.54
High HLR 17.5 cm/d (B-HH)	55.25 (±24.44)	15.06 (±5.22)	71.75	9.67 (±4.28)	2.24 (±0.73)	7.43	75.89
TKN							
Medium HLR 8.75 cm/d (B-MM)	208.78 (±65.72)	33.15 (±15.11)	82.99	18.27 (±5.75)	2.31 (±1.09)	15.95	86.43
High HLR 17.5 cm/d (B-HH)	208.78 (±65.72)	72.49 (±26.73)	63.03	36.54 (±11.50)	10.84 (±3.96)	25.69	68.45
NO$_3$-N							
Medium HLR 8.75 cm/d (B-MM)	34.07 (±38.65)	25.48 (±18.22)		2.98 (±3.38)	1.78 (±1.29)		
High HLR 17.5 cm/d (B-HH)	34.07 (±38.65)	9.74 (±13.04)		5.96 (±6.76)	1.51 (±2.08)		
TN							
Medium HLR 8.75 cm/d (B-MM)	244.20 (±78.23)	58.80 (±24.48)	75.29	21.37 (±6.85)	4.11 (±1.80)	17.26	80.36
High HLR 17.5 cm/d (B-HH)	244.20 (±78.23)	82.50 (±31.87)	65.76	42.74 (±13.69)	12.39 (±4.90)	30.34	70.71

No. of samples, N = 10

MRR= Mass removal rate

RE= Removal efficiency

* Values presented as the average REs or MRRs calculated from N samples of N experimental runs

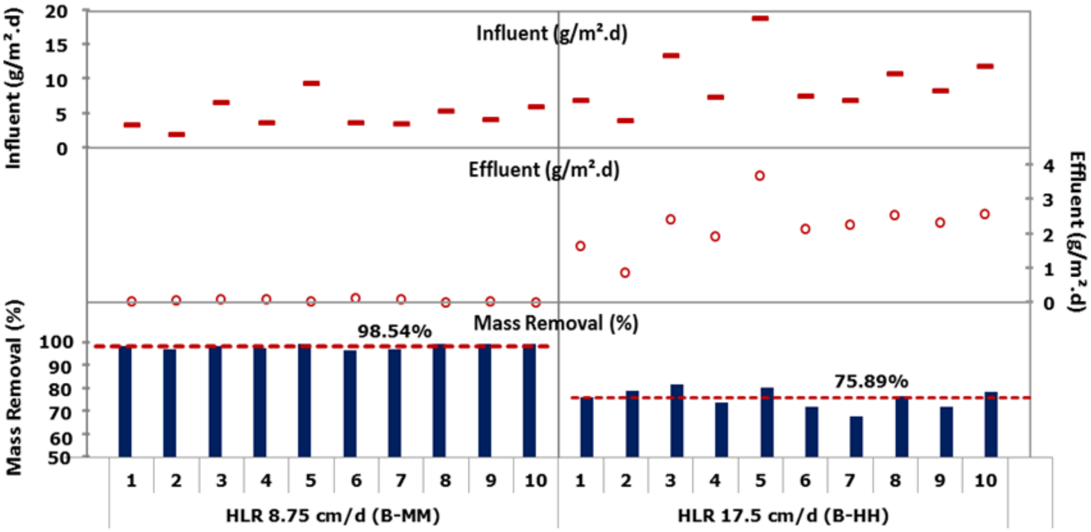


Figure 5.5 Influent NH_3-N areal loading rates and the resulting effluent loads for wetland B-MM and B-HH, with the percentages (%) of mass removal for each treatment (horizontal line indicates mean removal efficiencies for the wetland units)

The increased HLR was found to significantly lower the level of ammonia mass treatment. An average of 98.5% of ammonia mass was eliminated under the HLR of 8.75 cm/d, and 75.9% of ammonia mass was removed from the influent when the hydraulic load was increased by 2 fold in wetland B-HH. Removal percentage at 80.4% and 70.7% was recorded for TN mass in wetlands B-MM and B-HH, respectively. With the removal efficiency of TN being significantly lower at higher HLR, it was suggested that removal of nitrogen was most likely limited by the insufficient supply of NO_3−N, as the results revealed consistently greater N mass recovered from the effluent of wetland B-HH in the form of NH_3-N (Table 5.4).

The areal mass removal rates (MRRs) for NH_3-N and TN in the study were clearly shown to be affected by the influent loading rates (ILRs) as shown in Figure 5.6 and Figure 5.7, respectively. There was a significant linear relationship between the incoming areal loads and the removal rates for NH_3-N ($R^2>0.99$, $P<0.01$, n=10) and TN ($R^2>0.90$, $P<0.01$, n=10) under both loading conditions, indicating high predictability of the wetland performance with more than 99% of the variation in the N fraction mass removal rates data being explainable by the strength of the incoming N fraction loads. Decreasing slope of the regression line for wetland B-HH indicates reduced treatment efficiency of the unit under the higher influent loads, possibly due to a less oxygenated bed as a result of filter clogging that prolonged the period of influent ponding on the surface of the wetland, or as a result of increased oxygen consumption in the bed due to the increased pollutant loading.

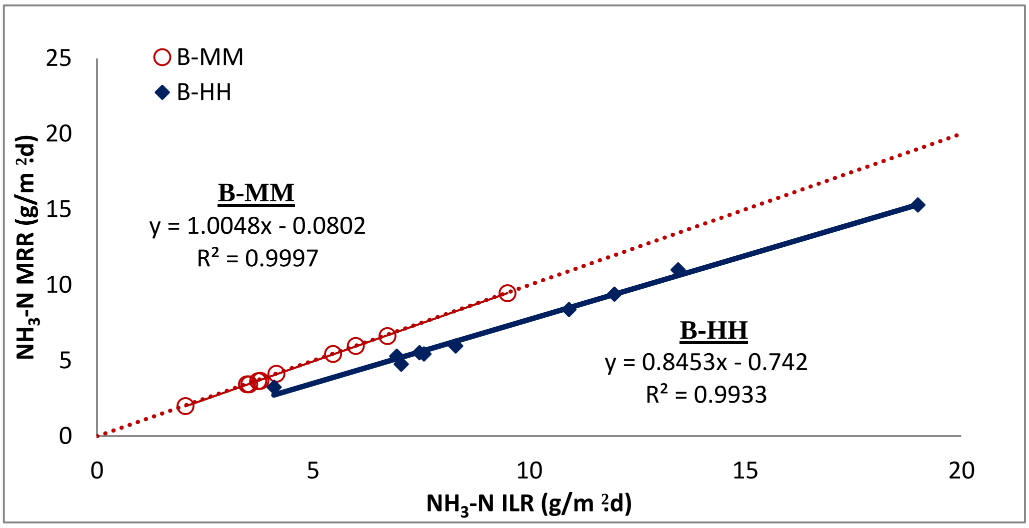


Figure 5.6 Regression graph of NH_3-N mass removal rate (MRR) against influent loading rate (ILR) (g/m^{2}d) for B-MM and B-HH. The dotted line represents complete removal

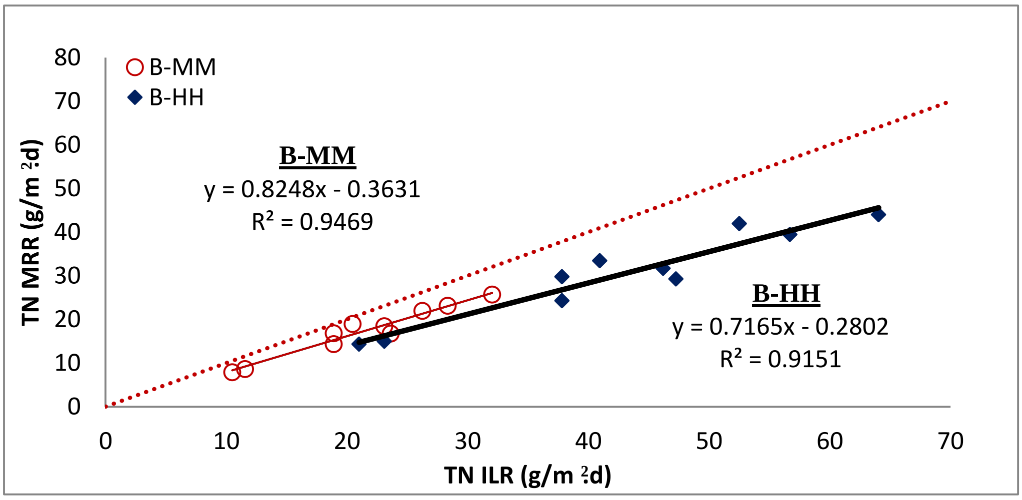


Figure 5.7 Regression graph of TN mass removal rate (MRR) against influent loading rate (ILR) (g/m^{2}d) for B-MM and B-HH. The dotted line represents complete removal.

Increased HLR can significantly increase the oxygen demand in the wetland due to the greater pollutant load, which subsequently deteriorates the level of ammonia treatment. Ammonia oxidation bacteria are strictly aerobic and thus DO availability is one of the critical factors governing the process of nitrification. Nitrification rates were primarily limited by oxygen availability in the wetland loaded with higher hydraulic load in this study. In fact, the dissolved oxygen (DO) content of the effluent from wetland B-HH were consistently found to be lower than the effluent of wetland B-MM throughout the study duration. As summarised in Table 5.2, the mean DO concentration of the effluent collected from wetland B-HH was 1.3 ± 0.43 mg/L and was significantly lower compared to the DO concentration in the effluent of wetland B-MM (4.9 ± 1.1 mg/L).

During the 12 weeks of the study, the effluent of wetland B-MM had ORP values ranging from 125 – 310 mV, which suggested an improved redox status of the treated effluent. Effluent of wetland B-HH presented significantly lower ORP values than B-MM, indicative of the occurrence of less aerobic or reductive conditions in the bed loaded under high HLR (Figure 5.8). Towards the end of the experimental phase at week 9, the ORP values of effluent from wetland B-HH dropped into the negative range. The DO in the effluent reduced concurrently with the ORP to below 1 mg/L. The lower DO content and ORP in the wetland had consequentially caused inefficient transformation from NH_3-N to NO_3-N in wetland B-HH, which was reflected by the low ammonia elimination efficiency.

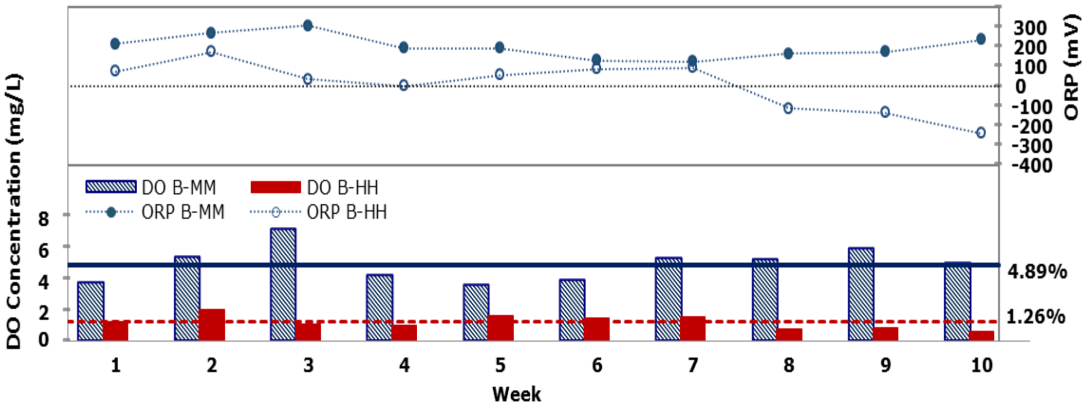


Figure 5.8 Dissolved oxygen (DO) contents and oxygen reduction potential (ORP) readings in effluent collected from wetland B-MM and B-HH

Increasing HLR would generally reduce the contact time between influent and the biofilms, enhance the detachment of microbes off the substrate surfaces due to higher infiltration rates (IR), and decrease the oxygen availability (Toet et al. 2005) due to prolonged surface ponding. As discussed in section 5.3.1 previously, the wetland B-HH effluent discharge rates experienced a decreased trend with time due to the occurrence of surface clogging under the high loading. Consequently the removal efficiencies of almost all the pollutants tested were negatively affected by the increase of HLR to 17.5 cm/d. Deterioration of the pollutant removal efficiency had also been observed in previous studies, which reported that pollutants elimination performance in wetlands decreased significantly with the increased HLR (Tanner, Clayton and Upsdell 1995a; Tanner, Clayton and Upsdell 1995b; Trang et al. 2010; Huang, Reneau Jr. and Hagedorn 2000).

5.3.3 Particulate Solids Removal

The pre-treated septage influent for wetlands B-MM and B-HH had TS and TSS concentration of 4,059.6 mg/L and 2,366.7 mg/L, respectively (Table 5.5). The influent TSS loading ranged between 94.5 - 326.4 g/m^2.d and 189 - 649.25 g/m^2.d with a mean of 49.7 g/d and 99.4 g/d of TSS applied onto wetlands B-MM and B-HH, respectively. The fluctuation of influent and effluent TSS loads with their corresponding removal efficiencies are presented in Figure 5.9. The mean TSS mass reduction efficiency up to 98.1% was achieved with wetland B-MM and the treatment level dropped 2.1% to 96.1% at wetland B-HH (Table 5.5). As shown in Table 5.5, VSS mass was removed by an average of 98.4% at the bed with lower loading rate (B-MM) and 95.7% in the bed applied with 2 times greater hydraulic load (B-HH). The ratio of VSS/TSS in the effluent was 0.59 for bed B-MM and 0.74 for bed B-HH, which was reduced from 0.77 in the influent. This suggested a significantly lower degree of effluent mineralization in wetland B-HH, with the effluent presenting a considerably greater amount of organic matter than in the effluent of wetland B-MM.

Table 5.5 Particle solids indices concentration and mass statistics for the influent (pre-treated septage) and the resulting bed effluent of wetlands B-MM (8.75 cm/d) and B-HH (17.5 cm/d). Corresponding bed performances are reported in terms of pollutant removal efficiencies (%). Standard deviation for means given in parenthesis to indicate range.

	Concentration (mg/L)		RE (%)*	Mass (g/m^2.d)		Removal	
	IN	OUT		IN	OUT	g/m^{2}d *	RE (%)*
TS							
Medium HLR 8.75 cm/d (B-MM)	4,060 (±1,350)	1,599 (±586.02)	60.42	355.21 (±118.11)	112.46 (±47.27)	242.75	68.50
High HLR 17.5 cm/d (B-HH)		1,321.20 (±527.40)	67.52	710.43 (±236.21)	199.58 (±85.58)	510.85	72.01
TSS							
Medium HLR 8.75 cm/d (B-MM)	2,367 (±856.22)	45.70 (±36.67)	97.68	207.08 (±74.92)	3.24 (±2.70)	203.84	98.12
High HLR 17.5 cm/d (B-HH)		103.00 (±33.80)	95.39	414.17 (±149.84)	15.29 (±4.61)	398.87	96.05
VSS							
Medium HLR 8.75 cm/d (B-MM)	1,814 (±939.12)	27.40 (±22.31)	98.01	158.78 (±82.17)	1.91 (±1.56)	306.26	98.39
High HLR 17.5 cm/d (B-HH)		76.30 (±29.36)	94.96	317.57 (±164.35)	11.31 (±4.00)	155.93	95.66

No. of samples, N = 10

MRR= Mass removal rate

RE= Removal efficiency

* Values presented as the average REs or MRRs calculated from N samples of N experimental runs

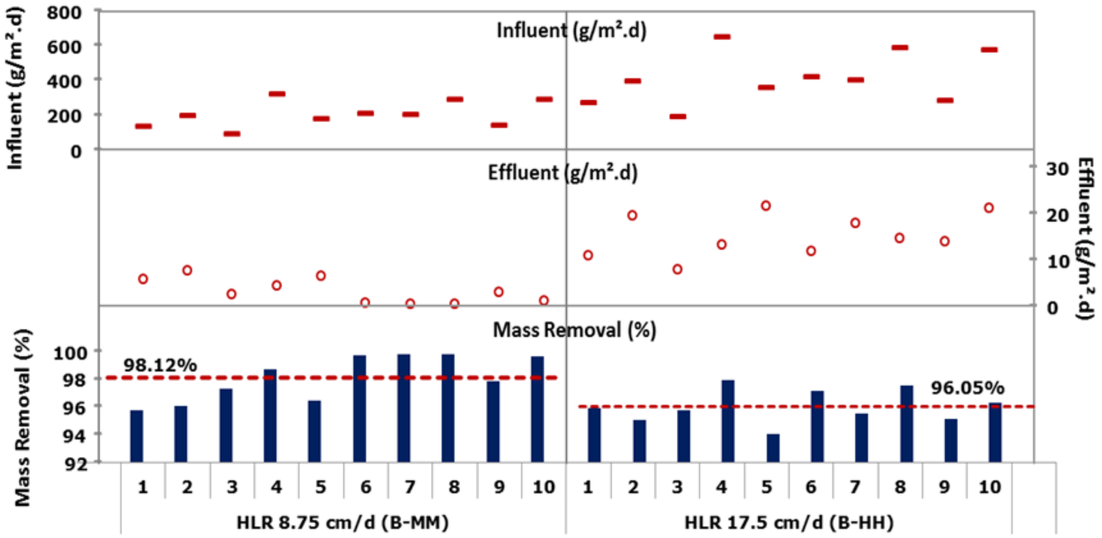


Figure 5.9 Influent TSS areal loading rates and the resulting effluent loads for wetland B-MM and B-HH, with the percentages (%) of mass removal for each treatment (horizontal line indicates mean removal efficiencies for the wetland units)

The increased HLR resulted in increased organic and suspended solids loading. Depending on the nature of solids, the design of the substrate and the operation of the wetlands, increased TSS and organic pollutant loading may result in bed surface clogging that usually leads to poor effluent quality. In this study, with intermittent dosing of influent once every 3 hours (8 times daily), minor soil clogging was observed to occur towards the end of the experimental period of 12 weeks due to overfeeding when the dose volume was increased from approximately 2.6 L/dose (8.75 cm/d) to 5.2 L/dose (17.5 cm/d). The decreased outflow rates of wetland B-HH as described in section 5.3.1 was recorded and indicated deterioration of the substrate hydraulics due to the increased HLR.

Similar to the trend exhibited in the OM and nitrogen mass elimination, the particulate solids rates of removal was greatly affected by the incoming solids loads. Figure 5.10 presents the relationship between TSS mass loading rates and the corresponding mass removal rates (MRRs). MRRs of TSS were very high in all beds (Table 5.5 and Figure 5.10). A linear relationship is suggested by the relatively high r^2 value, where the TSS MRRs were strongly dependent on the TSS ILRs (Figure 5.10). At mass loading up to 325 $g/m^2.d$ for HLR 8.75 cm/d and 650 $g/m^2.d$ for HLR

17.5 cm/d, all the data points laid close to the line representing complete removal, especially for wetland B-MM.

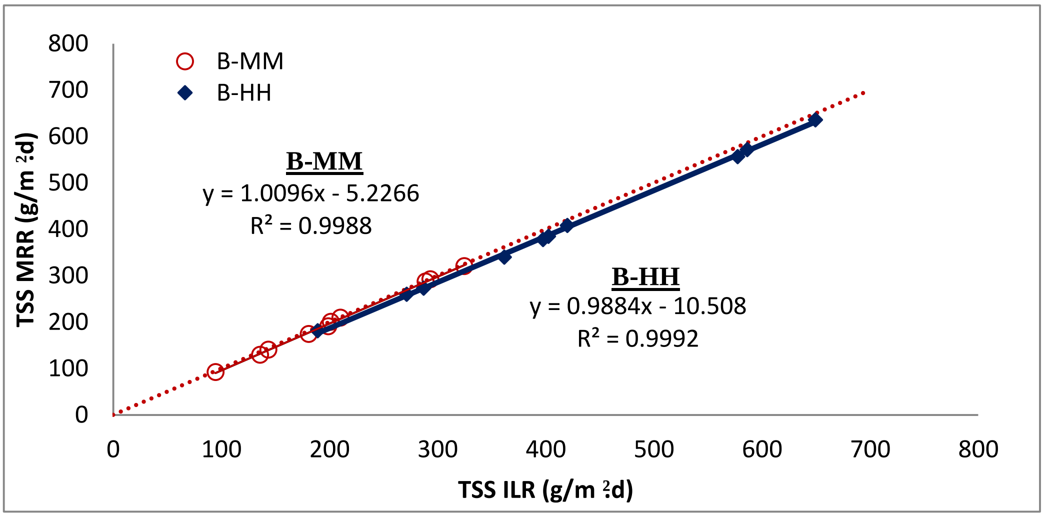


Figure 5.10 Regression graph of TSS mass removal rate (MRR) against influent loading rate (ILR) (g/m ²d) for B-MM and B-HH. The dotted line represents complete removal.

5.4 Effects of Dosing Frequency

In addition to a suitable design of hydraulic loading rates (HLRs), proper feeding practices are important to preserve the system hydraulics and to maintain the treatment performance of the system in long run. The wetlands intermittent feeding allows alternating feeding and drainage of the units. Oxygen diffusion and convection processes in VFEWs are dependent on feed operation (Molle et al. 2006). The dosing frequency of a wetland is practiced by fractioning the daily hydraulic loads into smaller doses. This section reports the effects of the daily dosing frequency under medium and high HLRs (8.75 and 17.5 cm/d, respectively) on treatment levels of pollutants. Under the same HLR, lesser number of daily dosing corresponds with longer rest periods between each feeding and a higher volume of influent applied per dose, and vice-versa. Dosing frequency of 4 and 8 times daily were studied and discussed.

Table 5.6 summarises the physico-chemical characteristics of the influent and the wetland effluent under the different feeding strategies. A mean pH drop to below 7 was observed in the effluent of all wetlands after treatment. Both the wetlands loaded under the medium HLR (B-MM (4x) and B-MM (8x)) showed a significant improvement in the effluent quality with important increment of the DO concentration from 1.32 ± 0.68 mg/L in the influent to 4.32 ± 0.62 mg/L and 4.86 ± 1.20 mg/L in the effluent of wetlands B-MM (8x) and B-MM (4x), respectively (Table 5.6). The redox status of the effluent was also greatly improved from -262 - 215 mV to 89 - 312 mV in the effluent of the wetlands. However, no statistical significant differences of the DO concentrations and ORP values were found between the two wetlands fed under medium HLR at different feeding frequencies.

Table 5.6 also reports a more distinct variation in the characteristics of the effluent from the two wetlands fed under high HLR (17.5 cm/d). Generally with 4 times of daily dosing, both the DO content and the redox status of the effluent increased, indicating an improved quality of the effluent. However, the effluent in wetland B-HH (8x) appeared to be less oxygenated with the higher dosing frequency. The wetland loaded more frequently with smaller volume per dose recorded effluent with lower DO content at the mean of 1.26 mg/L and also a lower ORP value that ranged from -241 - 175 mV.

Table 5.6 Physico-chemical parameters statistics for influent and effluent of the wetlands fed under medium HLR (8.75 cm/d) and high HLR (17.5 cm/d), at 4 and 8 times daily. Standard deviation for means given in parenthesis to indicate range.

Parameter	Medium HLR 8.75 cm/d			High HLR 17.5 cm/d		
	Influent	B-MM (4x)	B-MM (8x)	Influent	B-HH (4x)	B-HH (8x)
Temperature (℃)	27.08 (1.31)	27.65 (2.13)	27.81 (1.81)	27.74 (1.27)	30.27 (1.58)	30.27 (1.59)
pH	7.50 (0.26)	6.90 (0.11)	6.95 (0.13)	7.81 (0.14)	6.89 (0.21)	6.94 (0.19)
ORP (mV)*	-262 - 215	118 - 403	89 - 312	-109 - 310	18 - 255	-241 - 175
DO (mg/L)	1.32 (0.68)	4.86 (1.20)	4.32 (0.62)	2.26 (1.73)	2.90 (0.67)	1.26 (0.43)
EC (mS/cm)	1.94 (0.16)	2.13 (0.16)	2.09 (0.15)	1.72 (0.71)	1.70 (0.46)	1.66 (0.42)

Number of samples, N = 10
* Values given as range

5.4.1 Organic Matter (OM) Removal

The influent and effluent OM indices (COD and BOD_5) concentrations and loads for wetlands inspected under medium and high HLR to examine the effects of dosing frequency are reported in Table 5.7. Generally, both the wetland B-MM (4x) and B-MM (8x) were very efficient in removing the pollutants with more than 94% and 96% of mean COD and BOD_5 mass removed, respectively from the influent of wetlands B-MM (4x) and B-MM (8x) at HLR 8.75 cm/d (Table 5.7). The dosing frequency of 4 or 8 times daily did not seem to affect the treatments of OM at the wetlands loaded under medium HLR (8.75 cm/d). Overall, although wetland B-MM (4x) was observed to perform slightly better in terms of NH_3-N removal than bed B-MM (8x) which was flushed more frequently with smaller dosages (section 5.4.2), the two wetlands achieved similar MRRs for COD and TSS (section 5.4.3). It was found that the concentrations and loads of OM, ammonia and particulate solids in the resulting effluent did not differ significantly between wetlands B-MM (4x) and B-MM (8x).

Table 5.7 OM indices concentration and mass statistics for the influent (pre-treated septage) and the resulting bed effluent of wetlands B-MM (8.75 cm/d) and B-HH (17.5 cm/d). Corresponding bed performances are reported in terms of pollutant removal efficiencies (RE %). Standard deviation for means given in parenthesis to indicate range.

		Concentration (mg/L)		RE (%)*	Mass (g/m^2.d)		Removal	
		IN	OUT		IN	OUT	g/m^2.d *	RE (%)*
Medium HLR (8.75 cm/d)	COD							
	B-MM (4x)	4,860 (±2,693)	199.00 (±69.51)	93.71	425.25 (±235.64)	14.58 (±5.21)	410.67	94.64
	B-MM (8x)	4,860(±2,693)	206.00 (±77.63)	93.34	425.25 (±235.64)	5.21 (±26.90)	410.58	94.47
	BOD							
	B-MM (4x)	247.31 (±84.65)	7.89 (±5.64)	96.87	21.64 (±7.41)	0.56 (±0.39)	21.08	97.47
	B-MM (8x)	247.31 (±84.65)	10.15 (±6.73)	95.74	21.64 (±7.41)	0.71 (±0.48)	20.93	96.60
High HLR (17.5 cm/d)	COD							
	B-HH (4x)	2,224(±834.24)	158.00 (±48.94)	91.45	389.20 (±145.99)	23.75 (±7.23)	365.45	92.68
	B-HH (8x)	2,224 (±834.24)	183.33 (±52.92)	90.11	389.20 (±145.99)	27.41 (±7.50)	361.79	91.58
	BOD							
	B-HH (4x)	182.70 (±351.60)	14.15 (±7.48)	93.77	42.36 (±10.46)	40.26 (±1.04)	40.26	94.70
	B-HH (8x)	182.70 (±351.60)	23.82 (±10.42)	89.69	42.36 (±10.46)	3.52 (±1.43)	38.83	91.25

No. of samples, N = 10

* Values presented as the average REs or MRRs calculated from N samples of N experimental runs

For wetlands fed under high HLR however, bed B-HH (4x) appeared to have greater daily mass removed than wetland B-HH (8x) for both the OM indices. Although the result statistics showed that wetland B-HH (4x) performed better than wetland B-HH (8x) in terms of OM reduction efficiency, especially for BOD_5, their difference was not found to be statistically important. Figure 5.11 and Figure 5.12 show the variations in influent loading rates and their resulting effluent mass, with the corresponding removal efficiencies for COD and BOD_5, respectively at both wetlands.

OM degradation was generally high and unaffected by the different hydraulic regimes used in this experiment. At 8 times of dosing daily, wetland B-HH (8x) was still able to achieve an average mass reduction up to 91.6% for COD and as high as 91.3% for BOD_5 at HLR 17.5 cm/d (Table 5.7, Figure 5.11 and Figure 5.12). Despite oxygen renewal is intensified at the wetlands under the lower dosing frequency (Table 5.6), the insignificant difference found between the wetlands for the removal of OM reflected that the majority of the OM was removed from the influent by physical filtration and sedimentation, instead of the biochemical processes.

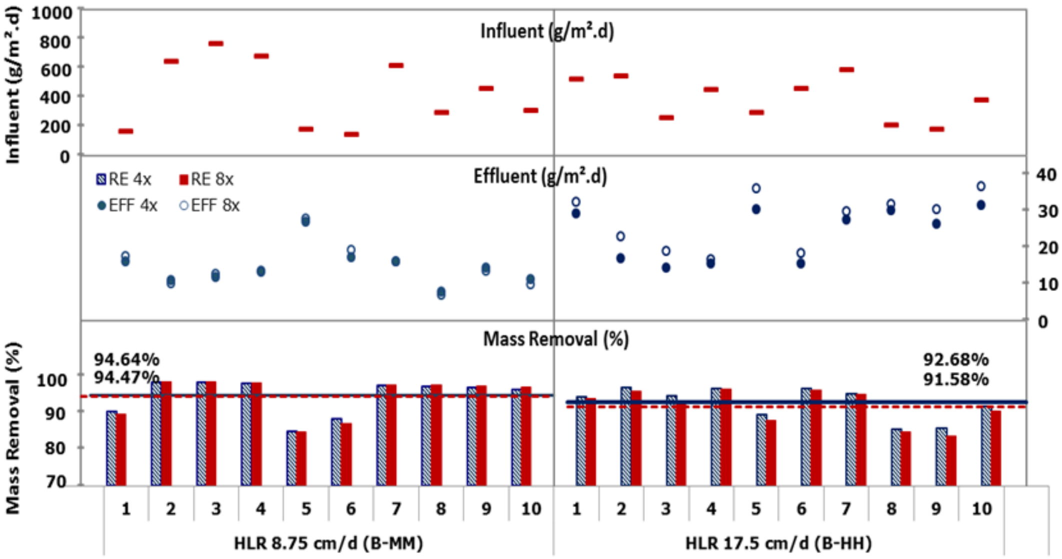


Figure 5.11 Influent COD areal loading rates and the resulting effluent loads for wetland B-HH (4x) and B-HH (8x), with the percentages (%) of mass removal for each treatment (horizontal line indicates mean removal efficiencies for the wetland units)

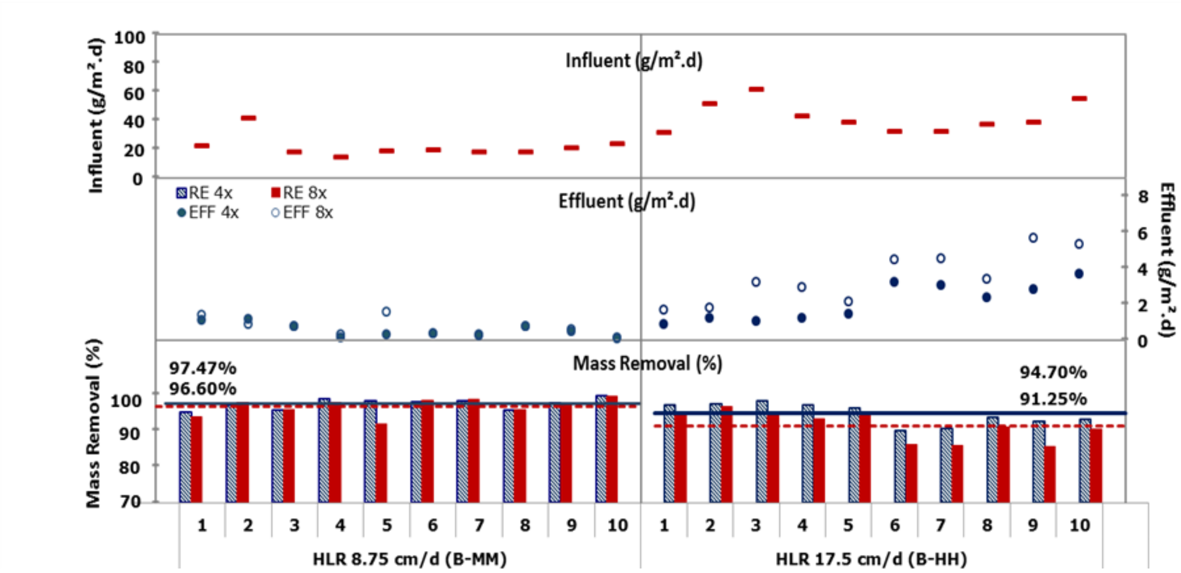


Figure 5.12 Influent BOD_5 areal loading rates and the resulting effluent loads for wetland B-HH (4x) and B-HH (8x), with the percentages (%) of mass removal for each treatment (horizontal line indicates mean removal efficiencies for the wetland units)

Figure 5.13 shows the COD regression chart of the mass removal rate (MRR) against the influent loading rate (ILR) for wetlands fed under HLR 17.5 cm/d. A linear relationship was observed between the variables which suggested a high predictability of the wetlands performance with the incoming loads. The COD MRRs at wetland fed at 4 times daily were at close proximity to the removal rates of wetland fed at 8 times daily, with the corresponding ILRs.

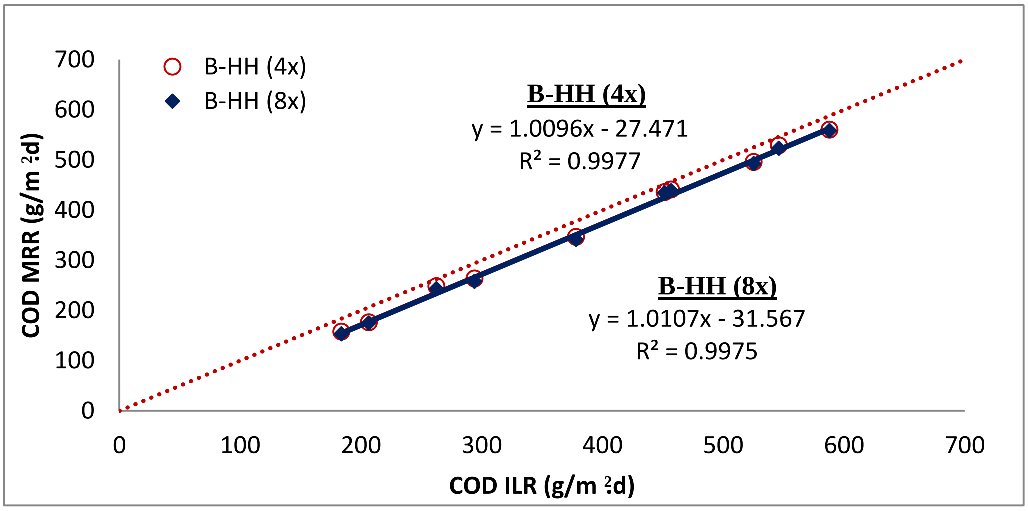


Figure 5.13 Regression graph of COD mass removal rate (MRR) against influent loading rate (ILR) (g/m ²d) for B-HH (4x) and B-HH (8x).The dotted line represents complete removal.

5.4.2 Nitrogen Removal

While the organic matter (OM) removal appeared to be relatively consistent with the dosing frequencies applied, the NH_3-N elimination efficiency on the other hand varied in accordance to the numbers of daily dosing. Ammonium and particulate nitrogen removal rates are more sensitive to the feeding conditions compared to the OM reduction rates. For ammonia removal, the wetlands should have a good supply of oxygen in order to nitrify efficiently as most nitrification occurs aerobically. The results recorded in this experiment revealed that the nitrogen oxidation was significantly affected by the number of daily dosing. Oxygen supply in the wetlands can originate from the diluted oxygen present in the influent itself and via physical transfer by diffusion and convection processes. For vertical engineered wetlands, the oxygen supplied by convection and diffusion mechanisms are most important (Molle et al. 2006) and is heavily affected by the influent application regimes (Kayser and Kunst 2005).

Molle et al. (2006) reported that under identical hydraulic load, greater load fractioning is advantageous to hydraulic retention time but detrimental to system oxygenation and control of wet deposit accumulation inside or on the top of the media. Bancole ́, Brissaud, and Gnagne (2003) showed that with increased number of daily flushing, biofilm tend to accumulate in the upper layers of the wetland substrate and subsequently reduced the oxygen diffusion into the substrate. Besides, frequent influent dosing also leads to higher volume of water retention in the top layers of the beds (Kayser and Kunst 2005; Boller et al. 1993). It was reported that O_2 diffusion is 300,000 times slower in water than in air (Roberts, Reiss and Monger 2000), thus the water layer could potentially lead to less oxygenated substrate. In this study, NH_3-N degradation was found to decrease with statistical importance when the wetland was flushed at 2 times more frequently with smaller batches of influent under the high hydraulic load (HLR 17.5cm/d) (Table 5.8).

Table 5.8 Nitrogen indices concentration and mass statistics for the influent (pre-treated septage) and the resulting bed effluent of wetlands B-MM (8.75 cm/d) and B-HH (17.5 cm/d). Corresponding bed performances are reported in terms of pollutant removal efficiencies (RE %). Standard deviation for means given in parenthesis to indicate range. N indicates number of samples.

		Concentration (mg/L)		RE (%)*	Mass (g/m^2.d)		Removal	
		IN	OUT		IN	OUT	g/m^{2}d *	RE (%)*
Medium HLR (8.75 cm/d); N =10	NH_3-N							
	B-MM (4x)	127.96 (±40.66)	3.40 (±3.65)	96.59	11.20 (±3.56)	0.25 (±0.27)	10.95	97.11
	B-MM (8x)	127.96 (±40.66)	6.54 (±4.90)	94.17	11.20 (±3.56)	0.47 (±0.38)	10.73	95.22
	TKN							
	B-MM (4x)	274.68 (±120.10)	22.69 (±15.96)	91.03	24.03 (±10.51)	1.64 (±1.15)	10.95	92.56
	B-MM (8x)	274.68 (±120.10)	30.64 (±16.67)	87.65	24.03 (±10.51)	2.16 (±1.16)	10.73	90.03
	NO_3-N							
	B-MM (4x)	33.78 (±28.92)	21.87 (±21.45)		2.96 (±2.53)	1.65 (±1.80)		
	B-MM (8x)	33.78 (±28.92)	16.68 (±16.35)		2.96 (±2.53)	1.16 (±1.14)		
	TN							
	B-MM (4x)	309.17 (±128.00)	83.10 (±11.43)	83.10	27.05 (±11.20)	3.30 (±1.77)	23.75	85.51
	B-MM (8x)	309.17 (±128.00)	47.40 (±23.03)	82.08	27.05 (±11.20)	3.32 (±1.55)	23.73	85.59
High HLR (17.5 cm/d); N = 10	NH_3-N							
	B-HH (4x)	55.25 (±24.44)	8.79 (±2.66)	83.21	9.67 (±4.28)	1.32 (±0.38)	8.35	85.57
	B-HH (8x)	55.25 (±24.44)	15.06 (±5.22)	71.75	9.67 (±4.28)	2.24 (±0.73)	7.43	75.89
	TKN							
	B-HH (4x)	208.78 (±65.72)	51.12 (±27.30)	73.41	36.54 (±11.50)	7.64 (±3.97)	28.90	77.29
	B-HH (8x)	208.78 (±65.72)	72.49 (±26.73)	63.03	36.54 (±11.50)	10.84 (±3.96)	25.69	68.45
	NO_3-N							
	B-HH (4x)	34.07 (±38.65)	15.11 (±19.28)		5.96 (±6.76)	2.35 (±3.10)		
	B-HH (8x)	34.07 (±38.65)	9.74 (±13.04)		5.96 (±6.76)	1.51 (±2.08)		
	TN							
	B-HH (4x)	244.20 (±78.23)	67.50 (±29.76)	72.07	42.74 (±13.69)	10.19 (±4.50)	32.54	75.98
	B-HH (8x)	244.20 (±78.23)	82.50 (±31.87)	65.76	42.74 (±13.69)	12.39 (±4.90)	30.34	70.71

* Values presented as the average REs or MRRs calculated from N samples of N experimental runs

Figure 5.14 shows the fluctuations of the incoming NH_3-N loads and the corresponding effluent quality in terms of the NH_3-N mass out, with the respective removal efficiencies for both wetlands loaded under HLR of 17.5 cm/d (B-HH (4x) and B-HH (8x). As shown in Table 5.8 and Figure 5.14, about 85.6% of average daily NH_3-N mass was removed at wetland B-HH (4x), and the reduction efficiency was around 12.8% greater than that at wetland B-HH (8x). A daily NH_3-N mass of 2 g was eliminated at wetland B-HH (4x) and effluent with significantly reduced ammonia mass of 0.32 g was recovered from the wetland outlet.

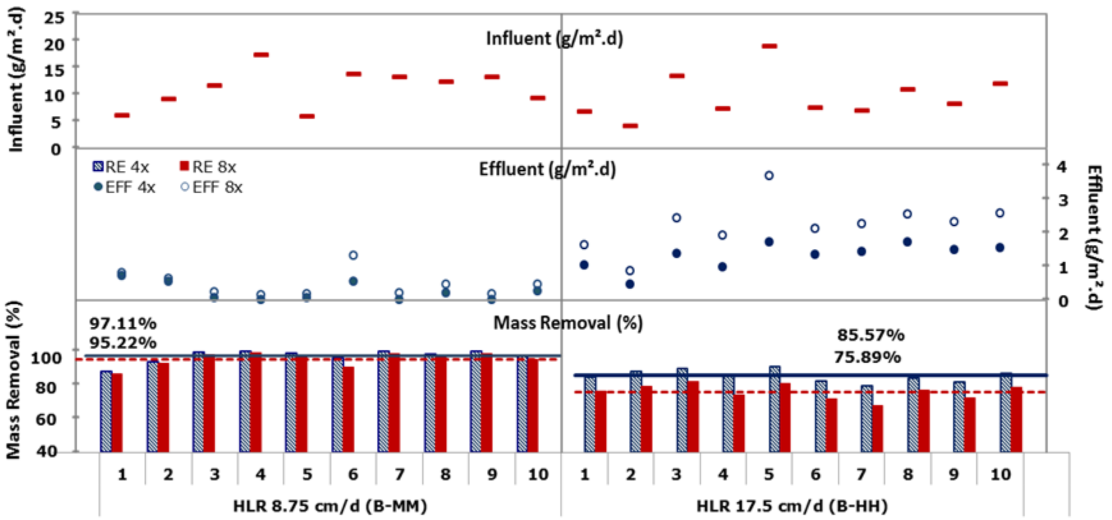


Figure 5.14 Influent NH_3-N areal loading rate and the resulting effluent mass for wetland B-HH (4x) and B-HH (8x), with the percentage (%) of mass removal for each treatment (horizontal line indicates mean removal efficiencies for the wetland units)

The intermittent loading regime with several smaller batches of daily influent feeding allows atmospheric air to be drawn into the wetlands by means of passive pump. Successive cycles of influent recharge and withdrawal promote oxygen renewal in the wetland substrate. The fresh air was drawn into the substrate at the same volume as the volume of the drained effluent due to the existence of a pressure gradient between the atmosphere and the pore spaces within the bed. Thus, a greater amount of oxygen was drawn into the wetland substrate by convection when a higher volume of influent per feeding was applied at wetland B-HH (4x).

As shown in Figure 5.15, the DO concentrations in the effluent of wetland B-HH (4x) present values that were constantly higher than in the effluent collected from the wetland with greater number of hydraulic fractioning (B-HH (8x)). The redox state in the wetland units was determined by measuring the ORP in the resulting effluent. The higher ORP values in the effluent of wetland B-HH (4x), which range between 18 - 288 mV also suggested a more oxidised micro-environment in the unit compared to wetland B-HH (8x). The bed fed more frequently with the high hydraulic load (17.5 cm/d) at wetland B-HH (8x) resulted in effluent with significantly lower ORP values (-241 - 175 mV), indicating a relatively more reduced state in the wetland.

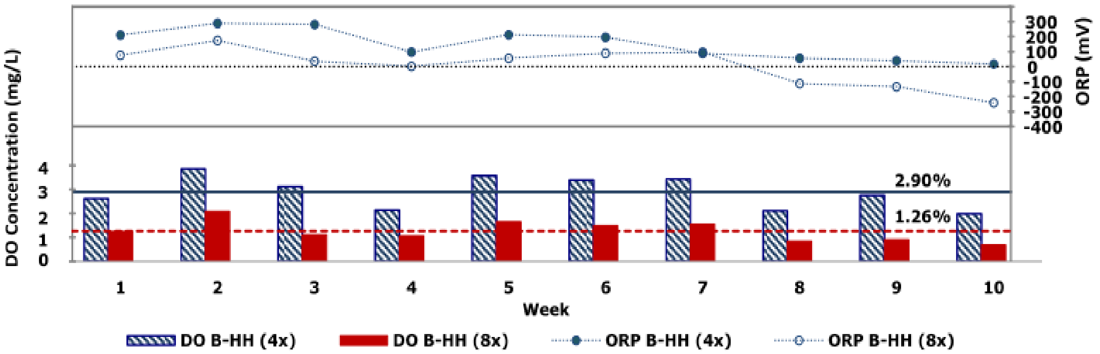


Figure 5.15 DO and ORP values of wetland effluents fed under high HLR (17.5 cm/d) with 4 and 8 times of daily load fractioning

In addition to the factors mentioned above, a longer rest period was associated with the wetlands fed less frequently as the time interval between each dose was longer than the wetlands loaded more regularly. It was agreed that the bed resting period is a more important factor than the influent contact time with the biofilm in the substrate (contact time termed as the hydraulic retention time (HRT)) that improves ammonia removal efficiency (Zhao et al. 2004; Hu et al. 2012). The rest period should be long enough to evacuate the oxygen depleted air from the substrate resulted from organic matter mineralization, besides allowing sufficient time for oxygen recovery by the diffusion of fresh atmospheric air into the wetland via the air-deposit interface. Resting of beds allowed air to get into the substrates for aeration and reduces the likelihood of anoxia. In this study, better infiltration rates were also observed when the interval between each feeding was longer, due to the existence of greater pressure gradients (due to sufficient drying of the media as a result of longer rest period between two successive batches).

In a recent study by Hu, Zhao, and Rymszewicza (2014), further validations on the importance of bed resting were reported. In their tidal flow wetland, nitrification performance was found to be governed by the bed resting time of which the bed was left unsaturated after effluent draining. The adsorbed NH_4^+-N was nitrified during this period when the required oxygen can be obtained directly from the air. Also, the extended rest period was found to enhance the adsorption of NH_4^+-N during the contact period, as a result of regeneration of the adsorption capacity during bed resting due to NH_4^+-N removal by nitrification (Hu, Zhao and Rymszewicza 2014).

With the reoxygenation capability of the wetland units being heavily affected by the numbers of daily dosing especially under high hydraulic load, the ammonia removal rates of wetlands B-HH (4x) and B-HH (8x) were found to vary between the beds in response to the incoming loads. As shown in Figure 5.16, both regression lines represent linear relationship between the NH_3-N MRRs and the ILRs. However, it was evident that removal rates of wetland B-HH (4x) with slope of 0.94 exhibit a trendline closer to the dotted line which indicates complete removal. The NH_3-N removal rates were found to be greater in the wetland unit that was fed less frequently with larger doses, which resulted in a longer dosing interval between each successive dose.

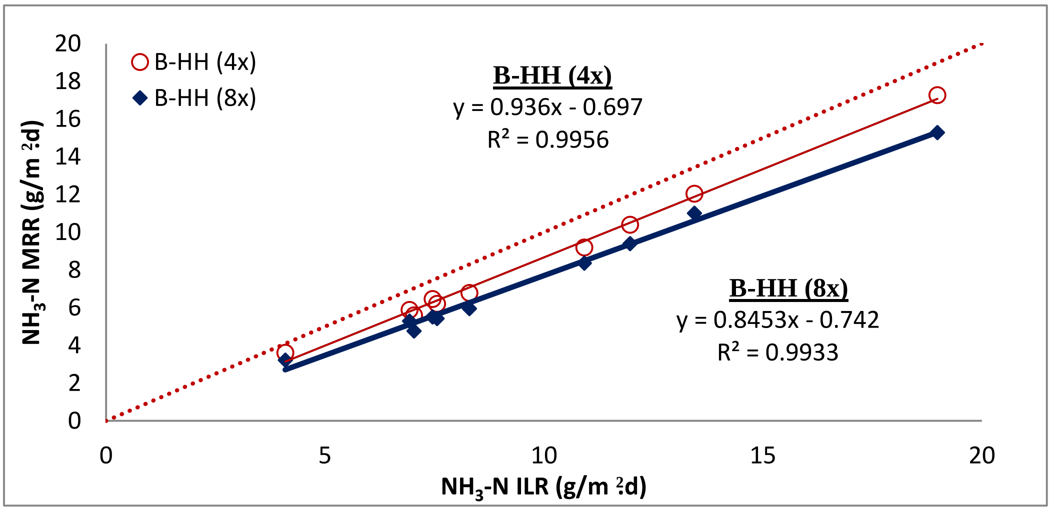


Figure 5.16 Regression graph of NH_3-N mass removal rate (MRR) against influent loading rate (ILR) (g/m ²d) for B-HH (4x) and B-HH (8x). The dotted line represents complete removal.

The slope of the regression line is interpreted as differences in the rate of change; and thus with wetland B-HH (4x) having greater slope (0.94) than wetland B-HH (8x) (0.85), a more substantial change in the removal rates per unit increase in the ILR was demonstrated at bed B-HH (4x) compared to wetland B-HH (8x). The greater slope in wetland B-HH (4x) reflects higher degree to which the MRRs vary linearly as a function of change in the ILRs. The differences of the MRRs in response to the ILRs between the two beds were shown to increase with the increment of the incoming ammonia loads. At high hydraulic loads, the feeding practice is an important factor that could help to prevent bed clogging and maintain the N treatment performance of the wetland units.

5.4.3 Particulate Solids Removal

Influent mean TS concentration was around 8.5 g/L and 4.1 g/L for wetlands loaded at medium (B-MM (4x); B-MM (8x)) and high HLR (B-HH (4x); B-HH (8x)), respectively (Table 5.9). Areal loading of 0.75 kg TS/m^2.d was applied onto wetlands loaded with HLR of 8.75 cm/d at 4 and 8 times daily with mean mass removal efficiency of 72.3% and 74.3%, respectively (Table 5.9). At high HLR of 17.5 cm/d with influent areal loading of 0.71 kg TS/m^2.d, mean TS mass removal efficiency of wetland B-HH (4x) was found to be slightly lower at 69.4% than wetland B-HH (8x) at 72%, due to the accumulations of dissolved compounds (such as nitrite and nitrate) in the wetland fed less frequently with larger doses.

Table 5.9 Particulate solids indices concentration and mass statistics for the influent (pre-treated septage) and the resulting bed effluent of wetlands B-MM (8.75 cm/d) and B-HH (17.5 cm/d). Corresponding bed performances are reported in terms of pollutant removal efficiencies (RE %). Standard deviation for means given in parenthesis to indicate range.

		Concentration (mg/L)		RE (%)*	Mass ($g/m^2.d$)		Removal	
		IN	OUT		IN	OUT	$g/m^2.d$ *	RE (%)*
Medium HLR (8.75 cm/d)	TS							
	B-MM (4x)	8,541(±4,613)	2,372 (±457.14)	66.81	747.36 (±403.66)	172.81 (±32.65)	574.56	72.30
	B-MM (8x)	8,541(±4,613)	2,289 (±482.81)	67.97	747.36 (±403.66)	161.89 (±37.88)	585.47	74.26
	TSS							
	B-MM (4x)	2,666 (±1,140)	91.90 (±51.87)	96.35	233.26 (±99.72)	6.72 (±3.71)	226.54	96.92
	B-MM (8x)	2,666 (±1,140)	108.30 (±59.75)	95.67	233.26 (±99.72)	7.71 (±4.28)	225.55	96.45
	VSS							
	B-MM (4x)	2,106 (±1,298)	44.80 (±27.84)	97.32	184.28 (±113.54)	3.25 (±2.00)	181.03	97.75
	B-MM (8x)	2,106 (±1,298)	45.30 (±35.54)	97.31	184.28 (±113.54)	3.24 (±2.56)	181.05	97.77
High HLR (17.5 cm/d)	TS							
	B-HH (4x)	4,060 (±1,350)	14,34 (±535.95)	64.65	710.43 (±236.21)	217.43 (±87.53)	493.00	69.41
	B-HH (8x)	4,060 (±1,350)	1,321 (±527.40)	67.52	710.43 (±236.21)	199.58 (±85.58)	510.85	72.01
	TSS							
	B-HH (4x)	2,367 (±856.22)	100.80 (±33.64)	95.50	414.17 (±149.84)	15.05 (±4.67)	399.12	96.13
	B-HH (8x)	2,367(±856.22)	103.00 (±33.80)	95.39	414.17 (±149.84)	15.29 (±4.61)	398.87	96.05
	VSS							
	B-HH (4x)	1,815 (±939.12)	68.60 (±25.33)	95.50	317.57 (±164.35)	10.21 (±3.42)	307.36	96.11
	B-HH (8x)	1,815 (±939.12)	76.30 (±29.36)	94.96	317.57 (±164.35)	11.31 (±4.00)	306.26	95.66

No. of samples, N= 10

* Values presented as the average REs or MRRs calculated from N samples of N experimental runs

Figure 5.17 shows the TSS influent and effluent mass statistics for wetlands dosed at 4 and 8 times daily under medium and high HLR. At all wetlands, more than 96% of the TSS mass was removed from the influent up to 8 times of daily feeding frequency. Based on the statistical analyses of the results on TS and TSS removal performances (Table 5.9), no significant differences were found between the wetlands operated under the two dosing regimes for both HLRs. The wetland performance was also found to be similar for both feeding frequencies under the medium and high HLRs in terms of VSS removal efficiency, indicating that the beds were capable of achieving an equally high removal rates under the loading practices, with more than 43.5 g and 73.5 g of VSS eliminated daily at the wetlands loaded with medium and high HLRs, respectively.

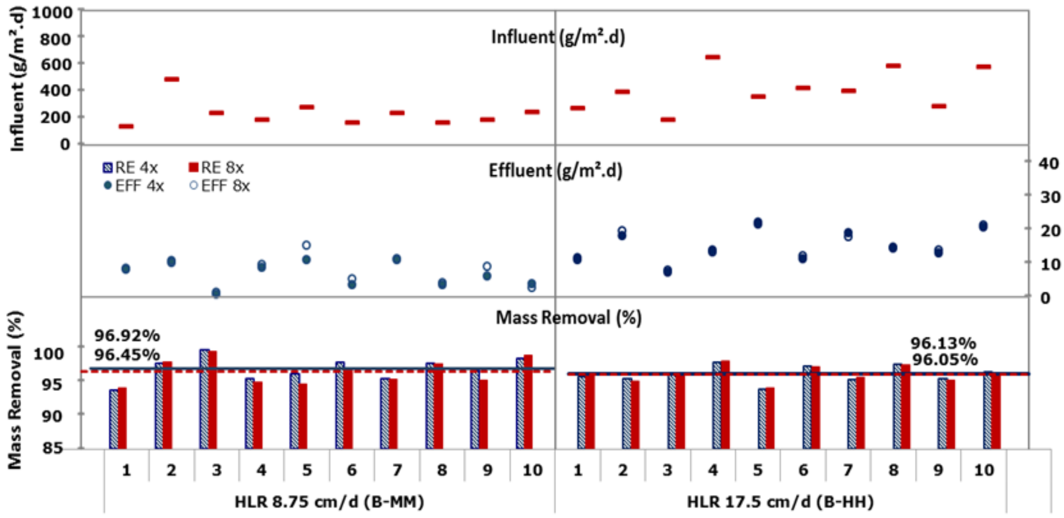


Figure 5.17 Influent TSS areal loading rates and the resulting effluent loads for wetland B-HH (4x) and B-HH (8x), with the percentages (%) of mass removal for each treatment (horizontal line indicates mean removal efficiencies for the wetland units)

The results showed that the influent solids content was reduced noticeably in general, with high solids reduction capability of the wetlands at the second stage of the VFEWs system. This confirmed that the wetland units were efficient in the process of particulate and soluble organic matter retention and removal, at both 4 and 8 times of daily dosing frequency. The influent particulate solids concentration and mass were significantly reduced from the influent, resulting in effluent with improved quality under both feeding regimes. As shown in Figure 5.18, the correlation between the MRRs of TSS with the applied loadings up to 0.65 kg TSS/m^2.d was strong (r^2>0.99). The regression analysis suggested that the influent TSS loading rates have important effects on the MRRs under both dosing frequencies ($P<0.001$). There was no significant difference found between the performance of the wetlands loaded at 4 and 8 times daily in terms of TSS removal, with both wetlands demonstrating similar rate of change in the TSS MRRs with the change in ILRs. The linear regression trend suggested that the TSS MRRs could be accurately predicted by the incoming TSS loading rates under all the tested feeding practices.

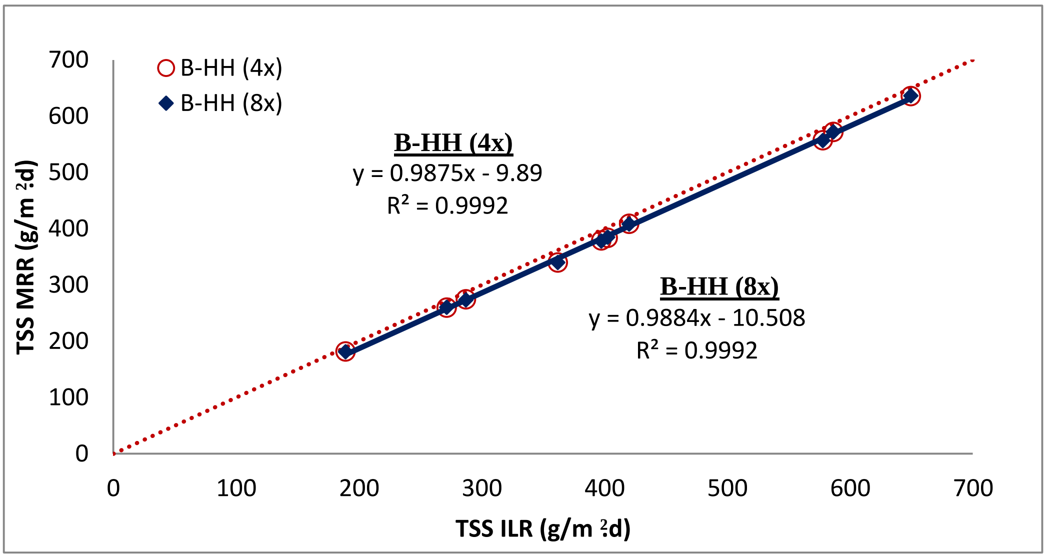


Figure 5.18 Regression graph of TSS mass removal rate (MRR) against influent loading rate (ILR) (g/m ²d) for B-HH (4x) and B-HH (8x). The dotted line represents complete removal.

5.5 Effects of Pond and Rest (P:R) Period

The mode of operation (batch, continuous or intermittent) was reported to have an important influence on the wetlands redox potential, according to Kadlec and Knight (1996) and García et al. (2004). VFEWs are usually efficient in the removal of organics (COD and BOD_5) and suspended solids. In addition, VFEWs operated with intermittent feeding are also capable of providing high removal of ammonia nitrogen (NH_3-N) due to good oxygenation of the filtration bed as a result of the operational regime. On the other hand, this type of wetland is less efficient in removing total nitrogen (TN) or nitrate (NO_3-N) due to several limitations. To complete the N removal cycle, NO_3^- can be converted to nitrogen gas (N_2) via denitrification.

Among the limitations that can inhibit denitrification process are the availability of nitrate, deficient source of carbon and the dominancy of anoxic/anaerobic conditions (Saeed and Sun 2011c).

Similar to natural wetlands, engineered wetlands are high in microscale heterogeneity which promotes simultaneous nitrification–denitrification (Kadlec and Knight 1996; Hunt, Krabbenhoft and Anderson 1997). Limitations on either process can restrict elimination of nitrogen from the wetland influent. In this study, palm kernel shells (PKS) were incorporated as part of the wetland substrate at the second stage of the VFEWs system and its performance in nitrogen removal is reported in Chapter 6 (section 6.5). In this system where the second stage wetlands were provided with extra carbon source from the PKS, the N removal efficiency would most likely to be limited by the availability of aerobic and anaerobic microsites in the wetland beds. Under this section, the effects of prolonged bed ponding and resting period on the treatment performance of the VF wetlands are presented and discussed. The beds were fed in batches, with the wetlands filled rapidly to capacity, remained filled for an extended period of time before being drained completely, and in a repeating process, the beds are refilled, ponded, drained and left idle (rest) again.

The batch feeding strategy with the pond:rest (P:R) period of 1:1, 2:2 and 3:3 (day(s):day(s)) were studied to investigate the effects of different ponding and resting periods on the performance of wetlands treating pre-treated septage that was collected from the first stage wetlands. The ratio of the pond and rest period remained at 1 to 1, with the beds rested at the same extended period as the influent ponding time (days). Besides, the batch fed wetlands were also compared against the intermittently fed wetlands (where the wetlands were fed 4 times a day at HLR of 8.75 cm/d, i.e. at 21 L/d) to study the effects of prolonged ponding and resting period on the treatment efficiency of the wetland units. All batch loaded wetlands were fed with 21 L of influent per cycle. Table 5.10 summarises the physico-chemical characteristics of the wetlands influent and effluent.

Table 5.10 Physico-chemical parameters statistics for influent and effluent of the wetlands fed with batch mode at P:R (days) of 1:1 (wetland B-PR1), 2:2 (wetland B-PR2) and 3:3 (wetland B-PR3), and with intermittent mode at 4 times daily (B-MM (4x))

Parameter		Sampling Point	Statistics			
			N	Range	Mean	Std Dev.
Temperature (℃)	Batch	Influent	11	27.00 - 29.00	27.65	0.78
		B-PR1	11	26.90 - 30.70	28.45	1.32
		B-PR2	11	26.50 - 32.90	28.32	1.67
		B-PR3	11	26.90 - 30.90	28.61	1.23
	Intermittent	Influent	10	25.10 - 29.50	27.08	1.31
		B-MM (4x)	10	24.50 - 31.50	27.65	2.13
pH	Batch	Influent	11	7.58 - 8.30	7.83	0.26
		B-PR1	11	6.63 - 6.84	6.71	0.06
		B-PR2	11	6.47 - 6.79	6.64	0.11
		B-PR3	11	6.41 - 6.84	6.59	0.13
	Intermittent	Influent	10	7.12 - 8.05	7.50	0.26
		B-MM (4x)	10	6.77 - 7.09	6.90	0.11
DO (mg/L)	Batch	Influent	11	0.48 - 0.85	0.61	0.13
		B-PR1	11	0.51 - 1.35	0.91	0.31
		B-PR2	11	0.74 - 1.57	1.09	0.29
		B-PR3	11	1.12 - 1.89	1.47	0.22
	Intermittent	Influent	10	0.50 - 2.54	1.32	0.68
		B-MM (4x)	10	3.65 - 7.59	4.86	1.20
ORP (mV)	Batch	Influent	6	-113 - (- 84)		
		B-PR1	6	-82 - 2		
		B-PR2	6	-56 - 17		
		B-PR3	6	111 - 178		
	Intermittent	Influent	10	-262 - 215		
		B-MM (4x)	10	118 - 403		
EC (mS/cm)	Batch	Influent	11	1.35 - 1.77	1.59	0.15
		B-PR1	11	1.74 - 2.14	1.91	0.14
		B-PR2	11	1.78 - 2.17	2.05	0.12
		B-PR3	11	2.28 - 2.89	2.48	0.19
	Intermittent	Influent	10	1.70 - 2.17	1.94	0.16
		B-MM (4x)	10	1.98 - 2.50	2.13	0.16

During the cyclic ponding and resting period, the pH values fluctuated marginally and remained below 7 for all the effluent samples collected from the wetlands. The average pH value of the influent was alkaline with values ranging between 7.58 - 8.30. The EC readings of the effluent was found to be significantly higher than that of the influent, with the effluent from wetland B-PR3 having the highest EC value at 2.48 ± 0.19 mS/cm. Also throughout the experimental period, it was observed that the DO concentration was increased with the improved redox status in the effluent after treatment in all beds. In batch loaded wetlands, the improvement was more evident at wetland B-PR3 with P:R=3:3. Wetland B-PR1 with P:R=1:1 was observed to experience clogging issues with a notable thin layer of influent waterlogging the bed surface after 1 day of resting, before the subsequent feeding cycle. The results also revealed that the intermittently loaded wetland produced effluent with relatively greater fluctuations in the DO and ORP values (higher standard deviations) compared to the batch loaded beds.

During the experimental run, the top sand and PKS layers of wetland B-PR2 (batch loaded bed) was occasionally disturbed and burrowed by rats. It was unclear if the incident had affected the performance of the wetland and so the treatment results from wetland B-PR2 shall be used with care, bearing in mind that the burrowed substrate would have negatively impacted the hydraulics (short circuit flow and possible increase in water loss) and the treatment efficiency of the wetland.

5.5.1 Organic Matter (OM) Removal

Pre-treated septage with mean COD and BOD_5 concentration of 5.16 ± 2.88 g/L and 0.27 ± 0.08 g/L, respectively was used as the influent for the batch-loaded wetlands. The average COD and BOD_5 concentration removal efficiency was above 90% in wetland B-PR2 and B-PR3 (please see Appendix C3). Wetland B-PR1 with P:R=1:1 was found to have the poorest performance amongst the three wetlands. The OM concentrations recovered in the effluent of wetland B-PR1 were constantly higher than observed in the effluent of wetland B-PR3 which was left ponded and rested for a longer period. In terms of mass loading rate, a mean of 0.45 g COD/m^2 and 0.024 g BOD/m^2 was fed onto the batch loaded wetlands per cycle (Table 5.11). Comparing the treatment performances of the three batch loaded wetlands, statistical analysis on the data showed important differences with the COD removal efficiencies between wetland B-PR1 and B-PR3, and B-PR2 and B-PR3. Significant difference between wetland B-PR1 and B-PR3 was also found for the BOD_5 reduction efficiencies.

Table 5.11 OM indices concentration and mass statistics for the influent (pre-treated septage) and the resulting bed effluent of batch-fed and intermittently-fed units. Corresponding bed performances are reported in terms of pollutant removal efficiencies (%). Standard deviation for means given in parenthesis to indicate range.

		Concentration (mg/L)		RE (%)*	Mass (g/m^2.batch) or (g/m^2.d)		Removal	
		IN	OUT		IN	OUT	(g/m^{2}batch) or (g/m^2.d)*	RE (%)*
Batch Mode; N=11	COD							
	B-PR1	5,159 (±2,877)	473.64 (±339.96)	88.16	451.42 (±251.78)	28.88 (±19.57)	422.54	91.72
	B-PR2	5,159 (±2,877)	357.73 (±243.41)	90.96	451.42 (±251.78)	20.81 (±15.03)	430.61	93.73
	B-PR3	5,159 (±2,877)	173.27 (±83.34)	94.65	451.42 (±251.78)	7.65 (±3.98)	443.77	97.30
	BOD							
	B-PR1	274.78 (±76.94)	27.13 (±7.17)	89.16	24.04 (±6.73)	1.70 (±0.54)	22.34	92.24
	B-PR2	274.78 (±76.94)	22.17 (±5.40)	91.17	24.04 (±6.73)	1.27 (±0.40)	22.78	94.11
	B-PR3	274.78 (±76.94)	20.51 (±3.39)	92.01	24.04 (±6.73)	0.94 (±0.30)	23.11	95.97
Intermittent Mode; N=10	COD							
	B-MM (4x)	4,860 (±2,693)	199.00 (±69.51)	93.71	425.25 (±235.64)	14.58 (±5.21)	410.67	94.64
	BOD							
	B-MM (4x)	247.31 (±84.65)	7.89 (±5.64)	96.87	21.64 (±7.41)	0.56 (±0.39)	21.08	97.47

N= Number of samples

RE= Removal efficiency

* Values presented as the average REs or MRRs calculated from N samples of N experimental runs

Wetland B-PR3 with P:R=3:3 significantly outperformed the wetlands operated at lesser P:R period with 6.1% and 3.8% higher COD mass removal efficiency than wetland B-PR1 and B-PR2, respectively (Table 5.11 and Figure 5.19). The removal of BOD_5 mass was high at wetland B-PR3 with 96% reduction, which was significantly greater than the treatment at wetland B-PR1 with a total of 92.2% of BOD_5 mass removed. The average COD and BOD_5 MRR in wetland B-PR3 was 0.44 kg/m^2.batch and 23.1 g/m^2.batch, with the drained effluent mass being less than 3.3 g/batch and 0.33 g/batch, respectively throughout the experimental period (Figure 5.19 and Appendix C3). The experimental results suggested that the increased P:R helped to improve the OM elimination rates of the VF wetlands.

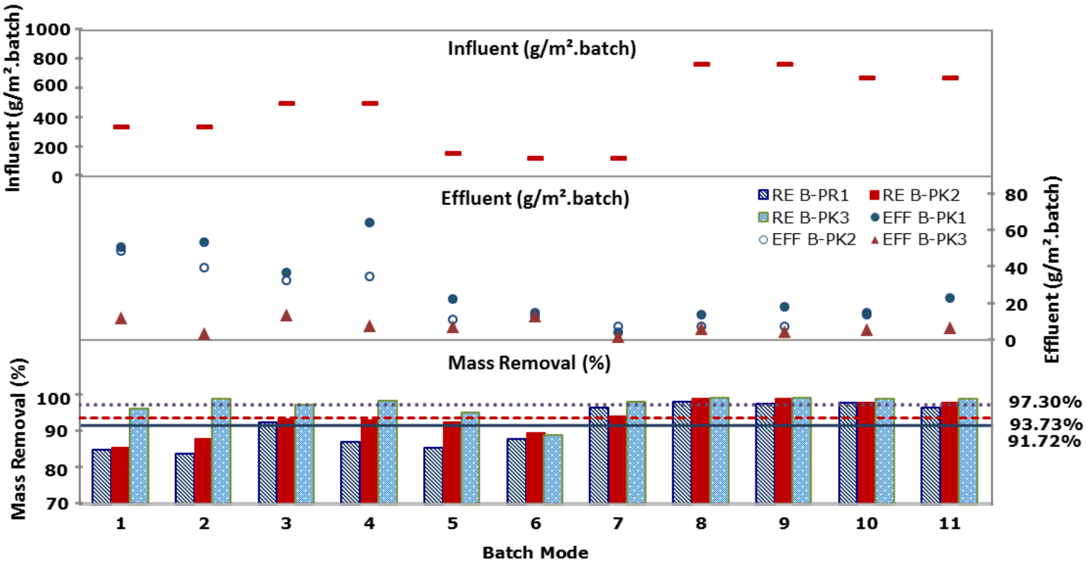


Figure 5.19 Weekly influent COD areal loading rates and the resulting effluent loads for wetlands B-PR1, B-PR2 and B-PR3, with the percentages (%) of mass removal for each treatment (horizontal line indicates mean removal efficiencies for the wetland units)

VFEWs remove pollutants with physical retention and by endogenous decay between batches (Mitchell and McNevin 2001). Since clogging is a commonly known problem for VFEWs, a proper application regime with adequate rest period is important to allow for sufficient endogenous decay to restore the substrate porosity. Wetland B-PR1 was found to experience clogging with P:R of 1:1, and the DO concentration in the effluent was observed to be relatively lower than the other wetlands. Standing water observed on the bed as a result of surface waterlogging could explain the less oxygenated environment in the substrate that subsequently retarded the overall bed performance. An average DO concentration below 1 mg/L was found in the effluent with ORP readings ranging between -82 mV to 2 mV (Table 5.10). It was speculated that the clogging was the result of insufficient resting period of 1 day, considering the high applied organic loading rates on the beds.

Wetland B-PR2 had 2 days of ponding period and 2 days of resting period, where no obvious standing water was observed on the surface of the wetland at the end of the 4 days fill-pond-drain-rest cycle. Increased ponding period can extend the hydraulic retention time of the influent, which lengthened the contact time between the influent and the biofilm in the substrate for improved pollutant treatment performance. During the ponding period, the hydrated wetlands provide food resources for microorganisms under aerobic (early period of ponding after sufficient rest period) and anaerobic (extended period of ponding) conditions; and when drained, the wetlands are re-aerated with oxygen replenishment by convection, but no food resources are supplied. The batch feeding frequency is important to ensure chronological oxygen, food, reduced condition and then re-oxygenation processes in the wetlands to sustain the microbial populations.

Comparisons were also made between the batch and the intermittently fed wetlands to study the effects of the different operational regime on OM removal. The intermittent feeding strategy was known to be effective in promoting aerobic condition in wetlands, which is implemented by fractioning the hydraulic load into several doses of feeding daily at specific intervals. Both the drained effluent from batch loaded wetland B-PR3 and intermittently fed wetland B-MM (4x) had COD concentrations below 200 mg/L, which satisfied at least Standard B according to the Environmental Quality (Sewage) Regulation 2009 for effluent discharge into inland waters or Malaysian waters (please see Appendix A).

The study results revealed statistically similar efficiency in COD removal between the two wetlands (B-PR3 and B-MM (4x)), but found significantly higher BOD_5 treatment performance at bed operated under the intermittent feeding mode. BOD_5 removal is dependent on oxygen concentration, which is affected by the oxygen transport and consumption in the wetland beds. DO concentrations recovered from the effluent of wetland B-MM (4x) averaged to 4.86 mg/L and for the effluent of wetland B-PR3 was 1.47 mg/L (Table 5.10).

Some effluent from B-PR3 was withdrawn after 30 minutes and 1 day of ponding to examine their DO content. A mean of 4.45 ± 0.7 mg/L and 1.72 ± 0.3 mg/L of DO was recovered in the effluent after ponding for 30 minutes and 1 day, respectively (Figure 5.20). This indicates that the prolonged ponding period to 3 days had left the wetland in a less aerobic state as shown in Figure 5.20, where no oxygen renewal was allowed. Based on the results, it was suggested that the rapid biodegradation of OM happened mainly during the first day of ponding, where the rate of organic decomposition slowed down after that due to less available oxygen in the bed. No drastic changes or drops in DO content was observed in wetland B-PR3 after the extended ponding period of up to 3 days.

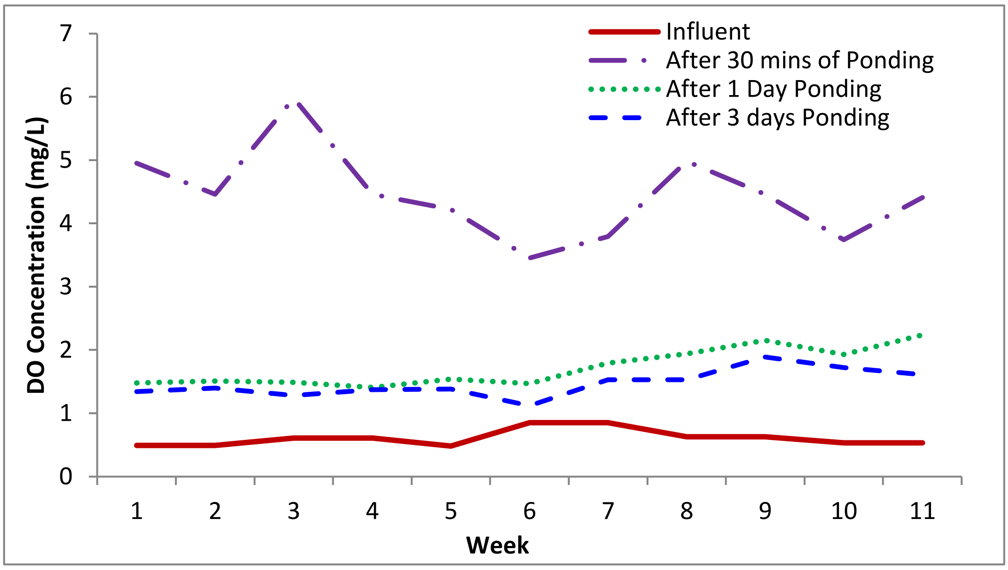


Figure 5.20 Effluent DO concentrations for wetland B-PR3 after 30 mins, 1 day and 3 days of ponding

Jia et al. (2010) reported almost immediate change in the DO concentrations after synthetic wastewater was pumped into the wetlands and fast depletion of DO concentration was observed during the first 5 hours. The authors also found minimal and insignificant changes in the DO concentrations after 5 hours of ponding. Unlike the batch feeding regime, intermittent feeding strategy does not involve prolonged ponding and allows free drainage at the wetlands, where the beds are re-oxygenated via passive aeration by drawing in atmospheric air into the substrate with every dose of influent applied. This has helped to maintain the system DO level with constant renewal of fresh air into the wetlands and subsequently leads to better OM removal in the beds operated under this regime.

5.5.2 Nitrogen Removal

As discussed previously, batch loading can help to avoid substrate clogging with sufficient rest period that leads to complete re-oxygenation of the filter. Usually the most important nitrogen removal process is by microbial assimilation, via the coupled nitrification and denitrification processes. In this study, the wetlands were fed with influent consisting of 82.4 mg/L of NH_3-N, 8.5 mg/L of NO_3-N and 225.1 mg/L of TKN as shown in Table 5.12. With a constant 21 L of influent applied at every batch, a total average of 1.7 g, 0.18 g and 4.7 g of NH_3-N, TKN and TN, respectively was loaded onto the beds (Table 5.12).

Table 5.12 Nitrogen indices concentration and mass statistics for the influent (pre-treated septage) and the resulting bed effluent of batch-fed and intermittently-fed units. Corresponding bed performances are reported in terms of pollutant removal efficiencies (RE %). Standard deviation for means given in parenthesis to indicate range. N denotes the number of samples.

		Concentration (mg/L)		RE (%)*	Mass (g/m^2.batch) or (g/m^2.d)		Removal	
		IN	OUT		IN	OUT	(g/m^2.batch) or (g/m^2.d)*	RE(%)*
Batch Mode; N=11	NH_3-N							
	B-PR1	82.36 (±45.71)	26.17 (±12.55)	65.81	7.48 (±4.00)	1.62 (±0.74)	5.86	75.46
	B-PR2	82.36 (±45.71)	20.13 (±5.70)	72.13	7.48 (±4.00)	1.17 (±0.43)	6.32	81.45
	B-PR3	82.36 (±45.71)	13.68 (±9.51)	83.64	7.48 (±4.00)	0.67 (±0.53)	6.82	91.13
	TKN							
	B-PR1	225.11 (±81.15)	52.01 (±18.70)	74.33	19.70 (±7.10)	3.23 (±1.17)	16.47	81.63
	B-PR2	225.11 (±81.15)	42.32 (±14.61)	80.08	19.70 (±7.10)	2.38 (±0.91)	17.32	86.69
	B-PR3	225.11 (±81.15)	24.96 (±12.35)	87.64	19.70 (±7.10)	1.16 (±0.67)	18.54	93.49
	NO_3-N							
	B-PR1	8.52 (±6.61)	1.05 (±0.82)		0.75 (±0.58)	0.06 (±0.05)		
	B-PR2	8.52 (±6.61)	1.57 (±1.85)		0.75 (±0.58)	0.09 (±0.10)		
	B-PR3	8.52 (±6.61)	4.30 (±2.73)		0.75 (±0.58)	0.18 (±0.11)		
	TN							
	B-PR1	233.73 (±81.03)	53.18 (±19.42)	74.97	20.45 (±7.09)	3.30 (±1.21)	17.15	82.07
	B-PR2	233.73 (±81.03)	44.05 (±15.07)	80.15	20.45 (±7.09)	2.48 (±0.94)	17.97	86.75
	B-PR3	233.73 (±81.03)	29.32 (±10.33)	86.31	20.45 (±7.09)	1.34 (±0.60)	19.11	92.91
Intermittent Mode; N=10	NH_3-N							
	B-MM (4x)	127.96 (±40.66)	3.40 (±3.65)	96.59	11.20 (±3.56)	0.25 (±0.27)	10.95	97.11
	TKN							
	B-MM (4x)	274.68 (±120.10)	22.69 (±15.96)	91.03	24.03 (±10.51)	1.64 (±1.15)	10.95	92.56
	NO_3-N							
	B-MM (4x)	33.78 (±28.92)	21.87 (±21.45)		2.96 (±2.53)	1.65 (±1.80)		
	TN							
	B-MM (4x)	309.17 (±128.00)	83.10 (±11.43)	83.10	27.05 (±11.20)	3.30 (±1.77)	23.75	85.51

* Values presented as the average REs or MRRs calculated from N samples of N experimental runs

As reported in Table 5.12, mass removal efficiency as high as 93.5% and 92.9% for TKN and TN, respectively was achieved by the wetland with the longest P:R period. Figure 5.21 and Figure 5.22 present the NH_3-N and TN mass fluctuations in the wetlands influent and effluent, and their corresponding removal efficiencies. Comparisons between the batch loaded wetlands revealed significantly higher removal efficiencies of all nitrogen species examined at wetland B-PR3 with P:R=3:3. The NH_3-N mass reduction performance at wetland B-PR3 was about 20.8% greater to that of wetland B-PR1. Insufficient removal of ammonia in wetland B-PR1 was due to the occurrence of minor clogging in the unit with inadequate bed resting period. As mentioned previously in section 5.5.1, in the event of waterlogging due to accumulation of particulate solids on the bed surface the standing water can hinder oxygenation of the wetlands, creating an anoxic state that decreased the removal performance of most pollutants.

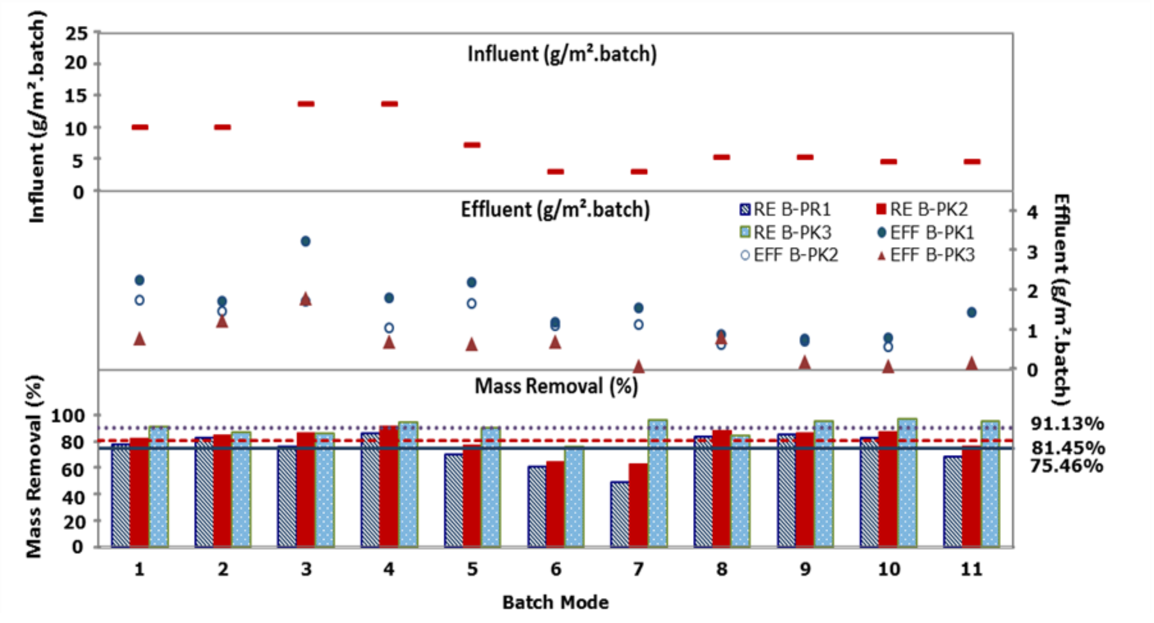


Figure 5.21 Weekly influent NH_3-N areal loading rates and the resulting effluent loads for wetlands B-PR1, B-PR2 and B-PR3, with the percentages (%) of mass removal for each treatment (horizontal line indicates mean removal efficiencies for the wetland units)

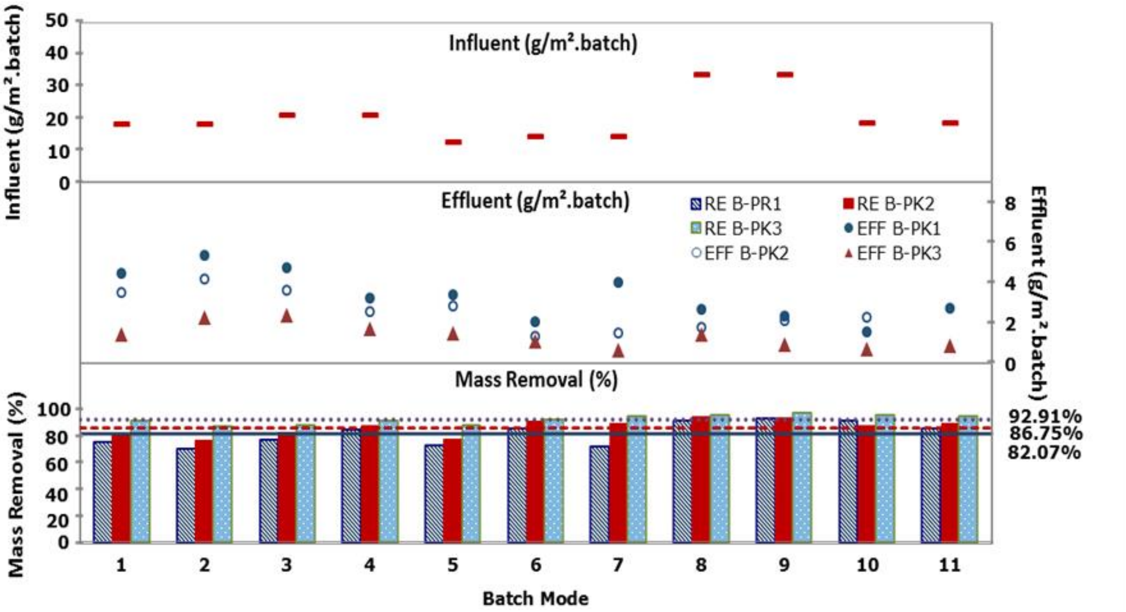


Figure 5.22 Weekly influent TN areal loading rates and the resulting effluent loads for wetlands B-PR1, B-PR2 and B-PR3, with the percentages (%) of mass removal for each treatment (horizontal line indicates mean removal efficiencies for the wetland units)

Meanwhile, wetland B-PR3 which was the bed operated with 3 days of ponding followed by 3 days of resting was observed to have shrinkage cracks on the surface of the septage deposit layer. This suggests effective influent draining and deposit drying after the bed was left idle for 3 days. 3 days of resting enhanced nitrification with the dried septage layer encouraging oxygen diffusion into substrate biofilms, where the subsequent batch feeding promoted oxygen replenishment via convection. The effective removal of TN in wetland B-PR3 was most likely related to the high nitrification prior to denitrification. As it was claimed by Lowrance et al. (1998) and Sartoris et al. (2000) that denitrification rates are positively influenced by increase NO_3-N concentrations, improved nitrification is advantageous to TN removal if provided with an anaerobic environment and sufficient carbon source to boost denitrification at a later stage. This explains the importance of both ponding and resting period for effective TN removal, which is to promote an oxygen-deficient microenvironment in the wetland and ensure a sufficient contact period between the influent and the PKS via prolonged ponding to encourage denitrification; and support bed re-oxygenation for nitrification by sufficient bed resting after the ponding period.

Hybrid systems comprising of two or more types of engineered wetlands were used in several previous studies to achieve, in addition to OM removal, nitrification and denitrification for TN elimination. The different kinds of wetlands were arranged in the system such that TN removal can be enhanced. In this current study where two stages of vertical wetlands were used for septage treatment, the first stage of beds were meant to filter out majority of the OM and particulate solids before discharging the effluent into the second stage for further OM and nutrient removal. In the batch loaded wetlands with P:R=3:3, elimination efficiency of TN concentration was as high as 86% on average, which is higher than those reported in the literature using hybrid wetland systems. A study conducted in Italy with a hybrid system featuring one vertical flow and one horizontal flow subsurface wetland to treat sewage achieved an overall TN removal efficiency of 78% with a hydraulic load of 123 L/m^2.d, and organic loads of 87 g COD/m^2.d and 10 g TKN/m^2.d. Meanwhile, Oovel et al. (2007) reported 63% of TN reduction in a hybrid system, consisting of a two-chamber vertical subsurface flow filter bed followed by a horizontal subsurface flow filter bed for treatment of sewage in Estonia.

Although the NH_3-N mass removal in the intermittently fed wetland (B-MM (4x)) appeared to be higher compared to the batch fed unit (B-BR3) (Table 5.12), no statistically significant difference was found between the treatment efficiency of the two wetlands. With an average of 97.1% of NH_3-N mass removed from wetland B-MM (4x), the wetland did not significantly outperform wetland B-PR3 which achieved 91.1% of NH_3-N reduction efficiency ($P>0.05$). However, the TN removal between the wetlands was found to be significantly different with the batch loaded wetland B-PR3 being more efficient in nitrogen elimination than the intermittently loaded bed. 20.5 ± 7.1 g/m^2.batch and 27.1 ± 11.2 g/m^2.d of TN mass was applied onto wetland B-PR3 and B-MM (4x), respectively as reported in Table 5.12. An average of 92.9% of TN mass was removed by wetland B-PR3 and was 8.6% higher than wetland B-MM (4x).

Batch feeding can increase the hydraulic retention time (HRT) of the influent and create less aerobic conditions in the wetland during the ponding period to promote denitrification. Extended bed resting period which provides time for the surface layer to dewater and mineralize can help to ensure that the hydraulic conductivity of the bed is maintained. This is important to enhance the coupled process of nitrification-denitrification for improved total nitrogen removal from the wetland influent.

5.5.3 Particulate Solids Removal

Table 5.13 showed the result statistics of the wetlands influent and effluent concentrations and loads, for wetlands fed with batch and intermittent mode. Statistical analyses on the data revealed no significant differences between the treatment performance in terms of TS and VSS removal for wetland B-PR1, B-PR2 and B-PR3. The highest TS reduction up to 83% was achieved in wetland B-PR3 with a mass removal rate of 468.4 g/m^2.batch. In terms of TSS removal, wetland B-PR3 yielded a mean reduction efficiency of 97.3% which was found to be statistically higher than wetland B-PR1 and B-PR2 (Table 5.13 and Figure 5.23). As described in the sections 5.5.1 and 5.5.2 previously, 1 day of rest period for wetland B-PR1 applied with influent volume of 21 L/batch was found to be inadequate for the septage deposit layer to dry up sufficiently. Standing water at the surface hindered oxygenation, creating an anoxic state that decreased removal performance of most of the parameters (such as BOD_5, NH_3-N and TN). With inadequate septage drying and mineralisation time, the porosity and consequently the hydraulic conductivity of the substrate are expected to be negatively affected. Controlling the ponding and resting periods is thus of great importance to ensure the durability and reliability of the system.

Table 5.13 Particulate solids indices concentration and mass statistics for the influent (pre-treated septage) and the resulting bed effluent of batch-fed and intermittently-fed units. Corresponding bed performances are reported in terms of pollutant removal efficiencies (%). Standard deviation for means given in parenthesis to indicate range. N indicates number of samples.

		Concentration (mg/L)		RE (%)*	Mass (g/m^2.batch) or (g/m^2.d)		Removal	
		IN	OUT		IN	OUT	(g/m^{2}batch) or (g/m^2.d) *	RE (%)*
Batch Mode; N=11	TS							
	B-PR1	6,415 (±1,044)	1,911 (±454.57)	69.06	561.30 (±91.34)	118.54 (±28.77)	442.77	77.98
	B-PR2	6,415 (±1,044)	2,104 (±465.77)	66.64	561.30 (±91.34)	120.99 (±36.52)	440.31	77.81
	B-PR3	6,415 (±1,04)	1,996 (±458.29)	67.87	561.30 (±91.34)	92.86 (±34.65)	468.44	82.95
	TSS							
	B-PR1	2,345 (±1,194)	136.73 (±109.98)	93.83	205.20 (±127.01)	8.74 (±7.63)	196.46	95.56
	B-PR2	2,345 (±1,194)	159.91 (±105.08)	92.49	205.20 (±127.01)	9.44 (±6.56)	195.76	95.11
	B-PR3	2,345 (±1,194)	111.64 (±91.62)	94.76	205.20 (±127.01)	4.65 (±3.22)	200.55	97.33
	VSS							
	B-PR1	1,208 (±736.85)	100.27 (±102.44)	91.76	118.59 (±74.71)	6.48 (±7.13)	112.12	93.97
	B-PR2	1,208 (±736.85)	97.45 (±81.71)	91.31	118.59 (±74.71)	5.81 (±5.26)	112.78	94.43
	B-PR3	1,208 (±736.85)	63.64 (±72.93)	94.89	118.59 (±74.71)	2.57 (±2.58)	116.02	97.48
Intermittent Mode; N=10	TS							
	B-MM (4x)	8,541 (±4,613)	2,372 (±457.14)	66.81	747.36 (±403.66)	172.81 (±32.65)	574.56	72.30
	TSS							
	B-MM (4x)	2,666 (±1,140)	91.90 (±51.87)	96.35	233.26 (±99.72)	6.72 (±3.71)	226.54	96.92
	VSS							
	B-MM (4x)	2,106 (±1,297)	44.80 (±27.84)	97.32	184.28 (±113.54)	3.25 (±2.00)	181.03	97.75

RE= Removal efficiency

* Values presented as the average REs or MRRs calculated from N samples of N experimental runs

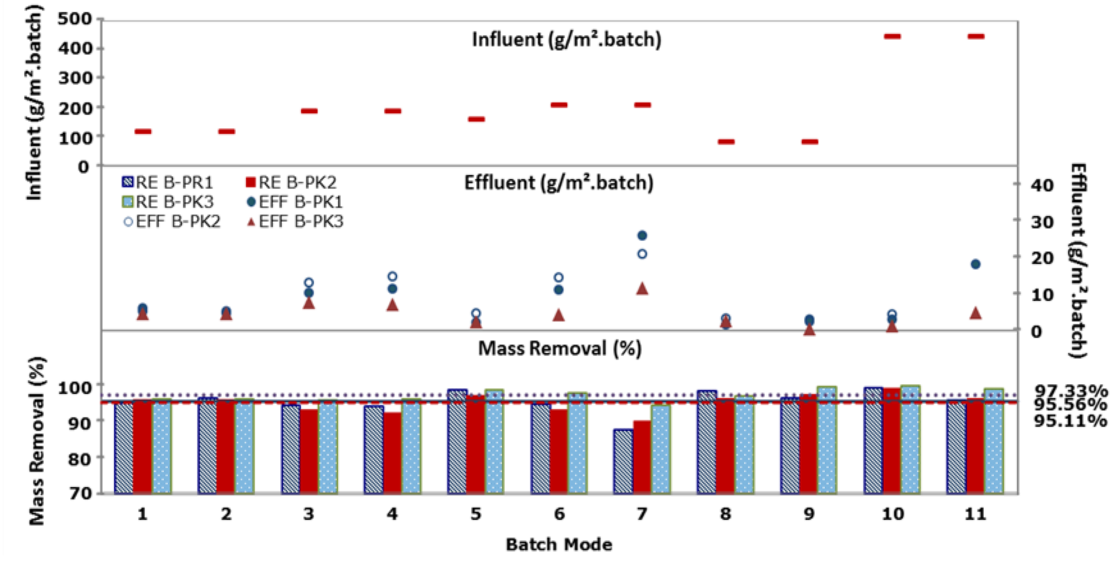


Figure 5.23 Weekly influent TSS areal loading rates and the resulting effluent loads for wetlands B-PR1, B-PR2 and B-PR3, with the percentages (%) of mass removal for each treatment (horizontal line indicates mean removal efficiencies for the wetland units)

5.6 Summary

The study has revealed that the choice of an appropriate feeding regime for the engineered treatment wetlands is essential. The wetlands operational strategy which includes the design of hydraulic loading rates (HLRs), daily dosing frequency and pond:rest period were all found to affect the treatment efficiency of the beds. The removal of organic matters (OM), ammonia nitrogen (NH_3-N) and particulate solids was found to be HLR dependent, where the results indicated that the increase of HLR from 8.75 to 17.5 cm/day impaired the overall treatment performance of the wetland units. Notably, a colour difference between the effluent of wetlands B-MM (medium HLR of 8.75 cm/d) and B-HH (high HLR of 17.5 cm/d) was observed during the study period. The effluent of wetland B-HH presented a significantly lower oxygen reduction potential (ORP) and dissolved oxygen (DO) values than wetland B-MM, indicative of the occurrence of less aerobic and reductive conditions in the bed. The mass removal efficiency of COD and BOD_5 dropped from 95.4% to 91.6% and 99% to 91.3%, respectively when the HLR was increased. An average of about 98.5% of NH_3-N mass was eliminated at wetland B-MM, while only 75.9% of the NH_3-N mass was removed from the influent when the hydraulic load was increased by 2 fold in wetland B-HH. A decrease of wetland B-HH outflow rates were observed, due to the occurrence of gradual bed clogging with the operational time at the high loading rates which subsequently decreased the rate of re-oxygenation of the substrate.

The reoxygenation capability of the wetland units was found to be heavily affected by the frequency of daily influent dosing, especially under high hydraulic load (17.5 cm/d). An average of 85.6% of NH_3-N mass was found to be removed at wetland fed less regularly (B-HH (4x)), and the reduction efficiency was 12.8% greater than that at the wetland loaded more frequently (B-HH (8x)). The effluent of wetland B-HH (4x) presented higher DO concentration than in the effluent collected from wetland B-HH (8x) (2.90 mg/L against 1.26 mg/L) under the same hydraulic load. The wetland fed more frequently resulted in effluent with significantly lower ORP values varying between -241 - 175 mV (against 18 - 288 mV in effluent of wetland B-HH (4x)), indicating a relatively more reduced state in the bed. Frequent influent flushing led to accumulation of biofilm in the upper layers of the wetland substrate and higher volume of water retention in the top layers of the beds, which subsequently reduced the oxygen diffusion into the wetlands. Besides, passive aeration due to intermittent feeding of the wetlands allow greater amount of oxygen to be drawn into the beds by convection, when a higher volume of influent was applied per feeding at wetland B-HH (4x).

In batch loaded wetlands, wetland B-PR1 (P:R=1:1) was observed to experience clogging issues due to insufficient bed resting period. Shrinkage cracks were observed to develop on the surface of the septage deposit layer before the subsequent feeding cycle at wetland B-PR3 (P:R=3:3). This suggested effective influent draining and deposit drying after the bed was left idle for 3 days. The extended resting time enhanced OM degradation and nitrification, with the dried septage layer encouraging oxygen diffusion into substrate biofilm, where the subsequent batch feeding promotes oxygen replenishment via convection. Wetland B-PR3 was found to outperform wetland B-PR1 in terms of the COD mass treatment efficiency by 6.1%. The removal of BOD_5 was high at wetland B-PR3 with 96% of reduction, which was significantly greater than the treatment at wetland B-PR1 with 92.2% of BOD_5 mass removed. An average NH_3-N mass removal efficiency of 91.1% was achieved in wetland B-PR3, and was 20.8% greater than the NH_3-N treatment performance at wetland B-PR1. For the wetland B-PR3, the DO profile was found to decay drastically after one day of ponding with less significant DO drop after 24 hours. The results suggested that the rapid biodegradation of OM and the transformation of NH_3-N happened mainly during the first day of ponding, where the rate of organic decomposition and nitrification slowed down after that.

Hybrid systems comprising of two or more types of engineered wetlands were used in several previous studies to achieve, in addition to OM removal, nitrification and denitrification for TN elimination. In our study with batch loaded wetlands filled with PKS substrate and operated at P:R=3:3, the elimination efficiency of TN concentration was as high as 86.3% on average, which is greater than those reported in the literature using hybrid wetland systems. The nitrogen elimination removal efficiency in the batch loaded wetland B-PR3 was also found to be 8.6% greater than the intermittently loaded bed B-MM (4x) with an average of 92.9% of mass removed at the batch fed wetland. Intermittent feeding regime was found to be effective in maintaining the system performance by supporting aerobic decompositions by obligate aerobes, but the hydraulic loading rates, the frequency of influent dosing per day and the volume applied per dose should be limited and customised to different climates and wetland designs, and the type of wastewater being treated for improved wetland treatment performance. For all the implemented feeding regimes, the pollutants mass removal rates were found to be accurately predicted by the incoming pollutants loading rates.

The vertical types of engineered wetlands are accumulative systems (retention of solids and pollutants on top and in the media profile) and it is of great importance to predict the hydraulic limits and manage the feeding strategies to guarantee the treatment performance and minimise the chances of filter clogging. For all modes of feeding, a sufficient period of resting was found to be important to restore aerobic conditions within the bed and to ensure sufficient treatment of the wastewater. The study has shown that the bed resting time is a more important factor than influent hydraulic retention time (contact time with the biofilm in the substrate).

Chapter 6 Results and Discussions: Second Stage of Treatment: Effects of System-related Parameters on Treatment Efficiencies

6.1 Overview

The system-related parameters examined at the second stage of the VFEWs treatment system in this study include plant presence, plant type and the substrate type. The influent of the second stage wetlands was the pre-treated septage effluent collected from the first stage wetlands. In this chapter, the research outcomes on the effects of plant presence and the use of a commercially valuable ornamental plant, *Costus woodsonii* as a substitute for conventional reeds (*Phragmites karka*) on the treatment of pre-treated septage are reported and discussed. The effects of the addition of palm kernel shells (PKS) as part of the wetlands substrate on the beds treatment performance at the second stage of the system were also evaluated. The conventional wetland aggregate-based substrate was compared side-by-side with the aggregates-PKS-based substrate to discuss on the effects of PKS inclusion as part of the treatment medium on the wetlands pollutants removal performance.

Many early studies reported greater pollutant removal in planted wetlands compared to the unplanted wetlands in terms of concentration (Dornelas, Machado and von Sperling 2009; Wang et al. 2001; Zhang et al. 2012), but most did not measure the outflow volumes and calculate the reduction efficiencies in terms of the pollutant mass elimination by taking into account the hydrological mass balance of the system. Evapotranspiration (ET) by plants can differ depending on species and plant biomass, and can significantly affect the hydrological balance of the wetlands ecosystem. It is therefore important to do the comparative assessments on the treatment performance between different wetlands on the basis of mass removal efficiencies, to take into account for the waster loss via ET from the system. The following sections presented the results and discussions of the wetlands performance in terms of both concentration-based and mass-based reduction efficiencies.

6.2 Operating Conditions

Each experimental run in the second stage wetlands designed to study the working hypotheses lasted for twelve weeks, including 2 weeks of stabilization period and 10 weeks of experimental period with data collection to analyse the wetland performance. Table 6.1 describes the parametric studies and operational conditions adopted in each of the experimental run. To evaluate the performance of the wetlands, influent and effluent samples were collected once a week and analysed for organic matter, nitrogen and particulate solids compounds, besides monitoring their pH, DO, EC, ORP and temperature changes. Irrigations in the second stage wetlands were carried out either in batches or by intermittent loading mode.

Table 6.1 Parametric studies to examine the effects of plant presence, plant type and the inclusion of PKS on the organic matter, nitrogenous compounds and particulate solids treatment of pre-treated septage at the second stage wetlands

Parameter	Plant			Substrate		Feeding Mode		Wetland Denotation
	Nil	*Phragmites karka*	*Costus woodsonii*	PKS-based	SD-based	Int.*	Batch**	
Plant Presence	✓			✓		4x		B-UP
		✓		✓		4x		B-P
Plant Type		✓		✓		8x		B-*Phrag*
			✓	✓		8x		B-*Costus*
Substrate Type		✓		✓			3:3	B-PKS (I)
		✓			✓		3:3	B-SD (I)
		✓		✓		4x		B-PKS (II)
		✓			✓	4x		B-SD (II)

All beds were operated for 12 weeks, inclusive of 2 weeks of acclimatization period

*All intermittently-fed (int.) wetlands were loaded at a hydraulic loading rate (HLR) of 8.75 cm/d at 4 or 8 times daily. Beds were loaded with pre-treated septage daily by fractions and the effluent was allowed to drain freely.

**All batch-fed wetlands were loaded with 21L/batch with pond:rest (days:days) period of 3:3

Loading in batch mode involves cyclic loading of feed-pond-drain-rest, i.e. loading of a designated volume of influent in one go and retaining it inside the wetland for a time period, before releasing it completely after, and leaving the bed idle for a specific time frame. In this study, each cycle of the batch operation included rapid influent feeding followed by 3 days of ponding, and 3 days of bed resting following complete effluent release. The intermittent loading mode was implemented by fractioning the daily hydraulic load into smaller doses and applying them onto the wetland in portions at a certain time interval in correspondence with the studied dosing frequencies (as described in Table 6.1). This feeding mode did not involve effluent ponding and the wetland was not drained completely before a fresh batch of influent was added into the system. It was expected that the oxidative condition of the substrate could be improved during the drying period between each dose of intermittent operation, and during the drained (rest) period of the batch operation.

All the effluent samples were collected and tested in the laboratory as per the methods and procedures stated in section 3.6.1.2. The volume of effluent collected from each bed was measured and recorded to account for the water loss from the system. Overall removal for each constituent was calculated based on its concentration and mass at the inlet and outlet of the treatment system. Relative removal at each stage of the system was calculated based on concentration and mass of the pollutants at the inlet of the facility and the outlet of the particular stage. The wetland substrate thickness, sizing and arrangement were as described previously in section 3.5.

6.3 Effects of Plant Presence

A unit of planted and unplanted wetlands (B-P and B-UP, respectively) were placed at the second stage of the system to study their treatment performance on the pre-treated septage collected from the first stage wetlands. Weekly measurements on the influent volume and the variations of the effluent volume between the planted and unplanted bed had revealed significant differences between the quantities of the outflow collected from the two units. Under the same hydraulic loading rate (HLR) and mode of feeding, the unplanted bed was found to have a significantly lesser amount of volume loss from the effluent due to the absence of plants. In addition, the unplanted unit had higher substrate porosity and hydraulic conductivity, due to the absence of root system that occupied the interstitial pore spaces between the aggregates. A greater drained effluent volume was thus observed with the B-UP bed compared to the B-P unit. Table 6.2 presents the data for the insitu testings on the influent and effluent of both wetlands, at the second stage of the treatment system.

Table 6.2 Physico-chemical parameters statistics for the pre-treated septage (influent), and effluent from wetlands B-P (planted) and B-UP (unplanted). N is the number of samples collected and analysed for each parameter during the study period.

Parameter	Sampling Point	Statistics			
		N	Range	Mean	Std Dev.
Temperature (℃)	Influent	10	25.10 - 29.50	27.08	1.31
	Planted (B-P)	10	24.50 - 31.50	27.65	2.13
	Unplanted (B-UP)	10	24.60 - 31.80	27.49	2.18
pH	Influent	10	7.12 - 8.05	7.50	0.26
	Planted (B-P)	10	6.77 - 7.09	6.90	0.11
	Unplanted (B-UP)	10	6.87 - 7.16	7.02	0.10
DO (mg/L)	Influent	10	0.50 - 2.54	1.32	0.68
	Planted (B-P)	10	3.65 - 7.59	4.86	1.20
	Unplanted (B-UP)	10	0.86 - 5.00	1.86	1.20
ORP (mV)	Influent	10	-262 - 215		
	Planted (B-P)	10	118 - 403		
	Unplanted (B-UP)	10	-162 - 225		
EC (mS/cm)	Influent	10	1.70 - 2.17	1.94	0.16
	Planted (B-P)	10	1.98 - 2.50	2.13	0.16
	Unplanted (B-UP)	10	1.56 - 2.06	1.94	0.15

The pre-treated septage was slightly alkaline with pH values falling in the range between 7.12 - 8.05. Generally, the pH of the effluent after treatment from both wetlands B-P and B-UP were lower than the pH of the pre-treated septage influent. Similar to the results recorded for the first stage wetlands, the pH in the effluent was found to be affected by plant presence. pH was generally lower with plant presence with values ranging between 6.77 - 7.09. According to Dakora and Phillips (2002), lower pH in the planted unit could be due to the release of root exudates that serves as a source of carbon (C) substrate for microbial growth and promotes chemotaxis of microbes to the rhizosphere. Besides, degradation of organic compounds by aerobic organisms could also lead to the pH reduction in the effluent as reported by Kyambadde et al. (2004). Apart from that, nitrification occurring in the wetland beds lowers the pH of the effluent with the process consuming alkalinity (Bezbaruah and Zhang 2004) as it is a carbon source for nitrifiers growth.

The pre-treated septage had a mean dissolved oxygen (DO) concentration of 1.32 mg/L with oxygen reduction potential (ORP) varying between -262 - 215mV. Both the B-P and B-UP wetlands produced effluent with higher DO concentrations and ORP readings than the beds influent. This indicates improved water quality after treatment in the wetlands regardless of plant presence under the applied hydraulic loading. The DO and ORP were relatively higher in the effluent of wetland B-P, indicative of a more oxygenated effluent than its unplanted wetland counterpart. The unplanted wetland B-UP had a more reduced condition and produced effluent with lower DO and ORP.

Such improvement of the effluent quality in the planted wetland was similar to the study outcomes reported in Chapter 4, section 4.4 for planted and unplanted wetlands at the first stage of the pilot system. Kickuth proposed the “roots theory” in 1977 which lays the foundations for the study of oxygen production and transportation processes in wetland plants (Calhound and King 1997). Plants were said to be able to contribute to the oxygen supplementation of wetland beds (Armstrong et al. 2000). This phenomenon creates an aerobic micro-environment, which in turn supports the decomposition efficacy of root microorganisms and enhances aerobic pollutant treatment.

6.3.1 Organic Matter Removal

Pre-treated septage used in the beds ranged between 1,692 - 8,734 mg COD/L and 163 - 473 mg BOD/L (Table 6.3). COD reductions occurred in both planted (B-P) and unplanted (B-UP) beds and the removal efficiency of the two wetlands appeared to be more or less similar. The mean relative removal efficiency of wetland B-P yielded 93.7% for COD and 96.9% for BOD_5, and these values were slightly higher than the unplanted beds by 1.7% and 0.82%, respectively. Wetland B-P produced effluent with a mean of 199 mg COD/L and 7.9 mg BOD/L, and this brought the overall system removal (two stages) of COD and BOD_5 removal to 99.38% and 99.76% respectively. With the hydraulic loading rate (HLR) of 8.75 cm/d, the mean areal OM loading was around 0.43 kg COD/m^2.d and 0.022 kg BOD/m^2.d in both beds (Table 6.3). As shown in Table 6.3, the mean mass removal efficiency of the planted bed was high at 94.6% and 97.5% for COD and BOD_5, respectively. The outflow of the B-P bed was significantly improved with the quality of effluent achieving a mean of 3.5 g/d and 0.13 g/d of COD and BOD_5, respectively.

Table 6.3 Organic matter concentration and mass statistics for the influent (pre-treated septage) and the resulting bed effluent of planted (B-P) and unplanted (B-UP) units

Parameter			Range	Mean (±SD)	MRR*	RE (%)*
COD	Concentration (mg/L)	Influent	1,692 - 8,734	4,860 (±2,693)		
		Planted (B-P)	120.00 - 370.00	199.00 (±69.51)		93.71
		Unplanted (B-UP)	70.00 - 445.00	227.50 (±126.39)		92.18
	Mass ($g/m^2.d$)	Influent	148.05 - 764.23	425.25 (±235.64)		
		Planted (B-P)	7.78 - 26.90	14.58 (±5.21)	410.67	94.64
		Unplanted (B-UP)	4.92 - 35.28	17.49 (±10.20)	407.76	93.03
BOD_5	Concentration (mg/L)	Influent	163.80 - 473.40	247.31 (±84.65)		
		Planted (B-P)	0.96 - 17.40	7.89 (±5.64)		96.87
		Unplanted (B-UP)	0.30 - 17.58	8.68 (±6.05)		96.11
	Mass ($g/m^2.d$)	Influent	14.33 - 41.42	21.64 (±7.41)		
		Planted (B-P)	0.08 - 1.19	0.56 (±0.39)	21.08	97.47
		Unplanted (B-UP)	0.02 - 1.41	0.67 (±0.47)	20.97	96.60

Number of samples, N =10
MRR= Mass removal rate
RE= Removal efficiency
* Values presented as the average REs or MRRs calculated from N samples of N experimental runs

Figure 6.1 shows the variation in influent loading rates (ILRs) and their resulting effluent mass with the corresponding removal efficiencies at wetlands B-P and B-UP. In order to compare the performance between the B-P and B-UP units, statistical analysis on the OM removal percentages of the two beds was carried out by ANOVA. The variances of the two data sets were analysed and compared, revealing P values of more than 0.05 ($P>0.05$) for both the OM indices, indicating that the difference in performance for the OM removal between the two units was not significant. Wetland B-UP with the absence of plants did not significantly underperform the planted one although the effluent collected from the bed was found with marginally higher amount of organic mass. The minimal improvement of OM removal in the planted bed was not found to be statistically important, thus suggesting that plants played a minor role in organic carbon retention at this second stage of treatment.

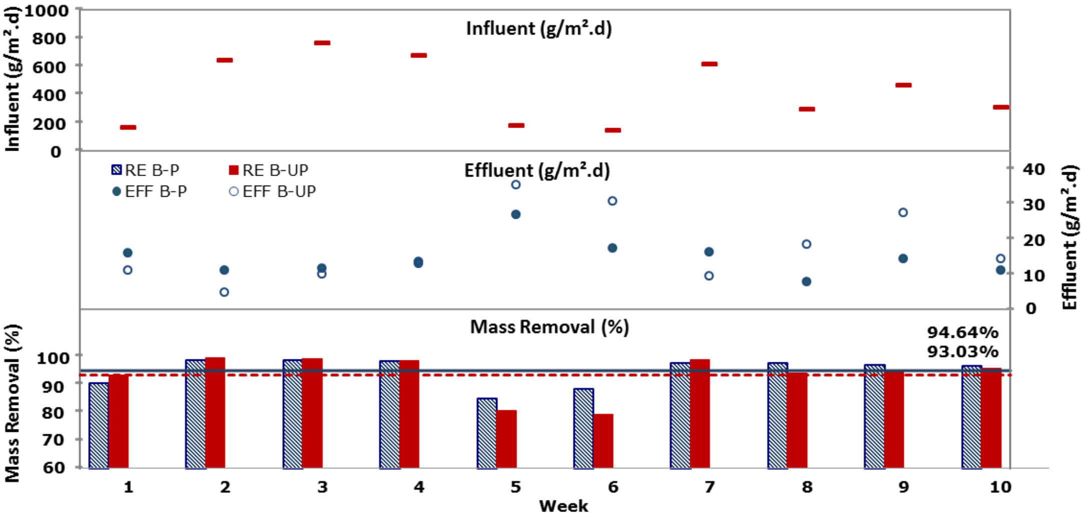


Figure 6.1 Influent COD areal loading rates and the resulting effluent loads for planted and unplanted bed, with the percentages (%) of mass removal for each treatment (horizontal solid line indicates mean removal efficiencies for planted unit; dashed line indicates mean removal efficiencies for unplanted unit)

Similar findings were reported by other researchers such that the presence of emergent plants only marginally improved the removal of OM. Fan et al. (2012) reported that Burgoon, Reddy, and DeBusk (1989) found only slightly higher removal of BOD_5 in planted beds (between 85% and 93%) compared to the unplanted units which had removal efficiency of 88%. It is commonly known that settleable organics are rapidly removed under quiescent conditions by deposition and filtration in wetland systems. Although it is generally assumed that planted wetlands can provide greater removal efficiency than the unplanted units (Tanner, 2001; Gagnon et al., 2006), the passive aeration effect of intermittent loading regime applied on the wetlands was also suggested to be very efficient in promoting micro-aerobic environment in the wetland substrate, which directly aided the high removal of COD and BOD_5 in beds, with or without presence of plants. Besides, the pre-treated septage used in this study was capable of supplying sufficient OM for the microbial degradation, and thus encouraging high removal efficiency in both units.

Figure 6.2 shows the relationship between COD influent loading rates (ILRs) and the corresponding mass removal rates (MRRs). The removal rates increased as the ILRs increased, with a maximum MRR value of 0.75 kg COD/m^2.d with the ILR of 0.76 kg COD/m^2.d. Good correlation was found between the ILRs and MRRs for both the

B-P and B-UP units. The graph revealed a high predictability of the beds treatment efficiency concerning the mass removal of the OM, with Pearson's $r^2>0.99$ which marked the strong correlation between the OM ILRs and the MRRs. The scatter plot and the regression trend for BOD_5 were similar to the ones of COD in Figure 6.2 (Appendix E). The regression trendlines for wetland B-P and B-UP were very close with one another, and both plots showed near complete removal of the COD with the increasing incoming mass.

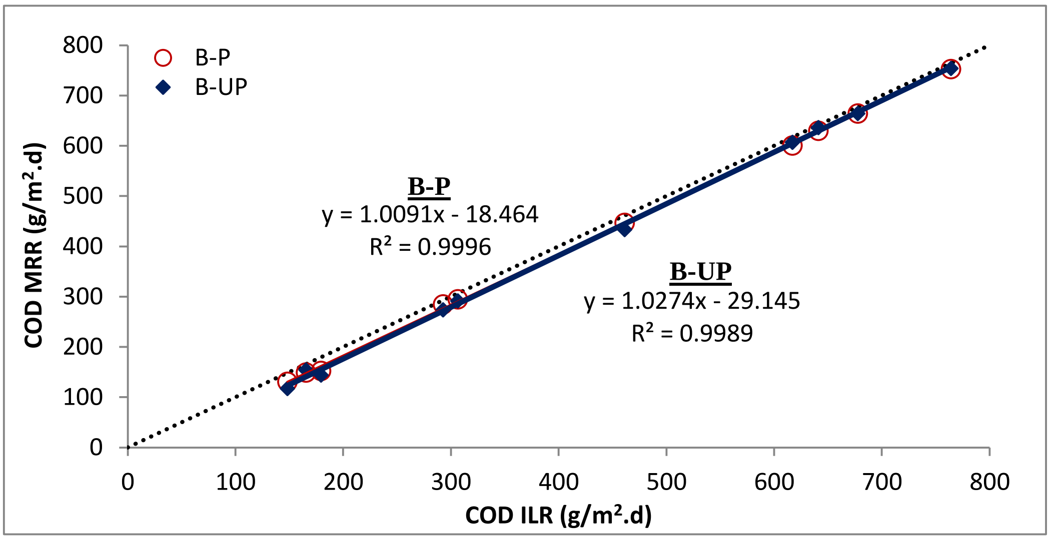


Figure 6.2 Regression graph of COD mass removal rate (MRR) against influent loading rate (ILR) (g/m ²d) for planted (B-P) and unplanted (B-UP) units. The dotted line represents complete removal.

6.3.2 Nitrogen Removal

Table 6.4 summarises the concentration statistics of various nitrogen (N) components and the removal efficiencies at the planted (B-P) and unplanted (B-UP) wetlands. The results showed that plants played an essential role in the removal of pollutants from the influent especially for ammonia nitrogen (NH_3-N). Figure 6.3 depicts the influent areal loading rates, and their corresponding effluent mass and mass removal efficiencies for NH_3-N at the planted and unplanted beds. The presence of plants was found to reduce ammoniacal N to a significantly lower level than the unplanted treatment. The study revealed that the planted wetland B-P had the ability to remove up to an average of 96.6% of ammonia and reduce its concentration from 127.96 ± 40.66 mg/L in the influent to 3.40 ± 9.70 mg/L in the effluent. The unplanted bed B-

UP was found to perform less effectively than the planted B-P bed with the NH_3-N concentration removal efficiency at only 75% (Table 6.4). A similar finding was illustrated in terms of the NH_3-N mean mass removed by 97.1% at wetland B-P, where the bed performance was observed to be constantly greater than its unplanted counterpart by an average of 24.1% during the study period Figure 6.3.

Table 6.4 Nitrogen concentration and mass statistics for the influent (pre-treated septage) and the resulting bed effluent of planted (B-P) and unplanted (B-UP) units

Parameter			Range	Mean (±SD)	MRR*	RE (%)*
NH_3-N	Concentration (mg/L)	Influent	68.34 - 197.96	127.96 (±40.66)		
		Planted (B-P)	0.00 - 9.70	3.40 (±3.65)		96.59
		Unplanted (B-UP)	3.60 - 57.30	30.08 (±21.17)		75.08
	Mass (g/m^2.d)	Influent	5.98 - 17.32	11.20 (±3.56)		
		Planted (B-P)	0.00 - 0.74	0.25 (±0.27)	10.95	97.11
		Unplanted (B-UP)	0.27 - 4.37	2.29 (±1.59)	8.91	78.27
TKN	Concentration (mg/L)	Influent	163.43 - 586.52	274.68 (±120.10)		
		Planted (B-P)	76.58 - 98.05	22.69 (±15.96)		91.03
		Unplanted (B-UP)	20.95 - 91.00	53.69 (±24.67)		77.79
	Mass (g/m^2.d)	Influent	0.00 - 0.00	24.03 (±10.51)		
		Planted (B-P)	0.28 - 3.28	1.64 (±1.15)	22.39	92.56
		Unplanted (B-UP)	1.60 - 6.84	4.06 (±1.80)	19.97	80.78
NO_3-N	Concentration (mg/L)	Influent	1.10 - 69.30	33.78 (±28.92)		
		Planted (B-P)	4.20 - 71.20	21.87 (±21.45)		
		Unplanted (B-UP)	0.00 - 4.20	1.84 (±1.57)		
	Mass (g/m^2.d)	Influent	0.10 - 6.06	2.96 (±2.53)		
		Planted (B-P)	0.29 - 6.11	1.65 (±1.80)		
		Unplanted (B-UP)	0.00 - 0.34	0.14 (±0.12)		
TN	Concentration (mg/L)	Influent	165.00 - 628.00	309.17 (±128.00)		
		Planted (B-P)	13.00 - 79.00	44.70 (±22.49)		83.10
		Unplanted (B-UP)	22.00 - 95.00	55.60 (±24.86)		78.98
	Mass (g/m^2.d)	Influent	14.44 - 54.95	27.05 (±11.20)		
		Planted (B-P)	0.97 - 6.70	3.30 (±1.77)	23.75	85.51
		Unplanted (B-UP)	1.68 - 7.17	4.21 (±1.82)	22.84	81.78

Number of samples, N =10
MRR= Mass removal rate
RE= removal efficiency

* Values presented as the average REs or MRRs calculated from N samples of N experimental runs

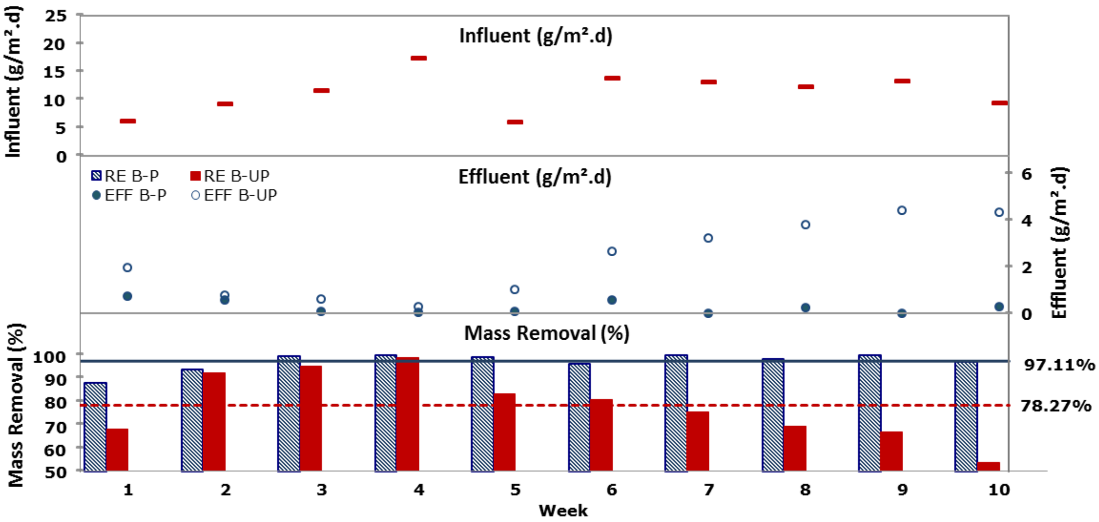


Figure 6.3 Influent NH_3-N areal loading rates and the resulting effluent loads for planted and unplanted bed, with the percentages (%) of mass removal for each treatment (horizontal solid line indicates mean removal efficiencies for planted unit; dashed line indicates mean removal efficiencies for unplanted unit)

As shown in Figure 6.4, a linear relationship is suggested by the relatively high regression coefficients and the r^2 values obtained. The correlation between the NH_3-N ILRs and their MRRs was apparently stronger with the planted unit than the unplanted one. The relationship between the ILRs and MRRs in wetland B-P has an r^2 of more than 0.99, indicating an excellent correlation. The close fit of the points to the regression trendlines implies a remarkably constant areal removal rate for NH_3-N at the planted bed. Poorer correlation observed for the unplanted bed (r^2 = 0.83) revealed relatively less consistent NH_3-N removal rates as affected by its corresponding incoming loads, while the general linearity of the relationship was preserved.

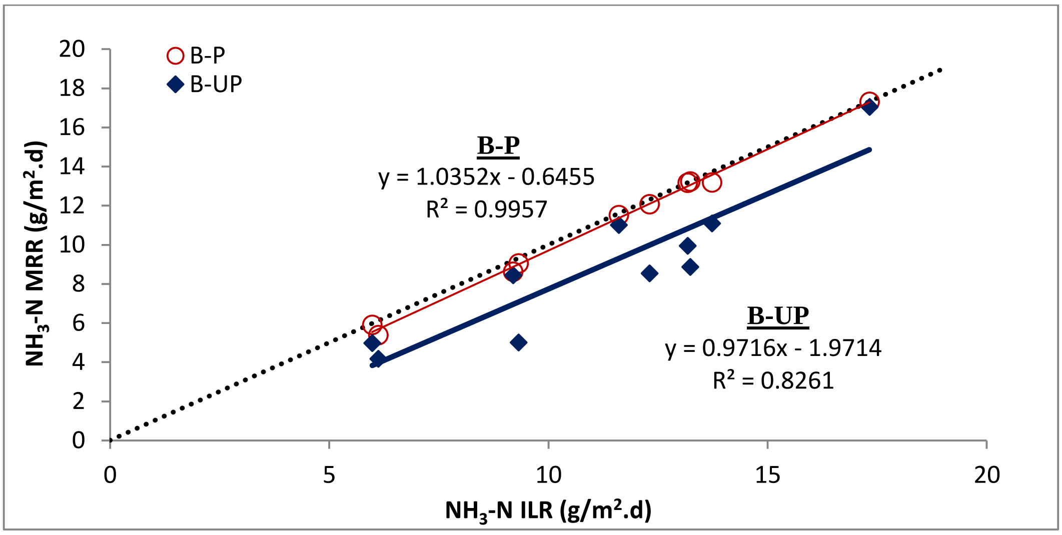


Figure 6.4 Regression graph of NH_3-N mass removal rate (MRR) against influent loading rate (ILR) (g/m ²d) for planted and unplanted units. The dotted line represents complete removal.

It has been recognized that plants are capable of transporting oxygen into the system through its extensive roots network to oxygenise the substrate, which subsequently help to create a more aerobic environment in the wetland for decomposition of organic matter. This assumption can be verified by comparing the DO concentrations and the ORP status of the wetland outflow between the planted and unplanted beds (Table 6.2). Statistical analysis on the data collected showed that the DO concentrations recovered from the effluent of wetland B-P which ranged between 3.65 - 7.59 mg/L, were significantly higher than in the effluent collected from the unplanted unit ($P<0.001$). This has indicated a fairly aerobic condition in wetland B-P. This feature was also reflected in the conserved positive ORP values recorded in the bed effluent throughout the 10 weeks of study period (Table 6.2). Such an array of ORP values signify aerated conditions within the wetland substrate which stimulates bacterial activities and accelerates nutrient breakdown.

Plants play an important role in engineered wetlands according to Brix (1997), as they encourage the assimilation and breakdown of nutrients within a wetland system. They have the ability not only to bind high amounts of nutrients within their system, but also to create an environment conducive to decreasing nutrients (Brix 1997). Plant roots system functions as site for microbial attachment and colonization. Microorganisms mediate many wetland processes and are mainly responsible for the transformation and mineralisation of degradable organic pollutants within wetlands (Sleytr et al. 2009).

Figure 6.5 depicts the influent areal loading rates, and their corresponding effluent mass and mass removal efficiencies for total Kjeldahl nitrogen (TKN) at wetlands B-P and B-UP. Mass differences in the reduced nitrogen (i.e. TKN) elimination between the effluent recovered from the operating planted and unplanted beds varied (between 0.22 - 1.5 g) and the reduction efficiency between the wetlands was found to be significantly different. Mean TKN MRR at the planted bed was found to be greater than the unplanted bed by an average of 12.1% (Table 6.4). The plant roots exudates as well as the decomposition of *Phragmites* in the planted wetland are potential sources of organic nitrogen besides organic carbon. The organic nitrogen can be easily converted into ammonia in aerobic conditions, therefore the presences of plants in wetland B-P could also possibly increased the ammonia content for nitrification.

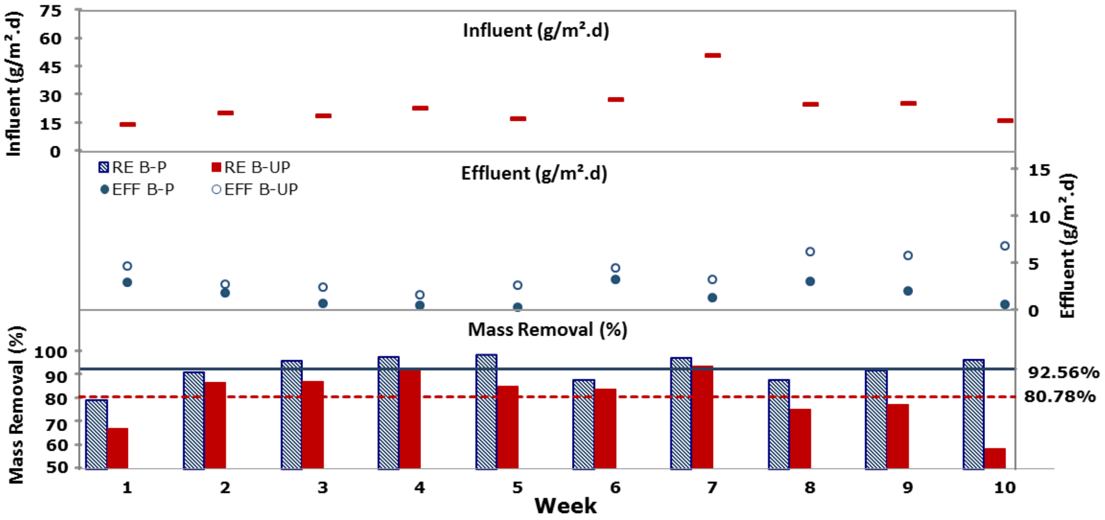


Figure 6.5 Influent TKN areal loading rates and the resulting effluent loads for planted and unplanted bed, with the percentages (%) of mass removal for each treatment (horizontal solid line indicates mean removal efficiencies for planted unit; dashed line indicates mean removal efficiencies for unplanted unit)

Good correlation was found for both beds, with the unplanted unit achieving slightly weaker strength of relationship (r^2 = 0.97 for unplanted unit against r^2 = 0.99 for planted bed). The r^2 and the linearity of regression plot of NH_3-N MRR against ILR of the wetlands in the system were generally greater than those reported by

Domingos S.S. (2011) with r^2 = 0.96 and coefficient of regression of 0.61 for treatment of inorganic industrial wastewater using laboratory-scaled vertical flow engineered wetlands planted with River Club Rush, *Schoenoplectus validus*. This indicates that the wetlands in this current study had shown relatively higher consistency and predictability than the wetlands studied by Domingos (2011) in terms of the ammonia nitrogen removal performance.

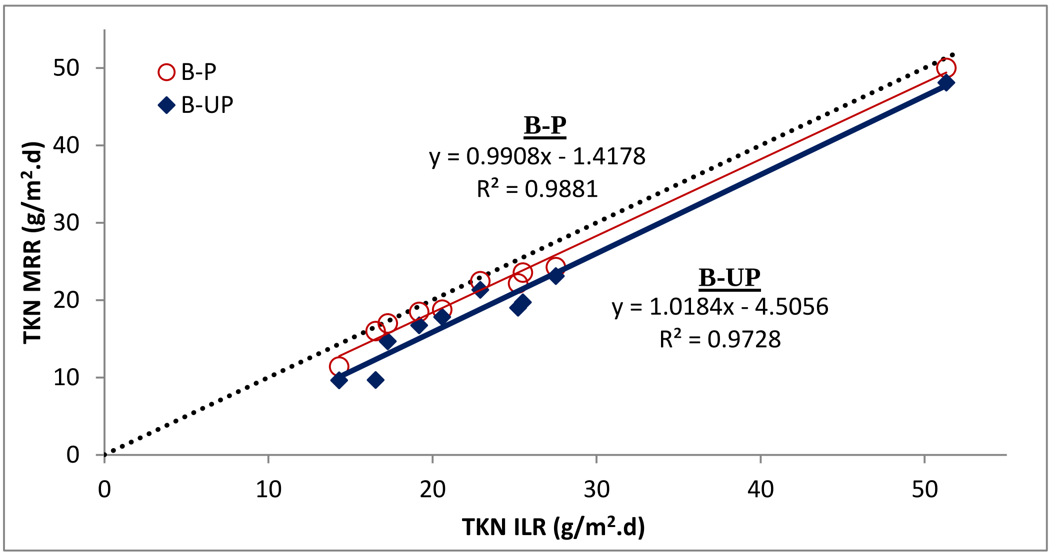


Figure 6.6 Regression graph of TKN mass removal rate (MRR) against influent loading rate (ILR) (g/m ²d) for planted and unplanted units. The dotted line represents complete removal.

Comparisons of total nitrogen (TN) removal performance between the planted B-P and unplanted B-UP systems are also shown in Table 6.4. With respect to mass removal efficiency, it was found that the planted wetlands did not show a clear improvement in the TN removal, with no statistical difference found between the TN reduction percentage at wetlands B-P and B-UP. The marginally lower TN removal rates in the unplanted unit obtained from this study is in agreement with the findings by several other researchers that reported only slightly lower N removal in the unplanted wetland system compared with the planted treatment system (Lin et al. 2002; Yang, Chang and Huang 2001).

Approximately 76 - 99.4% of the TN in the pre-treated septage was found to be in TKN form and 0.6 - 24% in NO_x form (Appendix D1). After treatment in the wetlands at HLR 8.75 cm/d using planted beds, the fraction of TKN in the effluent decreased to an average of 53.9% and the fraction of NO_x increased to a mean of 46% (Table 6.4). Effluent from wetland B-UP recorded a significantly lower mass content of nitrate (by 12-folds), and a greater content of NH_3-N (by 9-folds) than wetland B-P. These differences in the nitrogen fractions between the wetlands reflect the changes in biologic populations and microorganism diversity that stimulate nutrient transformation in the presence of plants.

The high TN mass removal efficiency up to a mean of 85.5% in wetland B-P and 81.8% in wetland B-UP indicated that both anaerobic and anoxic conditions can coexist at microscale in the wetland beds, in which nitrification and denitrification processes can take place. It has thus suggested that simultaneous reduction of nitrate and nitrite through denitrification occurred in all the beds. Figure 6.7 shows the nitrate (NO_3-N) mass of the wetlands influent and effluent at the planted and unplanted beds. NO_3-N accumulation in the effluent of the planted B-P bed was observed, where the NO_3-N concentrations (21.9 mg NO_3-N/L) were found to be statistically higher than in the effluent of the unplanted B-UP unit (1.84 mg NO_3-N/L) (Table 6.4 and Figure 6.7). The subsequent conversion of the oxidised nitrogen form (NO_3-N) to nitrogen gas is carried out by denitrifying bacteria (heterotrophs) under anoxic conditions to remove N from the system.

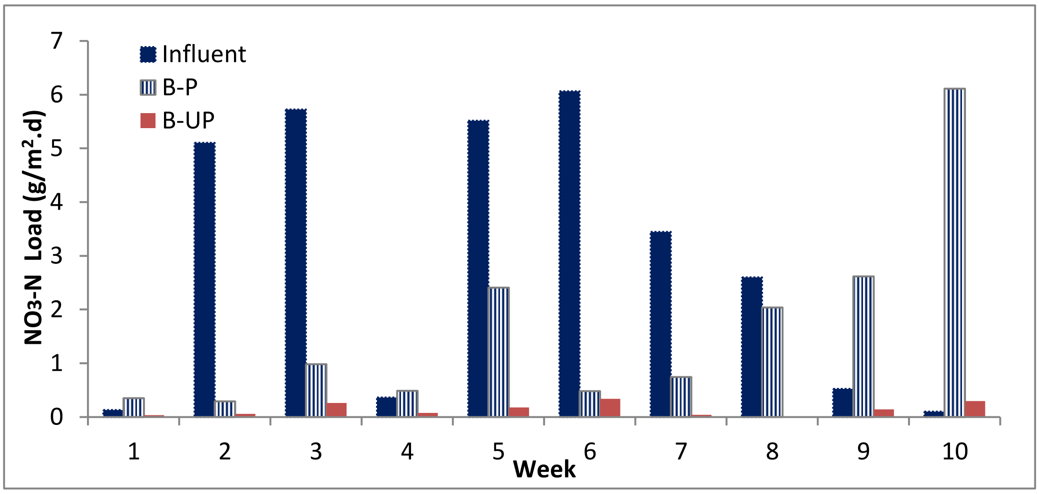


Figure 6.7 Influent and effluent NO_3-N loads at planted (B-P) and unplanted (B-UP) beds

Nitrification and denitrification are important microbiologically mediated treatment processes in nitrogen transformation affected directly by the level of oxygen availability. Nitrification can occur in the aerobic zones of the wetland, i.e., area around the plant roots zone, while denitrification takes place simultaneously in the anoxic zones of the wetland. It is believed that in engineered wetlands, microsites with steep oxygen gradients can be established with radial oxygen loss from the roots, which allow nitrification and denitrification to occur in sequence in very close proximity to each other (Lee, Fletcher and Sun 2009; Reddy, Patrick Jr. and Lindau 1989). Conversion of ammonia into nitrite and nitrate through nitrifications consume alkalinity and this contributed to the pH decrease in both beds after treatment (Table 6.2).

6.3.3 Particulate Solids Removal

Table 6.5 summarises the particulate solids concentrations and mass statistics of the wetlands influent (pre-treated septage) and effluent. TSS concentrations of the pre-treated septage ranged between 1,500 - 5,560 mg/L with high variations, explaining the high heterogeneity characteristic of the influent. Both the planted B-P and unplanted B-UP beds were loaded at HLR of 8.75 cm/d, with areal TSS mass loading varying between 136.5 - 486.5 g/m^2.d. The second stage of treatment provided excellent removal of TSS, with up to an average of 96.9% of mass removal efficiency in the planted unit (Table 6.5 and Figure 6.8). The quality of the septage was significantly improved after two stages of treatment, achieving final TSS concentration of 91.9 mg/L with mean overall reduction of 99.6% at the exit of the planted B-P unit. The unplanted B-UP bed produced effluent with considerably higher mean concentration and mass of TSS at 154.5 mg/L and 3 g/d respectively, which is 1.7 and 1.8 times greater than found in the effluent of the planted unit. The difference in the TSS elimination efficiency between the two beds was found to be statistically significant.

Table 6.5 Particulate solids concentration and mass statistics for the influent (pre-treated septage) and the resulting bed effluent of planted (B-P) and unplanted (B-UP) units

Parameter			Range	Mean (±SD)	MRR*	RE (%)*
TS	Concentration (mg/L)	Influent	4,308 - 18,800	8,541 (±4,613)		
		Planted (B-P)	1,612 - 2,996	2,372 (±457.14)		66.81
		Unplanted (B-UP)	1,640 – 3,348	2,358 (±589.36)		66.93
	Mass (g/m^2.d)	Influent	377 - 1,645	747.36 (±403.66)		
		Planted (B-P)	122.91 - 217.85	172.81 (±32.65)	574.56	72.30
		Unplanted (B-UP)	125.21 - 237.45	178.70 (±42.84)	568.66	71.47
TSS	Concentration (mg/L)	Influent	1,560 - 5,560	2,666 (±1,140)		
		Planted (B-P)	10.00 - 156.00	91.90 (±51.87)		96.35
		Unplanted (B-UP)	12.00 - 235.00	154.50 (±70.70)		93.24
	Mass (g/m^2.d)	Influent	136.50 - 486.50	233.26 (±99.72)		
		Planted (B-P)	0.65 - 10.92	6.72 (±3.71)	226.54	96.92
		Unplanted (B-UP)	0.86 - 17.44	11.80 (±5.39)	221.46	94.08
VSS	Concentration (mg/L)	Influent	955 - 5,372	2,106 (±1,298)		
		Planted (B-P)	6.00 - 84.00	44.80 (±27.84)		97.32
		Unplanted (B-UP)	-92.00 - 90.00	40.60 (±56.17)		97.31
	Mass (g/m^2.d)	Influent	83.56 - 470.05	184.28 (±113.54)		
		Planted (B-P)	0.39 - 5.76	3.25 (±2.00)	181.03	97.75
		Unplanted (B-UP)	-7.33 - 7.13	3.09 (±4.41)	181.19	97.63

Number of samples, N=10
MRR= Mass removal rate
RE= removal efficiency
* Values presented as the average REs or MRRs calculated from N samples of N experimental runs

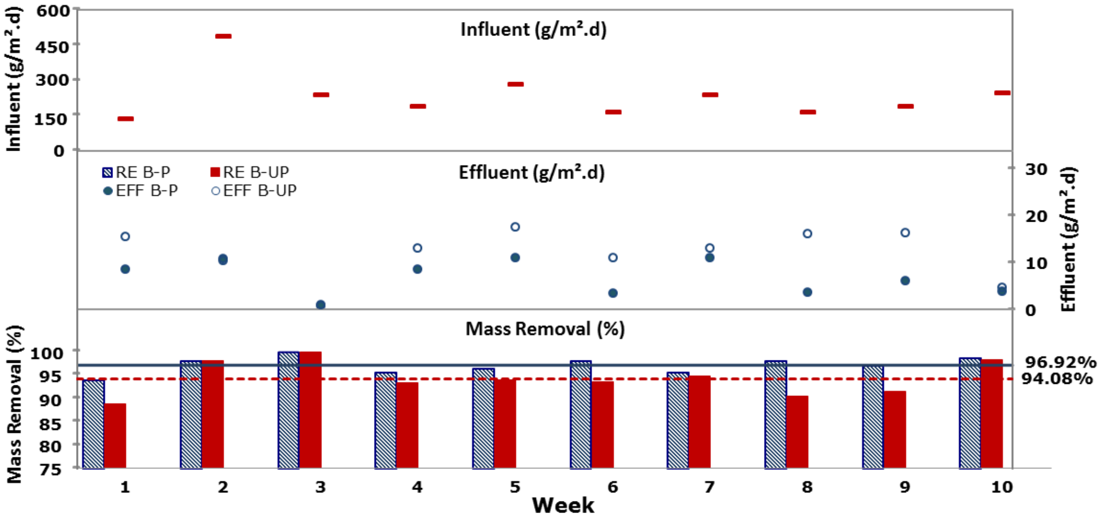


Figure 6.8 Influent TSS areal loading rates and the resulting effluent loads for planted and unplanted bed, with the percentages (%) of mass removal for each treatment (horizontal solid line indicates mean removal efficiencies for planted unit; dashed line indicate mean removal efficiencies for planted unit; dashed line indicates mean removal efficiencies for unplanted unit)

Comparisons of TSS removal between planted and unplanted wetlands showed obvious monotonic relationship between TSS mass loading and mass removal rates (Figure 6.9). The removals of TS and VSS display similar trend with the TSS regression plot, with a linear relationship and good correlation (r^2>0.99) between the ILRs and MRRs (Appendix E). ANOVA showed that the relationship between the loading and the removal rates are statistically important (P<0.001) for all the three parameters examined (TS, TSS and VSS). The good correlation observed indicates satisfactory response of the particulate solids MRRs to changes in incoming solid loads at both beds.

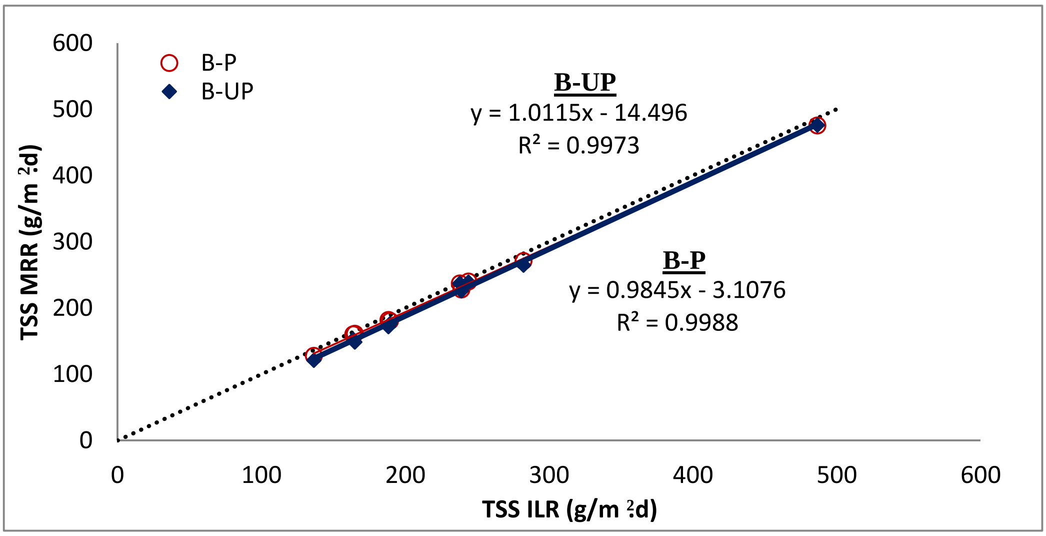


Figure 6.9 Regression graph of TSS mass removal rate (MRR) against influent loading rate (ILR) (g/m ²d) for planted and unplanted units. The dotted line represents complete removal

The TS and VSS influent concentrations fluctuated between 4,300 -18,800 mg/L and 955 - 5,372 mg/L, respectively with an overall average of 8,540 mg/L and 2,100 mg/L respectively (Table 6.5). The final effluent TS and VSS mass loads for the planted unit were found to range between 29.5 - 52.3 g/d and 0.09 - 1.4 g/d, with the mean removal of 72.3% and 97.8%, respectively (Table 6.5). The comparisons between the performance of the planted and unplanted beds revealed that the plant presence was not significantly important in improving the TS and VSS removal efficiencies. TS in general is the removal of both suspended and dissolved solids from the influent and often appears to be the parameter with the lowest removal efficiencies. This is likely due to the high total dissolved solids (TDS) content in the effluent as a result of accumulation of mobile ions produced during influent treatment (such as mineral nitrate, NO_3-).

The greater solids removal performance at the planted B-P unit was due to the better filtration capability provided by the developed plant roots. As described in section 4.4.1 previously, the plant roots network together with substrate were likely to provide a more effective settling medium than at the beds with absence of plants. Most of the solids were deposited on the surface of the beds and trapped at the vicinity of the plant roots network, with relatively lesser downward migration. It was reported by Nguyen (2001) that a higher content of refractory organic solids was found in the surface deposit and the top 100 mm of the gravel bed planted with *Schoenoplectus tabernaemontan* than its lower gravel substratum, which suggested that pore clogging by these fractions was more prominent in the top layer of the gravel substratum. Subsequently, these accumulated solids in the wetland system have to be removed eventually, even though some of the solids will be digested through time. Although the unplanted bed was not as efficient in TSS removal in comparison with the planted unit, the high mass reduction was preserved with a minimum of 89% elimination (Appendix D1) in the unplanted bed with aggregate substrata as the filter media.

6.4 Effects of Plant Type

As discussed in Chapter 4, section 4.4 and in previous section 6.3, plant presence was found to be important in improving the treatment performance of the VFEWs system at both the first and second stage, particularly in terms of ammonia (NH_3-N) and suspended solids (TSS) elimination. This section reports on the differences in pollutants removal efficiencies between two wetlands planted with different plant species. Bed B-*Phrag* was planted with a common wetland plant, *Phragmites karka* and bed B-*Costus* was planted with an ornamental species, *Costus woodsonii* (Figure 6.10). Both species of plants used in this study (*Phragmites* and *Costus*) grew well in the PKS-aggregate-based wetland units loaded with pre-treated septage and produced a good vegetation cover (with flowers for *Costus*). The ornamental plant, *Costus* had a survival rate of 100% throughout the entire study duration of 12 weeks. Plant *Costus* also seemed to exhibit a faster growth rate and was healthier than *Phragmites*.

No obvious sign of wilting was observed for plant *Costus* after the system was left unwatered at the end of the study period for 3 weeks' time.

Figure 6.10 *Costus woodsonii* planted in wetland B-*Costus*

The mean pH in the effluent of B-*Phrag* varied between 6.64 - 7.18 and between 6.52 - 6.87 for B-*Costus*, as Table 6.6 shows. The pH trend of the effluent was constantly slightly acidic for both beds and was generally lower than the pH of the influent. The DO concentrations and ORP values were observed to be higher in the treated effluent compared to the wetlands influent, indicating an oxygenated condition in both the planted wetland beds. ORP values were constantly above +100mV for both beds implying aerobic environment in the wetlands. As shown in Figure 6.11, the *Phragmites*-planted wetland was found to have greater water loss via evapotranspiration (ET) than the *Costus*-planted wetlands. An average of 20.4% of water was lost from the *Phragmites*-planted bed and only 13.9% of water was lost from the *Costus*-planted bed. The difference between the percentage of water loss via ET from the two beds was found to be statistically important.

Table 6.6 Physico-chemical parameters statistics for the pre-treated septage (influent), and effluent from wetland B-*Phrag* and B-*Costus*. N is the number of samples collected and analysed for each parameter during the study period.

Parameter	Sampling Point	Statistics			
		N	Range	Mean	Std Dev.
Temperature (℃)	Influent	10	26.10 - 29.90	27.74	1.27
	Phragmites karka (B-*Phrag*)	10	28.60 - 33.00	30.04	1.36
	Costus woodsonii (B-*Costus*)	10	27.60 - 35.10	30.11	2.12
pH	Influent	10	7.58 - 8.02	7.81	0.14
	Phragmites karka (B-*Phrag*)	10	6.64 - 7.18	6.87	0.17
	Costus woodsonii (B-*Costus*)	10	6.52 - 6.87	6.68	0.13
DO (mg/L)	Influent	10	0.41 - 4.69	2.26	1.73
	Phragmites karka (B-*Phrag*)	10	3.56 - 7.14	4.89	1.12
	Costus woodsonii (B-*Costus*)	10	1.71 - 5.88	3.23	1.22
ORP (mV)	Influent	10	-109 - 310	-	-
	Phragmites karka (B-*Phrag*)	10	125 - 310	-	-
	Costus woodsonii (B-*Costus*)	10	31 - 350	-	-
EC (mS/cm)	Influent	10	1.02 - 2.75	1.72	0.71
	Phragmites karka (B-*Phrag*)	10	1.31 - 2.49	1.73	0.48
	Costus woodsonii (B-*Costus*)	10	1.25 - 2.72	1.77	0.53

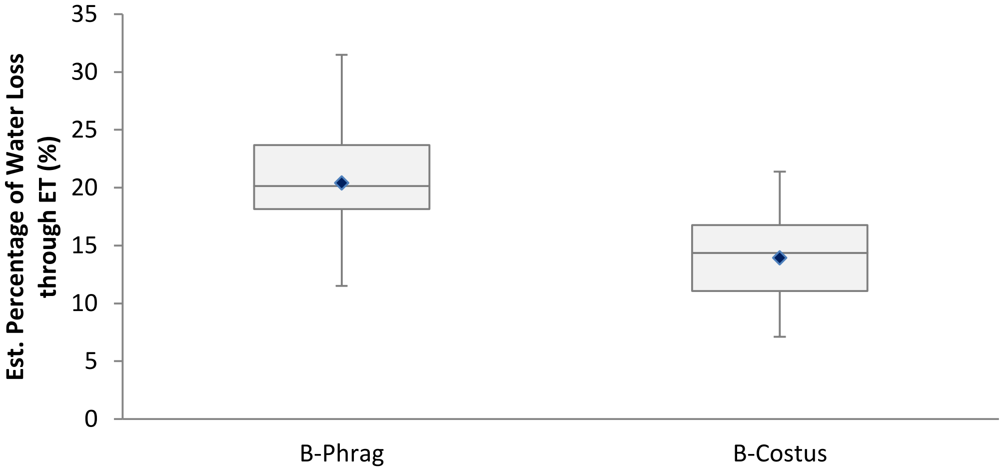


Figure 6.11 Estimated water loss from wetlands B-*Phrag* and B-*Costus* through evapotranspiration (%)

6.4.1 Organic Matter Removal

Influent COD and BOD_5 levels varied greatly during the study period, ranging between 1,050 - 3,360 mg/L and 180.7 - 351.6 mg/L, respectively as shown in Table 6.7. Concerning the removal efficiency of organic matter (OM) in the *Phragmites*-

planted (B-*Phrag*) and *Costus*-planted (B-*Costus*) wetlands, the elimination rate of B-*Costus* was not found to be statistically different from that of B-*Phrag* (Table 6.7). The effluent of wetland B-*Phrag* had mean OM concentration of 105 mg COD/L and 3.3 mg BOD_5/L, which appeared to be slightly lower than that of the effluent from B-*Costus* with 138.5 mg COD/L and 5.4 mg BOD_5/L. In terms of mass, average COD and BOD_5 loading rates varied between 91.9 - 294 g/m^2.d and 16 - 30.8 g/m^2.d, respectively for both systems (Table 6.7). Figure 6.12 shows the plot of influent COD areal loading rates and the resulting effluent mass for wetlands B-*Phrag* and B-*Costus*, and the mass removal efficiencies for each treatment.

Table 6.7 OM indices concentration and mass statistics for the influent (pre-treated septage) and the resulting bed effluent of B-*Phrag* and B-*Costus* units

Parameter			Range	Mean (±SD)	MRR*	RE (%)*
COD	Conc. (mg/L)	Influent	1,050 - 3,360	2,224 (±834.24)		
		Phragmites (B-*Phrag*)	20.00 - 170.00	105.00 (±50.33)		94.28
		Costus (B-*Costus*)	90.00 - 220.00	138.50 (±40.56)		92.67
	Mass (g/m^2.d)	Influent	91.88 - 294.00	194.60 (±73.00)		
		Phragmites (B-*Phrag*)	1.53 - 12.11	7.33 (±3.58)	187.27	95.44
		Costus (B-*Costus*)	7.02 - 17.88	10.42 (±3.21)	184.18	93.70
BOD_5	Conc. (mg/L)	Influent	182.70 - 351.60	182.70 (±351.60)		
		Phragmites (B-*Phrag*)	0.24 - 6.45	3.30 (±2.29)		98.63
		Costus (B-*Costus*)	0.30 - 12.72	5.43 (±3.48)		97.61
	Mass (g/m^2.d)	Influent	15.99 - 30.77	21.18 (±5.23)		
		Phragmites (B-*Phrag*)	0.02 - 0.50	0.23 (±0.17)	20.95	98.91
		Costus (B-*Costus*)	0.02 - 0.94	0.41 (±0.26)	20.77	97.96

No. of samples, N = 10

MRR= Mass removal rate

RE= Removal efficiency

* Values presented as the average REs or MRRs calculated from N samples of N experimental runs

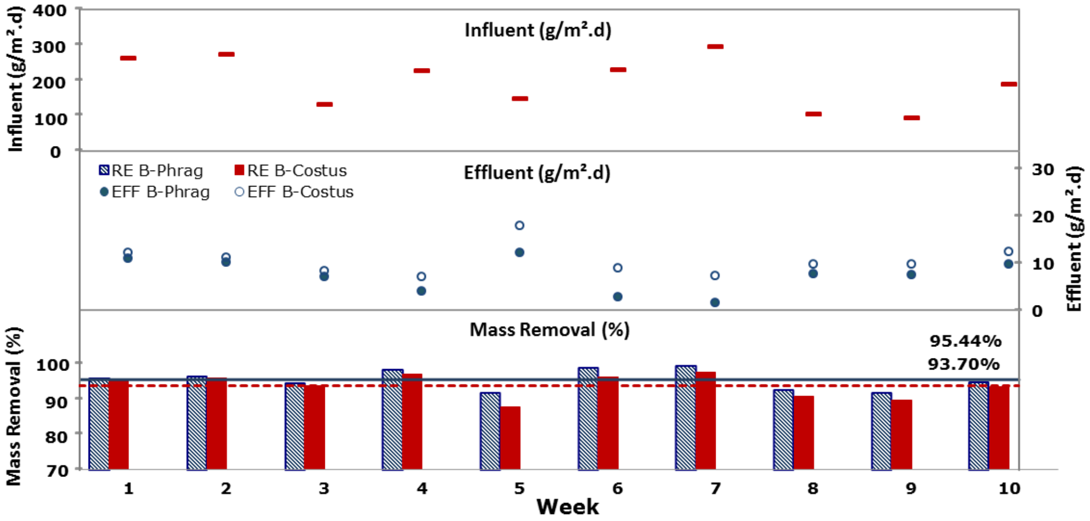


Figure 6.12 Influent COD areal loading rates and the resulting effluent loads for B-*Phrag* and B-*Costus* beds, with the percentages (%) of mass removal for each treatment (horizontal solid line indicates mean removal efficiencies for B-*Phrag* unit; dashed line indicates mean removal efficiencies for B-*Costus* unit)

The COD removal rates increased linearly with the loading rates at ratio very close to 1:1 as shown in Figure 6.13 which depicts the regression plot. The scatterplot and the regression trend for BOD_5 was fairly similar to the one of COD (Appendix E). The B-*Phrag* system showed marginally higher mean OM mass removal rates than the B-*Costus* beds (Table 6.7), with no statistical importance found between the efficiency the two systems. There was a positive, statistically significant relationship between the OM MRRs and their ILRs for both the planted system regardless of the plant species (P<0.001). These results demonstrate that the use of ornamental plants did not deteriorate the efficiency of the wetlands in the treatment of the organic loads in the influent. Almost all the weekly NH_3-N levels examined in the effluent of wetland B-*Phrag* and B-*Costus* met at least Standard B according to Malaysia Environmental Quality Act 1974 (Environmental Quality (Sewage) Regulation 2009 for effluent discharge into inland waters or Malaysian waters) (please see Appendix A).

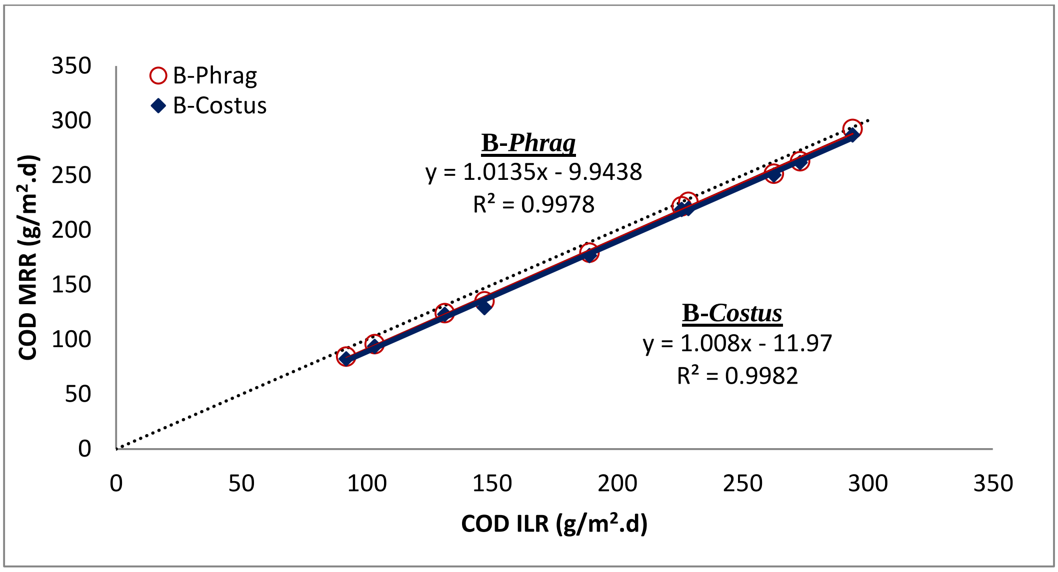


Figure 6.13 Regression graph of COD mass removal rate (MRR) against influent loading rate (ILR) (g/m ²d) for B-*Phrag* and B-*Costus*. The dotted line represents complete removal.

It is however, interesting to find that the unit planted with ornamentals (B-*Costus*) has statistically comparable removal efficiency with the one planted with the indigenous wetland species (B-*Phrag*). This outcome suggested that the use of *Costus woodsonii*, did not affect the performance of the wetlands on the overall OM mass reduction. Since sedimentation, adsorption and microbial metabolism are considered to be the primary mechanisms for OM removal, it is likely that the plant roots with the PKS-aggregate substrate had become a good settling medium for the incoming solid loads, where both the species were equally efficient in filtering and removing the organic compounds.

6.4.2 Nitrogen Removal

The high overall ammonia nitrogen (NH_3-N) and kjedahl nitrogen (TKN) removal efficiencies achieved by the two planted systems suggested that both plant species were very efficient in the ammoniacal N removal. Their dense rooting system provides large surface attachment area for the microorganism conducive for microbial metabolic activities, besides transporting atmospheric oxygen into the substrate through the plants' aerenhyma tissues (Tanner, Clayton and Upsdell 1995a). Their effluent pollutant concentrations were in general very low, indicating that the wetlands carried out an intensive process of particulate and soluble OM retention and removal, as well as the treatment of most of the ammonia. Higher mean NH_3-N and

TKN concentrations and mass were observed in the effluent of *Phragmites*-planted system compared with the *Costus*-planted system as shown in Table 6.8. The NH$_3$-N removal efficiency of wetland B-*Phrag* in terms of concentration was more than 95% (95.1 - 99.7%) and in terms of mass were above 96% (96.7 - 99.8%) (Figure 6.14). For TKN, the concentration-based removal efficiency at wetland B-*Phrag* was at least 73% (73.5 - 94%), and the mass-based removal efficiency was above 78% (78 - 95.1%) throughout the study period (Figure 6.15).

Table 6.8 Nitrogen concentration and mass statistics for the influent (pre-treated septage) and the resulting bed effluent of B-*Phrag* and B-*Costus* units

Parameter			Range	Mean (±SD)	MRR*	RE (%)*
NH$_3$-N	Concentration (mg/L)	Influent	23.40 - 108.50	55.25 (±24.44)		
		Phragmites (B-*Phrag*)	0.20 - 2.10	0.83 (±0.61)		98.14
		Costus (B-*Costus*)	0.50 - 5.10	2.11 (±1.51)		95.88
	Mass (g/m^2.d)	Influent	2.05 - 9.49	4.83 (±2.14)		
		Phragmites (B-*Phrag*)	0.01 - 0.13	0.06 (±0.04)	4.78	98.54
		Costus (B-*Costus*)	0.03 - 0.41	0.16 (±0.12)	4.67	96.45
TKN	Concentration (mg/L)	Influent	86.66 - 290.16	208.78 (±65.72)		
		Phragmites (B-*Phrag*)	13.67 - 56.70	33.15 (±15.11)		82.99
		Costus (B-*Costus*)	16.15 - 77.80	46.69 (±24.43)		76.81
	Mass (g/m^2.d)	Influent	7.58 - 25.39	18.27 (±5.75)		
		Phragmites (B-*Phrag*)	0.97 - 4.09	2.31 (±1.09)	15.95	86.43
		Costus (B-*Costus*)	1.31 - 5.88	3.53 (±1.90)	14.74	80.05
NO$_3$-N	Concentration (mg/L)	Influent	2.40 - 112.20	34.07 (±38.65)		
		Phragmites (B-*Phrag*)	5.80 - 54.60	25.48 (±18.22)		-
		Costus (B-*Costus*)	5.40 - 54.00	25.38 (±18.13)		-
	Mass (g/m^2.d)	Influent	0.21 - 9.82	2.98 (±3.38)		
		Phragmites (B-*Phrag*)	0.38 - 3.62	1.78 (±1.29)	-	-
		Costus (B-*Costus*)	0.39 - 4.01	1.91 (±1.37)	-	-
TN	Concentration (mg/L)	Influent	120.00 - 366.00	244.20 (±78.23)		
		Phragmites (B-*Phrag*)	21.00 - 89.00	58.80 (±24.48)		75.29
		Costus (B-*Costus*)	32.00 - 127.00	72.50 (±36.84)		70.47
	Mass (g/m^2.d)	Influent	10.50 - 32.03	21.37 (±6.85)		
		Phragmites (B-*Phrag*)	1.50 - 6.89	4.11 (±1.80)	17.26	80.36
		Costus (B-*Costus*)	2.60 - 9.60	5.47 (±2.83)	15.89	74.63

No. of samples, N = 10

MRR= Mass removal rate

RE= Removal efficiency

* Values presented as the average REs or MRRs calculated from N samples of N experimental runs

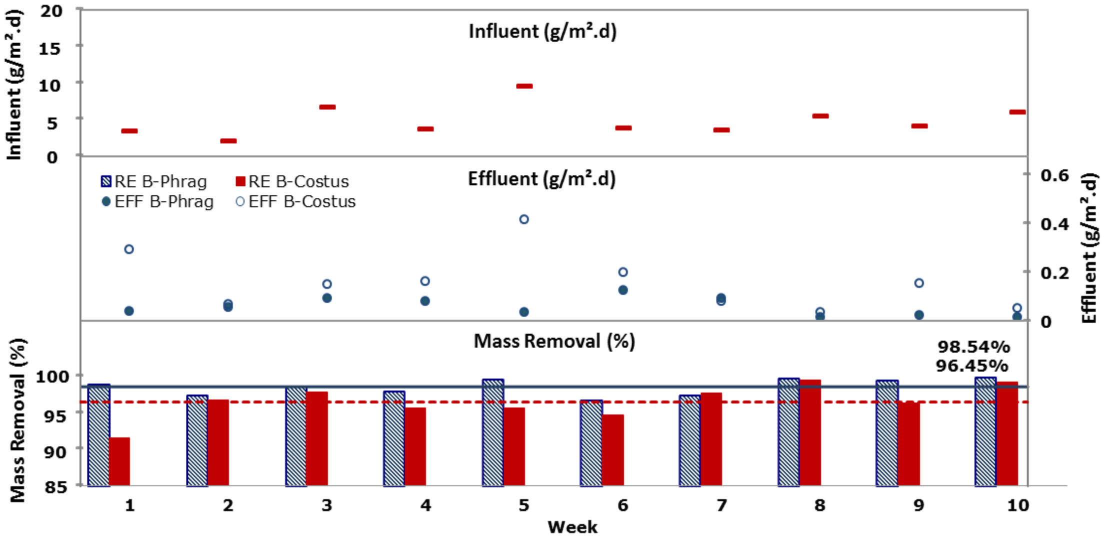


Figure 6.14 Influent NH_3-N areal loading rates and the resulting effluent loads for B-*Phrag* and B-*Costus* bed, with the percentages (%) of mass removal for each treatment (horizontal solid line indicates mean removal efficiencies for B-*Phrag* unit; dashed line indicates mean removal efficiencies for B-*Costus* unit)

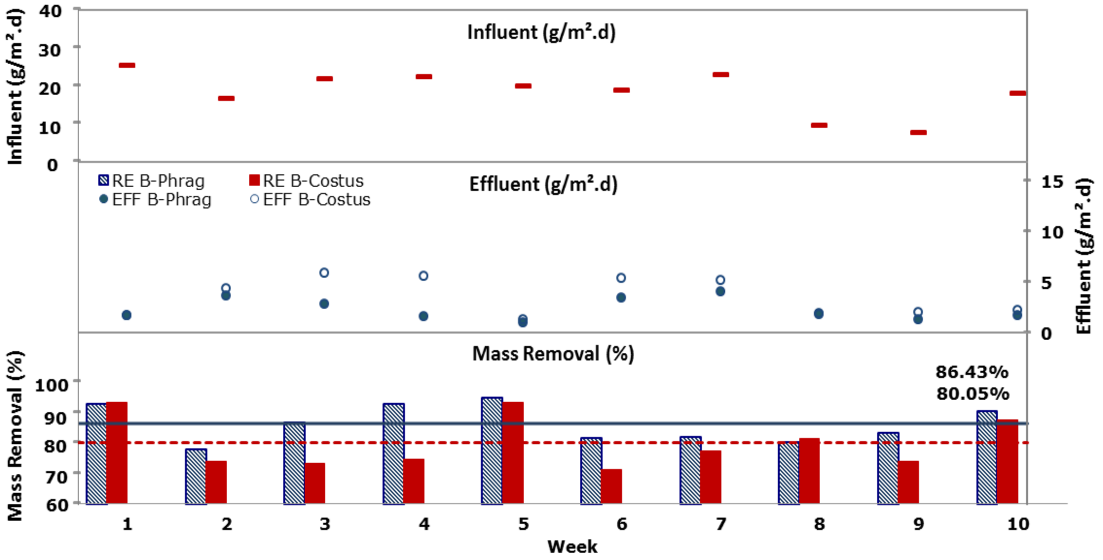


Figure 6.15 Influent TKN areal loading rates and the resulting effluent loads for B-*Phrag* and B-*Costus* bed, with the percentages (%) of mass removal for each treatment (horizontal solid line indicates mean removal efficiencies for B-*Phrag* unit; dashed line indicates mean removal efficiencies for B-*Costus* unit)

The NH_3-N and TKN removal efficiency of the B-*Phrag* bed falls within the range reported in the literature (Vázquez et al. 2013; Torrens et al. 2009). The B-*Phrag* unit produced effluent with a mean of 0.83 mg/L or 0.014 g/d of NH_3-N, which had been significantly reduced from the NH_3-N concentration and mass in the pre-treated septage influent (P<0.001). Although the performance of wetland B-*Costus* was found to be inferior to wetland B-*Phrag* in terms of NH_3-N elimination, the unit was still capable to produce effluent with a considerably low ammonia content of 2.11 mg/L and 0.038 g/d at a high rate of removal. The mean mass reduction efficiency between the two beds was statistically different for both NH_3-N and TKN. All weekly NH_3-N levels in the effluent collected from the *Phragmites*-planted and *Costus*-planted beds satisfied Standard A according to Malaysia Environmental Quality Act 1974 (Environmental Quality (Sewage) Regulation 2009 for effluent discharge into inland waters within catchment areas) (please see Appendix A).

Figure 6.16 reflects the relationship between the influent ammonia loading rates with their MRRs for the B-*Phrag* and B-*Costus* systems. The chart suggested a similarly strong positive correlation between the NH_3-N influent loads and their removal rates for both systems, with the B-*Phrag* unit outperformed the B-*Costus* unit in general with greater MRRs obtained. The close fit of the points to the regression lines indicates a remarkably constant areal removal rates for the ammoniacal N species. The area removal rates for the two beds were consistently high, with the slope nearing to 1 indicating the significant effects of NH_3-N ILRs on the MRRs (P<0.001).

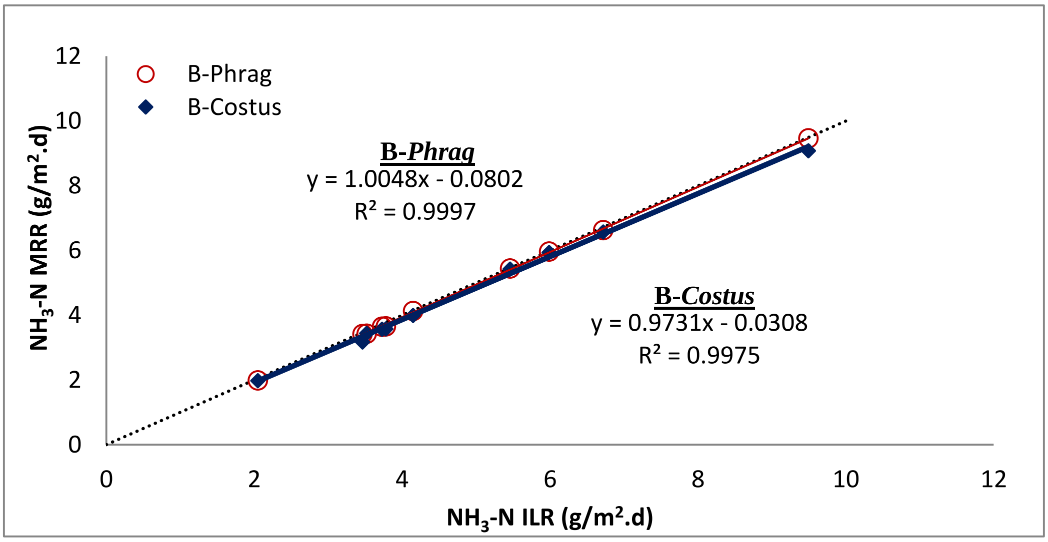


Figure 6.16 Regression graph of NH_3-N mass removal rate (MRR) against influent loading rate (ILR) (g/m ²d) for B-*Phrag* and B-*Costus* units. The dotted line represents complete removal.

However, the scatterplots of TKN for both systems showed relatively weaker correlation compared to NH_3-N, though the coefficient of correlations were still generally high ($r^2 = 0.96$ for B-*Phrag* and $r^2 = 0.89$ for B-*Costus*), as shown in Figure 6.17. The trendlines clearly indicate the greater TKN MRRs in the *Phragmites*-planted wetland than the *Costus*-planted unit.

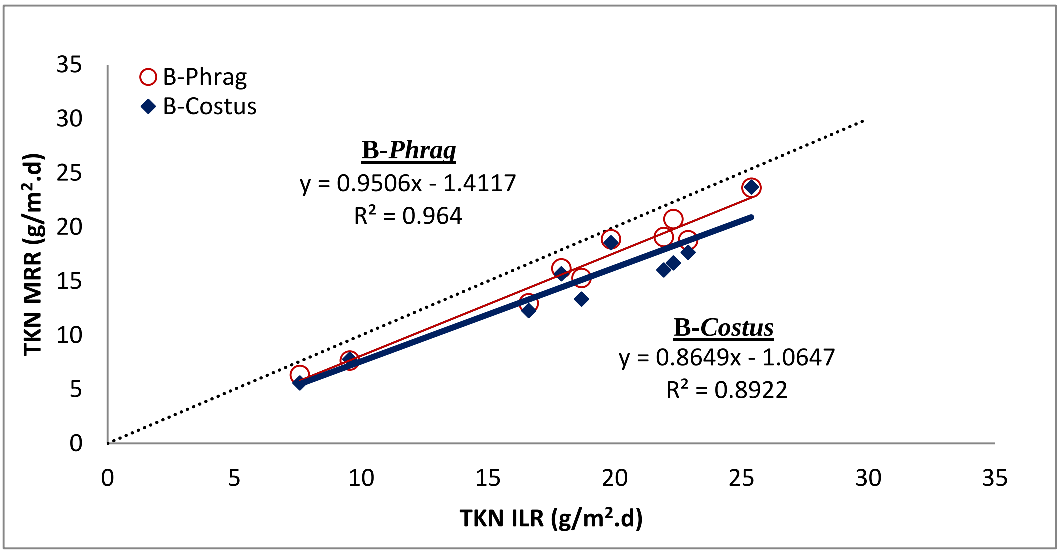


Figure 6.17 Regression graph of TKN mass removal rate (MRR) against influent loading rate (ILR) (g/m ²d) for B-*Phrag* and B-*Costus* units. The dotted line represents complete removal.

It has been known that reeds and other types of macrophytes such as cattail and bulrush are able to transport air through their hollow stems and roots to the substrate. The rhizomes of the reeds grow vertically and horizontally, allowing it to open up a hydraulic pathway to the substrate (Cooper and Boon 1987). Oxygen is passed from the atmosphere to the rhizosphere via the leaves and stems of the reeds through the hollow rhizomes and out through the roots (Cooper and Boon 1987); allowing aerobic microsites to be present near the root zone and thus promoting nitrification and enhance ammonia removal.

It is suggested that one of the reasons behind the underperformance of the *Costus*-planted bed compared to the *Phragmites*-planted bed in terms of ammonia removal was likely due to the lower rate of evapotranspiration (ET) by plant *Costus* as shown previously in Figure 6.11. The *Costus*-planted bed had 31.8% lesser water loss by ET than the *Phragmites*-planted wetland. Differences in the rate of ET can affect the treatment of the beds as claimed by Koottatep, Konnerup, and Brix (2009). The authors suggested that high evapotranspiration rates can contribute to a substantial water loss which in turn results in a longer retention time for the remaining water and hence more time for degradation of pollutants. The authors also reported that plant transpiration can drive a "transpiration pump" that could contribute to an upward flow of water to the upper layer of the bed substrate where most of the roots are located (Headley, Herity and Davison 2005), and thus subsequently improves aerobic removal of the pollutants.

The estimated average daily volume of water loss through ET in B-*Phragmites* was 20.5%, which was significantly higher than that of the B-*Costus* bed with mean of 14% of removal (in 10 weeks of study). *Costus woodsonii* has dark, green waxy leaves that could explain the lower percentage of water loss from the wetland planted with this ornamental species. Its leaves are coated with wax cuticles that help to retain water in the plant and reduce transpiration. The minimal signs of plant wilting observed at *Costus*-planted bed after the wetland was left unwatered for 3 weeks at the end of the experimental run further supports this suggestion. *Phragmites* on the other hand showed severe symptoms of wilting at two weeks of idle period (no influent loading) and was completely withered at 3 weeks' time.

There appears to be an unanimous agreement in the literature that the primary role of plants is not direct nutrient uptake, but more prominently to create microbial sites that support growth of microorganisms responsible for nitrification and denitrification via oxygen transport to the root zone and carbon generation. *Phragmites* could have more extensive root growth than that of *Costus,* which consequentially indicates the existence of a greater area of rhizophere to maintain a relatively more aerobic condition in wetland B-*Phrag*, besides providing larger residing sites for microbial attachment. These assumptions can be verified with the significantly higher content of DO concentrations found in the effluent from wetland B-*Phrag* than in the effluent from wetland B-*Costus* as shown in Table 6.6.

The high TN removal at both the wetlands with *Phragmites* and *Costus* was the evidence of coupled nitrification-denitrification processes that occurred in the beds.

Engineered wetlands are known to have a mosaic of aerobic and anaerobic microsites where nitrification and denitrification could occur at the same time. Aerobic treatment can take place in the rhizosphere, with anoxic and anaerobic treatment taking place in the immediate surrounding sites outside the aerobic zone. The average TN removal in wetland B-*Phrag* was high at 75.3% in terms of concentration, and 80.4% in terms of mass (Table 6.8). Although wetland B-*Costus* had generally lower treatment efficiency compared to its wetland counterpart B-*Phrag*, a mean TN removal of above 70% in terms of both concentration and mass were still achievable by the wetland B-*Costus*. No significant difference was found when the TN removal efficiency of the two beds was compared in ANOVA, indicating the comparable treatment performance between the two wetlands.

6.4.3 Particulate Solids Removal

The removal of total suspended solids (TSS), which is primarily a physical process of settling and retention, is similar for both the *Phragmites*-planted and *Costus*-planted beds. The removal of TSS was very efficient at all loadings and there was no difference in the treatment efficiencies between the wetlands planted with *Phragmites* and *Costus*. This confirms that the different plant types did not affect the TSS reduction, indicating comparable performance of the B-*Costus* unit with the B-*Phrag* bed in removing particulate matter. The mean TSS concentrations of the pre-treated septage ranged from 1,080 - 3,710 mg/L with great variations as shown in Table 6.9 and Figure 6.18.

Table 6.9 Particulate solids concentration statistics for the influent (pre-treated septage) and the resulting bed effluent of B-*Phrag* and B-*Costus* units

Parameter			Range	Mean (±SD)	MRR*	RE (%)*
TS	Conc. (mg/L)	Influent	2,716 - 7,476	4,060 (±1,350)		
		Phragmites (B-*Phrag*)	1052 - 2,904	1,599 (±586.02)		60.42
		Costus (B-*Costus*)	1024 - 2604	1,434 (±551.13)		64.40
	Mass (g/m^2.d)	Influent	237.65 - 654.15	355.21 (±118.11)		
		Phragmites (B-*Phrag*)	75.48 - 224.88	112.46 (±47.27)	242.75	68.50
		Costus (B-*Costus*)	78.94 - 193.44	107.50 (±39.68)	247.71	69.50
TSS	Conc. (mg/L)	Influent	1,080 - 3,710	2,367 (±856.22)		
		Phragmites (B-*Phrag*)	5.00 - 100.00	45.70 (±36.67)		97.68
		Costus (B-*Costus*)	40.00 - 145.00	74.60 (±29.03)		96.54
	Mass (g/m^2.d)	Influent	94.50 - 324.63	207.08 (±74.92)		
		Phragmites (B-*Phrag*)	0.38 - 7.74	3.24 (±2.70)	203.84	98.12
		Costus (B-*Costus*)	3.21 - 11.79	5.65 (±2.44)	201.43	97.00
VSS	Conc. (mg/L)	Influent	830 - 3,300	1,815 (±939.12)		
		Phragmites (B-*Phrag*)	0.00 - 65.00	27.40 (±22.31)		98.01
		Costus (B-*Costus*)	16.00 - 70.00	37.60 (±14.32)		97.60
	Mass (g/m^2.d)	Influent	72.62 - 288.75	158.78 (±82.17)		
		Phragmites (B-*Phrag*)	0.00 - 4.63	1.91 (±1.56)	156.87	98.39
		Costus (B-*Costus*)	1.19 - 5.69	2.85 (±1.20)	155.93	97.92

No. of samples, N= 10

MRR= Mass removal rate

RE= Removal efficiency

* Values presented as the average REs or MRRs calculated from N samples of N experimental runs

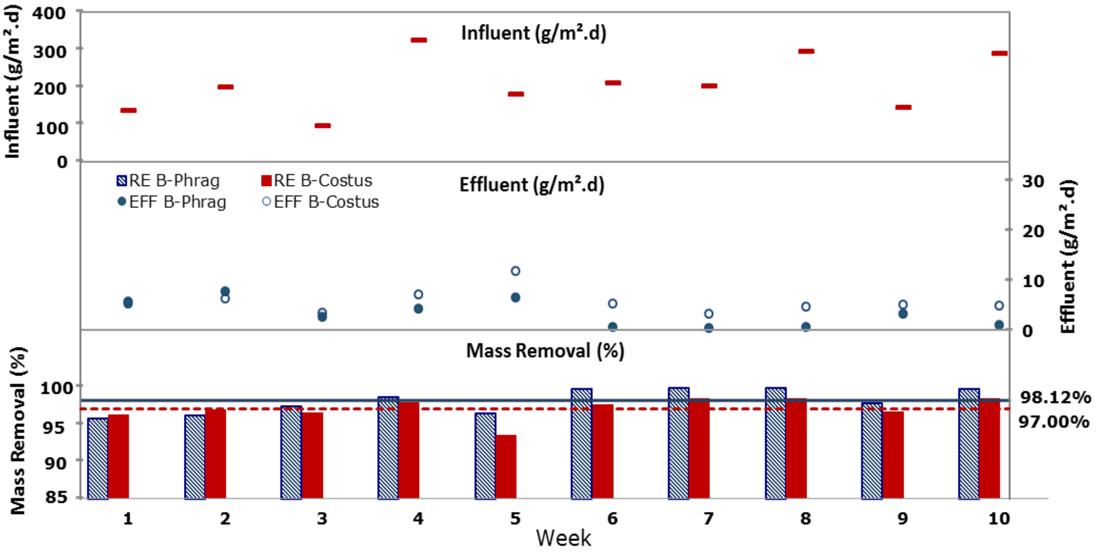


Figure 6.18 Influent TSS areal loading rates and the resulting effluent loads for B-*Phrag* and B-*Costus* bed, with the percentages (%) of mass removal for each treatment (horizontal solid line indicates mean removal efficiencies for B-*Phrag* unit; dashed line indicates mean removal efficiencies for B-*Costus* unit)

Both systems were operated with the loading rates between 94.5 - 324.6 g TSS/m^2.d (Table 6.9). The TSS mass of the resulting effluent from both beds was close with a mean of 3.2 g/m^2.d for wetland B-*Phrag* and 5.7 g/m^2.d for wetland B-*Costus*, yielding an average mass elimination efficiency of 98.1% and 97% for wetlands B-*Phrag* and B-*Costus*, respectively. Although both the concentration-based and mass-based reduction performances of wetland B-*Phrag* bed were generally greater than wetland B-*Costus*, the differences between them were statistically unimportant ($P>0.05$). The organic fraction (VSS/TSS) in the pre-treated septage was decreased from 0.77 to 0.6 in the effluent of wetland B-*Phrag* and to 0.5 in the effluent of wetland B-*Costus*, indicating that biodegradable solids, mainly, were removed. No significant difference for the VSS treatment efficiency between the beds were found, suggesting that both the *Phragmites*-planted and *Costus*-planted wetlands were equally efficient in reducing volatile solids content, likely due to the high populations of microorganism biomass present in the beds. Overall, the ornamental species used in this study appears to confer no significant disadvantage in terms of solids reduction for the septage treatment.

A vast majority of the weekly TSS levels in the effluent collected from *Phragmites*-planted and *Costus*-planted beds met with at least Standard B of the allowable effluent discharge limit according to Malaysia Environmental Quality Act 1974 (Environmental Quality (Sewage) Regulation 2009 for effluent discharge into inland waters or Malaysian waters) (please see Appendix A). The high mean TSS mass removal indicated high solids retention capacity of both beds. However in the present study, both wetlands did not experience clogging problems during the 12 weeks of operational period at the loading rate of 8.75 cm/d, under the intermittent feeding strategy. This suggested the occurrence of both biotic (organic biodegradation and possibly plant uptake in the wetlands) and abiotic (settling and sedimentation) processes in the wetlands.

The regression plots in Figure 6.19 showed great correlation between the TSS ILRs and the corresponding MRRs at both wetlands B-*Phrag* and B-*Costus*, with slopes nearing to 1. The TSS MRRs increased proportionally with the ILRs, having the highest rate of removal at 76.2 g/d with ILR of 77.9 g/d. This trend of consistent wetlands treatment efficiency showed excellent predictability of the bed performance, which is ultimately a valuable information for wetland design.

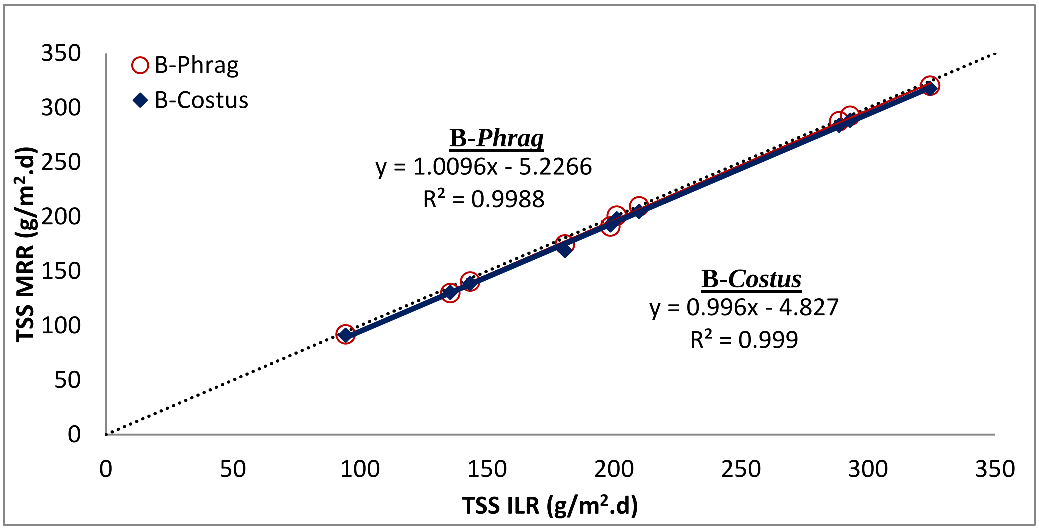


Figure 6.19 Regression graph of TSS mass removal rate (MRR) against influent loading rate (ILR) (g/m ²d) for B-*Phrag* and B-*Costus* units. The dotted line represents complete removal.

6.5 Effects of Substrate Type

The second stage of the vertical flow wetland system was tested for treatment of pre-treated septage using palm kernel shells (PKS), which is an organic substrate as part of the wetland's growing medium. Table 6.10 and Table 6.11 show the physico-chemical characteristics of the pre-treated septage and the corresponding wetlands effluent from the beds filled with and without PKS. The wetland substrate composed of mineral layers (45 cm of aggregates layer) and a 25 cm-layer of organic substrate (PKS) or sand, topping off with a 10 cm of sand. The substrates of the two beds were designed to have the same aggregates arrangement and material, except for the top layer where either sand or PKS were assessed as substrate. Beds with PKS are denoted as B-PKS and without PKS as B-SD. Table 6.10 summarises the characteristics of the influent and effluent for the wetlands fed with batch loading, whereas Table 6.11 reports on the characteristics the influent and effluent for the wetlands loaded with intermittent mode.

Table 6.10 Physico-chemical parameters statistics for the pre-treated septage (influent), and effluent from wetland B-PKS (I) and B-SD (I) under batch loading mode. N is the number of samples collected and analysed for each parameter during the study period

Parameter	Sampling Point	Statistics			
		N	Range	Mean	Std Dev.
Temperature (°C)	Influent	11	27.00 - 29.00	27.65	0.78
	B-PKS (I)	11	26.90 - 30.90	28.61	1.23
	B-SD (I)	11	27.00 - 34.10	28.78	1.92
pH	Influent	11	7.58 - 8.30	7.83	0.26
	B-PKS (I)	11	6.41 - 6.84	6.59	0.13
	B-SD (I)	11	6.23 - 6.73	6.48	0.18
DO (mg/L)	Influent	11	0.48 - 1.01	0.64	0.19
	B-PKS (I)	11	1.12 - 1.89	1.47	0.22
	B-SD (I)	11	1.17 - 2.29	1.62	0.35
ORP (mV)	Influent	6	-113- (-84)	-	-
	B-PKS (I)	6	51 - 128	-	-
	B-SD (I)	6	111 - 178	-	-
EC (mS/cm)	Influent	11	1.35 - 1.77	1.59	0.15
	B-PKS (I)	11	2.12 - 2.57	2.30	0.12
	B-SD (I)	11	2.28 - 2.89	2.48	0.19

The wetland influent (pre-treated septage) was oxidised in all treatments under both feeding modes, with significant increase in the DO and ORP values in the treated effluent (Table 6.10 and Table 6.11). This could be attributed to the feeding strategies employed and the good substrate design that concomitantly aided the oxygenation of the wetland influent. As shown in Table 6.10 and Table 6.11, the effluent DO and ORP values were clearly higher in the intermittently-fed bed than the batch-fed bed. The intermittent feeding strategy appears to be more efficient in promoting a more aerobic microenvironment in the wetland substrate. The effluent DO concentrations were found to be rather consistent with minimal fluctuations in the batch operated wetlands (Table 6.10). Higher DO content was also observed in wetland B-SD (I) with the batch operating regime, presumably on account of the dominancy of aerobic conditions in wetland B-SD with a thicker layer of sand topping the substrate media. However, in wetland B-PKS (II) and B-SD (II) which were loaded intermittently, their effluent DO values fluctuated to a greater extent (as indicated by higher standard deviation values) during the study period (Table 6.11).

Table 6.11 Physico-chemical parameters statistics for the pre-treated septage (influent), and effluent from wetland B-PKS (II) and B-SD (II) under intermittent loading mode. N is the number of samples collected and analysed for each parameter during the study period.

Parameter	Sampling Point	Statistics			
		N	Range	Mean	Std Dev.
Temperature (°C)	Influent	10	25.10 - 29.50	27.08	1.31
	B-PKS (II)	10	24.50 - 31.50	27.65	2.13
	B-SD (II)	10	24.70 - 30.70	27.47	2.04
pH	Influent	10	7.12 - 8.05	7.50	0.26
	B-PKS (II)	10	6.77 - 7.09	6.90	0.11
	B-SD (II)	10	6.54 - 6.98	6.73	0.15
DO (mg/L)	Influent	10	0.50 - 2.54	1.32	0.68
	B-PKS (II)	10	2.51 - 7.59	4.70	1.40
	B-SD (II)	10	3.66 - 5.74	4.56	0.65
ORP (mV)	Influent	10	-262 - 215	-	-
	B-PKS (II)	10	118 - 403	-	-
	B-SD (II)	10	101 - 387	-	-
EC (mS/cm)	Influent	10	1.70 - 2.17	1.94	0.16
	B-PKS (II)	10	1.98 - 2.50	2.13	0.16
	B-SD (II)	10	2.25 - 3.11	2.57	0.27

Effluent DO concentration has been accounted to be a less preferable indicator for describing the environmental conditions inside the media of wetland systems (Vymazal and Kröpfelová 2008b), due to possible coexistence of aerobic and oxygen limited zones inside the wetland substrate matrices (Sun and Austin 2007). This condition appeared to be more obvious with the intermittent feeding regime, where the wetlands were flushed at regular intervals with smaller doses of influent. This had allowed percolation and free draining of the influent with relatively shorter hydraulic retention time (HRT), thus resulting in less homogeneous effluent with greater range of DO values.

Under both feeding regimes, the pH of the effluent from both beds remained slightly acidic, with values ranging marginally below neutrality and was generally lower than the pH of the influent (Table 6.10 and Table 6.11). EC values were observed to increase in all treated effluent. Effluent from wetland B-SD was found to have lower pH and higher EC values than that of the effluent from wetland B-PKS, at beds operated under both intermittent and batch mode. The increased EC values in both wetlands after treatment could be due to the possible interactions between the PKS-aggregate or SD-aggregate substrate with the biofilm that released water-soluble salts, increasing conductivity.

6.5.1 Organic Matter Removal

Table 6.12 presents the data for organic matter (OM) removal in terms of COD and BOD_5 at wetlands fed with batch loading strategy. Both wetlands B-PKS (I) and B-SD (I) were operated cyclically with pond and rest (P:R) period of 3:3, that is with 3 days of influent ponding, followed by 3 days of drained (rest) period. The influent and effluent OM statistics for the two beds operated with intermittent mode at 6 hours interval between each dose are reported in Table 6.13. During the duration of operation, both wetlands B-PKS and B-SD did not experience issues with surface clogging as both beds demonstrated comparable filterabilty, and attaining similarly good removal of organic compounds for both feeding regimes.

Table 6.12 Organic matter concentration and mass statistics for the influent (pre-treated septage) and the resulting bed effluent of B-PKS (I) and B-SD (I) under batch loading mode (P:R=3:3)

Parameter			Range	Mean (±SD)	MRR*	RE (%)*
COD	Conc. (mg/L)	Influent	1,430 - 8,800	5,159 (±2,877)		
		Eff. B-PKS (I)	60.00 - 300.00	173.27 (±83.34)		94.65
		Eff. B-SD (I)	42.00 - 240.00	127.36 (±66.20)		96.12
	Mass (g/m^2.batch)	Influent	125.13 - 770.00	451.42 (±251.78)		
		Eff. B-PKS (I)	2.11 - 13.73	7.65 (±3.98)	443.77	97.30
		Eff. B-SD (I)	1.69 - 11.42	5.95 (±3.30)	445.47	97.91
BOD_5	Conc. (mg/L)	Influent	196.00 - 396.00	274.78 (±76.94)		
		Eff. B-PKS (I)	14.09 - 24.60	20.51 (±3.39)		92.01
		Eff. B-SD (I)	6.60 - 16.80	11.04 (±3.34)		95.57
	Mass (g/m^2.batch)	Influent	17.15 - 34.65	24.04 (±6.73)		
		Eff. B-PKS (I)	0.50 - 1.39	0.94 (±0.30)	23.11	95.97
		Eff. B-SD (I)	0.32 - 0.87	0.51 (±0.17)	23.53	97.73

No. of samples, N = 11

MRR= Mass removal rate

RE= Removal efficiency

* Values presented as the average REs or MRRs calculated from N samples of N experimental runs

Table 6.13 Organic matter concentration and mass statistics for the influent (pre-treated septage) and the resulting bed effluent of B-PKS (II) and B-SD (II) under intermittent loading mode

Parameter			Range	Mean (±SD)	MRR*	RE (%)*
COD	Conc. (mg/L)	Influent	1,692 - 8,734	4,860 (±2,693)		
		Eff. B-PKS (II)	120.00 - 370.00	199.00 (±69.51)		93.71
		Eff. B-SD (II)	80.00 - 260.00	145.00 (±56.22)		95.16
	Mass ($g/m^2.d$)	Influent	148.05 - 764.23	425.25 (±235.64)		
		Eff. B-PKS (II)	7.78 - 26.90	14.58 (±5.21)	410.67	94.64
		Eff. B-SD (II)	5.17 - 18.97	10.43 (±4.30)	414.82	95.97
BOD_5	Conc. (mg/L)	Influent	163.80 - 473.40	247.31 (±84.65)		
		Eff. B-PKS (II)	0.96 - 17.40	7.89 (±5.64)		96.87
		Eff. B-SD (II)	0.66 - 6.00	3.85 (±1.95)		98.41
	Mass ($g/m^2.d$)	Influent	14.33 - 41.42	21.64 (±7.41)		
		Eff. B-PKS (II)	0.08 - 1.19	0.56 (±0.39)	21.08	97.47
		Eff. B-SD (II)	0.05 - 0.42	0.27 (±0.14)	21.37	98.72

No. of samples, N = 10

MRR= Mass removal rate

RE= Removal efficiency

* Values presented as the average REs or MRRs calculated from N samples of N experimental runs

Generally, the performance of the beds in OM removal was satisfactory with more than 90% reduction at both B-PKS and B-SD wetlands operated under the feeding regimes. Both beds were able to appreciably reduce COD regardless of presence of PKS, producing effluent with a mean of 127 mg COD/L for wetland B-SD (I) and 173 mg COD/L for wetland B-PKS (I) under batch loading, and 145 mg COD/L for wetland B-SD (II) and 199 mg COD/L for wetland B-PKS (II) under intermittent loading (Table 6.12 and Table 6.13). This occurrence can most reasonably be explained by the possible dominancy of organic pollutants in particulate form, which allows them to be easily filtered by the substrate media in the vertical wetlands.

The subsurface flow wetland system is recognised as the type of engineered wetland with the best filtration efficiency (Rousseau, Vanrolleghem and De Pauw 2004). This is because the processes controlling contaminant retention in a engineered wetland sediment could be abiotic (physical and chemical) and/or biotic (microbial and phytological (i.e. botanical)) (United States Department of Agriculture 1995; Interstate Technology & Regulatory Council 2003), where settleable organics are primarily removed by physical deposition, sedimentation and filtration at the top of the beds. Particles are filtered out of the influent as the wastewater percolates vertically down through the substrate medium and the dissolved compounds undergo decomposition and mineralization by bacteria existing in the wetland cell.

Although both wetlands B-SD (I) and B-SD (II) appeared to have a higher mean COD removal efficiency than wetlands B-PKS (I) and B-PKS (II) (Table 6.12 and Table 6.13), the difference between them was found to be insignificant ($P>0.05$). Wetland B-PKS used organic substrate (PKS) as the treatment media, which acted as a carbon source that could potentially release soluble organic matter into the bed effluent, therefore increasing the COD content in the outflow water. However, no increment of COD concentrations and mass were observed in the effluent of wetland B-PKS apart from achieving slightly lower COD reduction efficiency than wetland B-SD.

In terms of the removal efficiency of biochemical oxygen demand (BOD_5), wetland B-SD (II) produced effluent with the lowest strength of BOD_5 which ranged between 0.6 - 6 mg/L or 0.01 - 0.1 g/d under intermittent loading mode (Table 6.13). The intermittent mode of feeding regime appeared to aid BOD_5 removal with or without PKS in the beds. According to Watson et al.'s study in 1989 published as the "Performance expectations and loading rates for constructed wetlands" in the book "Constructed Wetlands for Wastewater Treatment" (cited in Aslam et al. 2007), removal of BOD_5 in wetlands is primarily by aerobic microbial degradation and sedimentation or filtration processes. The intermittent dosing of a wetland bed facilitates aerobic biological wastewater treatment through bacterial growth, unsaturated flow, and bed aeration between doses.

Particulate OM is removed by settling or filtration, and then converted to soluble BOD. Soluble organic matter is fixed by biofilms and removed due to degradation by attached heterotrophic microorganisms both aerobically and anaerobically in the wetland systems (biofilm on stems, roots, sand particles etc.). Oxygen required for aerobic degradation can be supplied by diffusion, convection and oxygen leakage from the macrophyte roots into the rhizosphere according to Moshiri (1993). Thus, passive aeration by intermittent feeding can improve the treatment efficiency of the wetlands as the removal of organics is highly dependent on the oxygen availability in the bed.

Analysis of the experimental results had shown that the BOD_5 elimination efficiency between wetlands B-PKS and B-SD varied significantly, with the SD beds greatly outperformed the PKS beds under both operating conditions. The BOD_5 removal efficiency in terms of mass reduction percentage between wetlands B-PKS (I) and B-SD (I) under batch loading varied between 92.6 - 97.7% and 94.9 - 98.9%, respectively (Figure 6.20 (a) and Appendix D3); and between wetlands B-PKS (II) and B-SD (II) under intermittent loading between 95.2 - 99.7% and 98 - 99.8%, respectively (Figure 6.20 (b) and Appendix D3). The difference between the PKS and SD beds were statistically important, indicating the superiority of the SD-filled wetlands over the PKS-filled wetlands in terms of BOD_5 reduction regardless of the feeding mode (batch and intermittent).

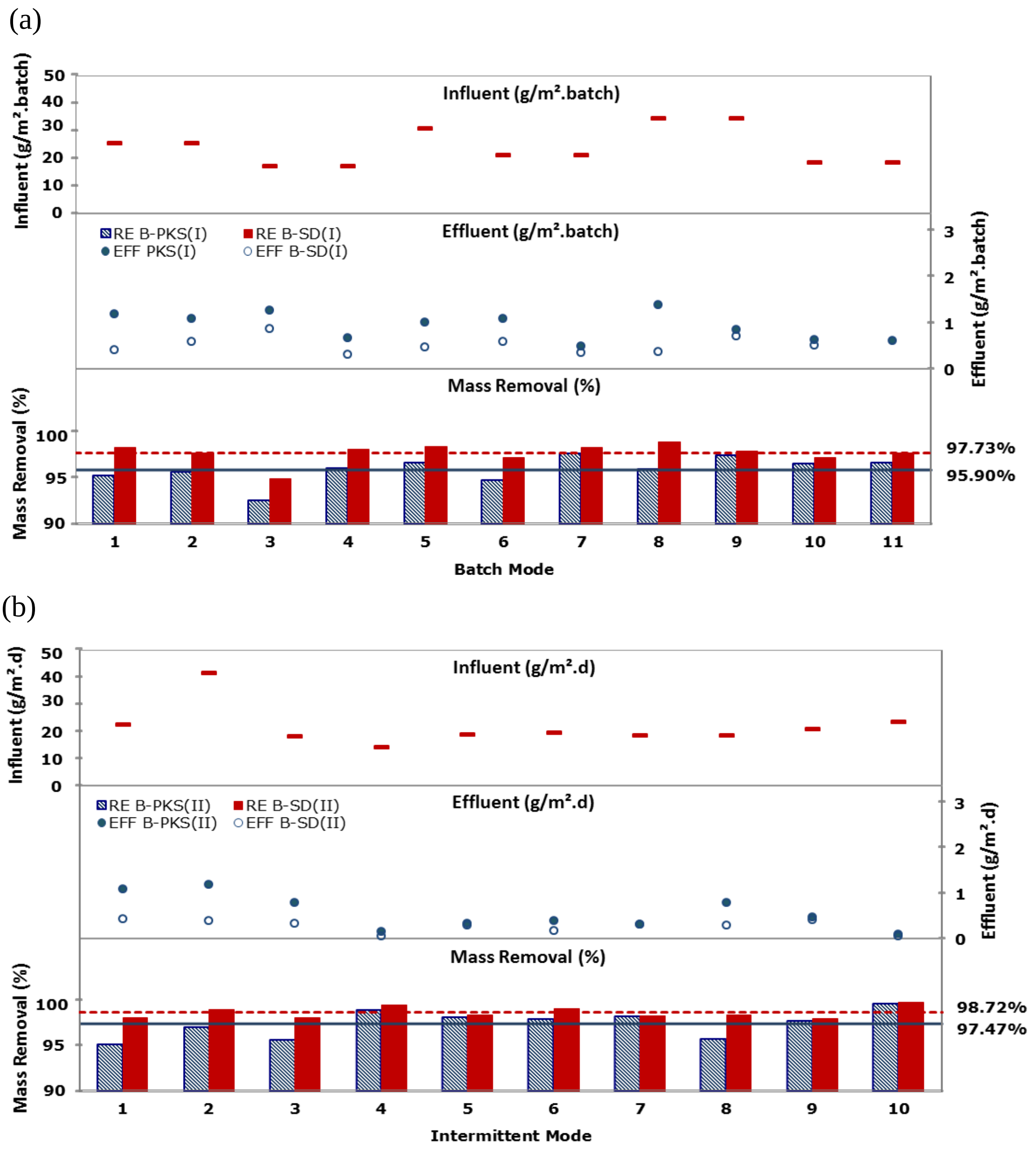
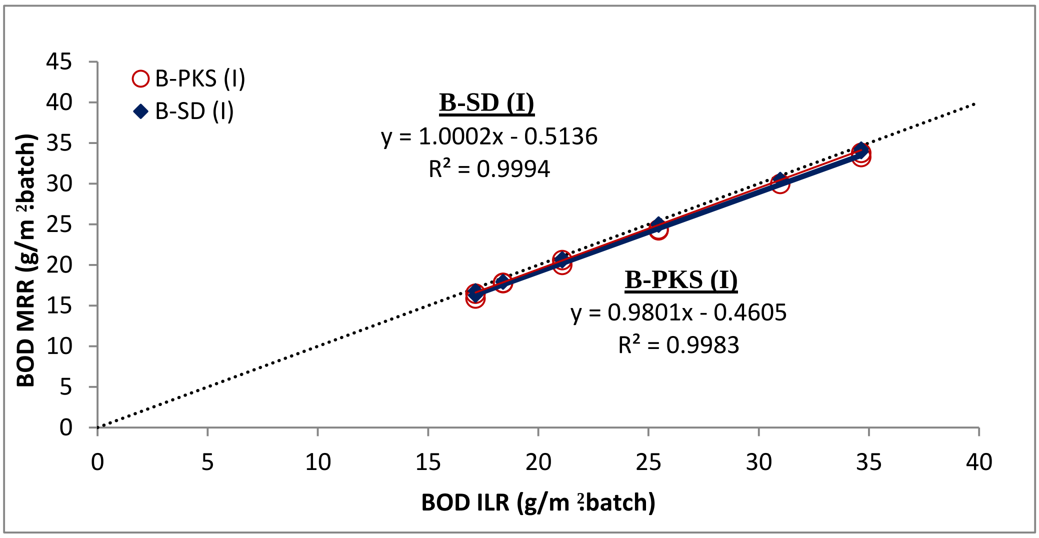


Figure 6.20 Weekly influent BOD_5 areal loading rates and the resulting effluent loads for wetland with and without PKS (B-PKS and B-SD), with the percentages (%) of mass removal for each treatment (horizontal solid line indicates mean removal efficiencies for B-PKS unit; dashed line indicates mean removal efficiencies for B-SD unit, under (a) Batch loading mode (b) Intermittent loading mode

According to Kadlec and Knight (1996), the function of substrate is principally to offer sufficient surface area for microbial attachment while maintaining a adequate hydraulic conductivity of the bed. Sand has significantly greater surface area than that of PKS, in which the subsequent thicker sand layer in wetland B-SD presents more attachment area for biofilms affixation that allows for oxygen renewal by diffusion into the biofilms and removes contaminants. Besides, sand also assists in decelerating the downflow of influent (Torrens et al. 2009), thus allowing for a longer contact time between the influent, the substrates and the plant roots that favours pollutant removal. This is likely the reason behind the better BOD_5 treatment performance in wetland B-SD, which had their main substrate layer substituted by sand instead of PKS.

A significant correlation was found between the COD and BOD_5 loading rates and their corresponding removal rates ($R^2>0.99$, $P<0.001$). Figure 6.21 (a) and (b) show the regression plots of the incoming BOD_5 loading rates against their mass elimination rates for both PKS-filled and SD-filled beds. The positive, strong linear correlation of the organic loading rates and the reduction rates suggested no inhibitory effect of the treatment for an organic loading up to 34.65 g/batch with the batch loading mode, and 9.94 g/d for the intermittent loading approach. The regression lines of both system indicated similarly high predictability of the wetland performance with more than 99% of the variation in the data for OM mass removal rates being explainable by the strength of the incoming OM loads. COD regression followed similar trend as the BOD's for both the beds under the two feeding strategies (Appendix E).

(a)



(b)

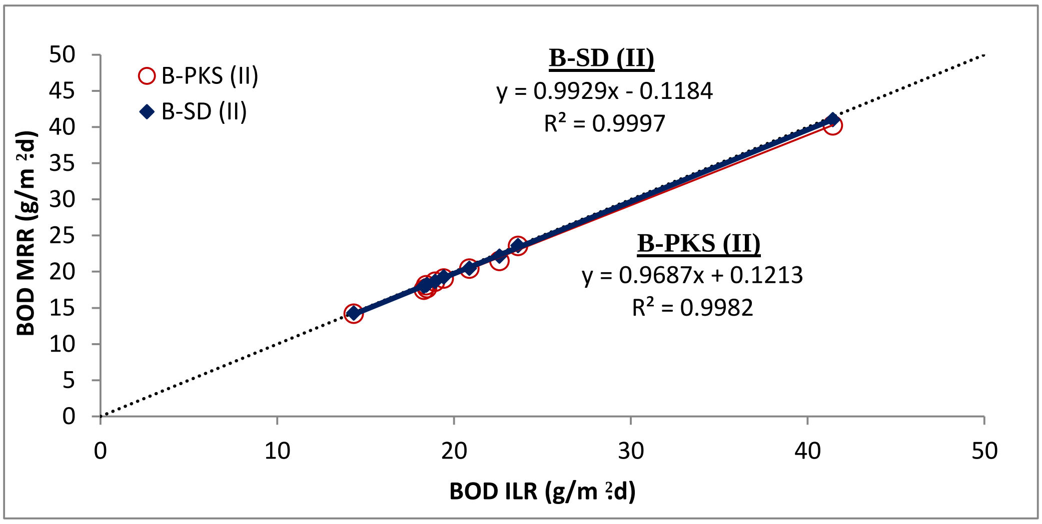


Figure 6.21 Regression graph of BOD_5 mass removal rate (MRR) against influent loading rate (ILR) for B-PKS and B-SD units under (a) Batch loading mode (b) intermittent loading mode. The dotted line represents complete removal.

6.5.2 Nitrogen Removal

The results in Table 6.14 and Table 6.15 demonstrate the influence of PKS presence as an additional carbon source in the wetlands on various N fractions removal efficiency. Generally, higher NH_3-N mean concentration-based removal efficiency was found in beds without PKS (B-SD) in both operating conditions by an average of 2.8% in the intermittently loaded wetland and 10% in the batch loaded wetland.

However, no statistically significant difference was found with the NH_3-N treatment efficiencies between the two beds under both operating conditions, indicating that the PKS and sand were equally effective in reducing ammonia content with the same substrate depth under the same feeding strategy.

Table 6.14 Nitrogen concentration and mass statistics for the influent (pre-treated septage) and the resulting bed effluent of B-PKS (I) and B-SD (I) under batch loading mode (P:R=3:3)

Parameter			Range	Mean (±SD)	MRR*	RE (%)*
NH_3-N	Concentration (mg/L)	Influent	35.70 - 159.08	85.52 (±45.71)		
		Eff. B-PKS (I)	2.70 - 34.17	13.68 (±34.17)		83.64
		Eff. B-SD (I)	0.90 - 33.15	9.33 (±11.04)		92.06
	Mass (g/m^2.batch)	Influent	3.12 - 13.92	7.48 (±4.00)		
		Eff. B-PKS (I)	0.09 - 1.82	0.67 (±0.53)	6.82	91.13
		Eff. B-SD (I)	0.03 - 1.71	0.47 (±0.58)	7.02	95.50
Org-N	Concentration (mg/L)	Influent	52.19 - 316.76	139.59 (±95.03)		
		Eff. B-PKS (I)	4.43 - 25.05	11.28 (±6.08)		86.86
		Eff. B-SD (I)	0.48 - 23.44	15.37 (±6.81)		82.68
	Mass (g/m^2.batch)	Influent	4.57 - 27.72	12.21 (±8.32)		
		Eff. B-PKS (I)	0.24 - 0.93	0.49 (±0.25)	11.72	93.34
		Eff. B-SD (I)	0.03 - 1.31	0.73 (±0.39)	11.49	90.57
NO_3-N	Concentration (mg/L)	Influent	0.00 - 0.00	8.52 (±6.61)		
		Eff. B-PKS (I)	1.20 - 8.40	4.30 (±2.73)		
		Eff. B-SD (I)	6.00 - 66.00	28.02 (±21.37)		
	Mass (g/m^2.batch)	Influent	0.00 - 0.00	0.75 (±0.58)		
		Eff. B-PKS (I)	0.07 - 0.38	0.18 (±0.11)		
		Eff. B-SD (I)	0.36 - 2.79	1.21 (±0.84)		
TN	Concentration (mg/L)	Influent	143.00 - 385.00	233.73 (±81.03)		
		Eff. B-PKS (I)	17.00 - 48.00	29.32 (±10.33)		86.31
		Eff. B-SD (I)	30.00 - 78.50	52.82 (±15.03)		75.56
	Mass (g/m^2.batch)	Influent	12.51 - 33.69	20.45 (±7.09)		
		Eff. B-PKS (I)	0.63 - 2.39	1.34 (±0.60)	19.11	92.91
		Eff. B-SD (I)	1.60 - 3.63	2.41 (±0.63)	18.04	87.51

No. of samples, N= 11

MRR= Mass removal rate

RE= Removal efficiency

* Values presented as the average REs or MRRs calculated from N samples of N experimental runs

Table 6.15 Nitrogen concentration and mass statistics for the influent (pre-treated septage) and the resulting bed effluent of B-PKS (II) and B-SD (II) under intermittent loading mode

Parameter			Range	Mean (±SD)	MRR*	RE (%)*
NH_3-N	Concentration (mg/L)	Influent	68.34 - 197.96	127.96 (±40.66)		
		Eff. B-PKS (II)	0.00 - 9.70	3.40 (±9.70)		96.59
		Eff. B-SD (II)	0.00 - 2.80	0.92 (±1.08)		99.26
	Mass (g/m^2.d)	Influent	5.98 - 17.32	11.20 (±3.56)		
		Eff. B-PKS (II)	0.00 - 0.74	0.25 (±0.27)	10.95	97.11
		Eff. B-SD (II)	0.00 - 0.20	0.06 (±0.07)	11.13	99.41
Org-N	Concentration (mg/L)	Influent	63.77 - 436.00	146.72 (±106.40)		
		Eff. B-PKS (II)	2.88 - 43.58	19.30 (±14.07)		85.28
		Eff. B-SD (II)	11.88 - 77.76	37.35 (±20.13)		71.97
	Mass (g/m^2.d)	Influent	5.58 - 38.15	12.84 (±9.31)		
		Eff. B-PKS (II)	0.21 - 2.83	1.39 (±1.00)	11.45	87.86
		Eff. B-SD (II)	0.91 - 6.20	2.84 (±1.56)	9.99	75.77
NO_3-N	Concentration (mg/L)	Influent	1.10 - 69.30	33.78 (±28.92)		
		Eff. B-PKS (II)	4.20 - 71.20	21.87 (±21.45)		
		Eff. B-SD (II)	23.20 - 94.00	56.55 (±23.99)		
	Mass (g/m^2.d)	Influent	0.10 - 6.06	2.96 (±2.53)		
		Eff. B-PKS (II)	0.29 - 6.11	1.65 (±1.80)		
		Eff. B-SD (II)	1.71 - 7.15	4.05 (±1.80)		
TN	Concentration (mg/L)	Influent	165.00 - 628.00	309.17 (±128.00)		
		Eff. B-PKS (II)	13.00 - 79.00	44.70 (±22.49)		83.10
		Eff. B-SD (II)	53.00 - 142.00	94.90 (±29.43)		64.24
	Mass (g/m^2.d)	Influent	14.44 - 54.95	27.05 (±11.20)		
		Eff. B-PKS (II)	0.97 - 6.70	3.30 (±1.77)	23.75	85.51
		Eff. B-SD (II)	3.99 - 10.20	6.78 (±2.17)	20.27	70.65

No. of samples, N = 10

MRR= Mass removal rate

RE= Removal efficiency

* Values presented as the average REs or MRRs calculated from N samples of N experimental runs

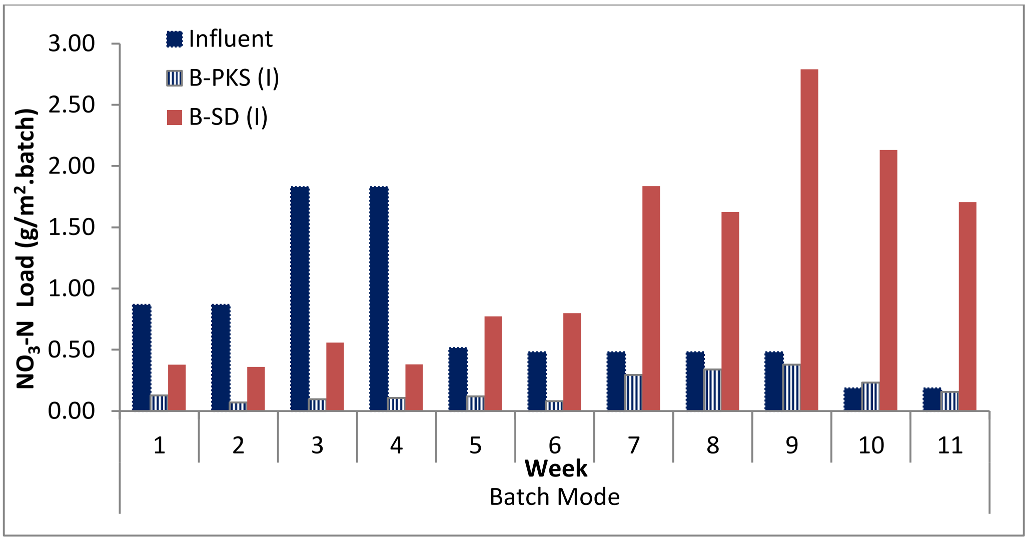
Both the intermittent and batch loading strategies presented good ammonia treatment (Table 6.14 and Table 6.15), presumably via nitrification as the major removal pathway. Nitrification is heavily dependent on the presence of DO (Ong et al. 2010), and this suggested that both the B-PKS and B-SD wetlands operated under the intermittent and batch mode had had a good amount of atmospheric oxygen supplied into the substrate via diffusion and convection. Effluent DO was found to range between 1.1 - 2.3 mg/L and 2.5 - 7.6 mg/L for both beds under batch and intermittent loading mode, respectively (Table 6.10 and Table 6.11). Both the feeding strategies had clearly improved the effluent quality with the increased DO content and thus the high nitrification efficiencies. Although it is well known that ammonia oxidisers compete poorly with aerobic heterotrophic microorganisms, the additional carbon source (PKS) in the substrate which contributed to greater growth and biomass of heterotrophs did not significantly deteriorate the ammonia removal efficiencies. This could be attributed to the ample oxygen supply that repressed the competition between nitrifiers and the heterotrophs for oxygen intake.

Besides, the VF wetlands itself have high hydraulic gradient in the substrate due to the influent vertical downflow direction and greater oxygen flux for nitrification. The intermittent and batch application of the influent together with the vertical drainage of the feed, restored aerobic environment in the bed, allowing aerobic condition to prevail in the wetlands regardless of the substrate material. The NH_3-N MRR of the B-PKS (II) bed was 10.9 g/m^2.d with mean NH_3-N input of 11.20 g/m^2.d. Sand-filled beds yielded NH_3-N elimination efficiency between 87.7 - 99.4% for batch-fed bed and 97.8 - 100% in the intermittently-fed bed (Appendix D3). Wetland B-PKS can achieve NH_3-N mass reduction efficiency up to an average of 91.1% with batch mode, and as high as 97.1% with intermittent mode (Table 6.14 and Table 6.15).

Such removal rate was relatively similar compared to a research conducted by Saeed and Sun (2011b) with 3-staged hybrid engineered wetland system treating mechanically pre-treated wastewater. In the study, with over 13.5 g/m^2.d of NH_4–N input, NH_4–N removal rate of more than 11.7 g/m^2.d was achieved at the vertical flow columns which consisted of wood mulch substrate (placed as the first stage of treatment). The final effluent from wetlands B-PKS (I) and B-SD (I) had concentration of 13.7 and 9.3 mg NH_3-N/L, respectively; and the effluent from wetlands B-PKS (II) and B-SD (II) bed had 3.4 and 0.92 mg NH_3-N/L, respectively.

Due to the tandem of ammonia and nitrite oxidation during nitrification process, nitrate was formed and accumulated when the denitrification process is hindered or limited. As shown in Table 6.14 and Table 6.15, and Figure 6.22 (a) and (b), nitrate accumulation was observed in wetland B-SD where PKS was absent. Most of the weekly effluent discharge of wetland B-SD (II) with intermittent feeding (Figure 6.22(b)) did not satisfy the acceptable nitrate nitrogen limit of sewage discharge into any inland waters or Malaysia waters according to the Malaysia Environmental Quality Act 1974 (Environmental Quality (Sewage) Regulation 2009) (please see Appendix A).

(a)



(b)

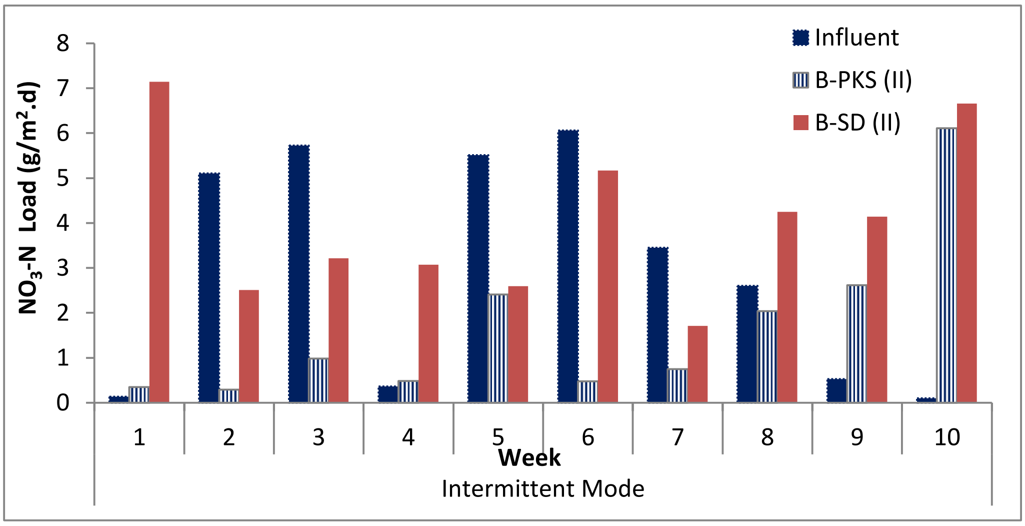


Figure 6.22 Influent and effluent NO_3-N mass for B-PKS and B-SD at (a) batch loading mode (b) intermittent loading mode

Denitrification can be induced with oxygen levels less than 0.2 mg/L, a sufficient supply of nitrate and carbon food, and the presence of a physical site where the bacteria required in the process can attach to (Horne 1995). Thus denitrification can typically be limited by the availability of NO_3, O_2 or labile organic carbon. Organic carbon in the designed wetland was supplied by the PKS which was added in as part of the bed substrate. Wetland with absence of PKS (B-SD) had significantly higher nitrate content in the effluent, most likely as a result of a lower rate of denitrification to convert the inorganic nitrogen component into gaseous N_2. In the sand-aggregate wetland B-SD, the organic carbon availability appeared to have limit denitrification as there was insufficient labile C to supply the metabolic needs of denitrifiers. This is because sand is relatively inert and devoid of carbon and N.

In Figure 6.23 (a) and (b) which show that the lower NO_3-N concentrations are associated with the higher COD concentrations in the effluent of wetland B-PKS, have supported the statement such that the PKS was supplying additional organic carbon in the wetlands for influent treatment. This indicates the leaching of organic carbon from the substrate that elevates denitrification and removes nitrate. NO_3-N concentrations in the effluent of wetland B-SD on the other hand showed positive gradient in the plot with the increment of NO_3-N related to the increment of COD concentrations. These result trends were similar to the study outcome reported by Saeed and Sun (2011a), which suggested that the trend of increased NO_3-N with increased COD concentrations was related to the limited denitrification in their gravel column, due to the lack of organic carbon that resulted in NO_3-N accumulation. Thus in wetland B-SD which did not have extra supply of C, the nitrate pooling phenomena was observed.

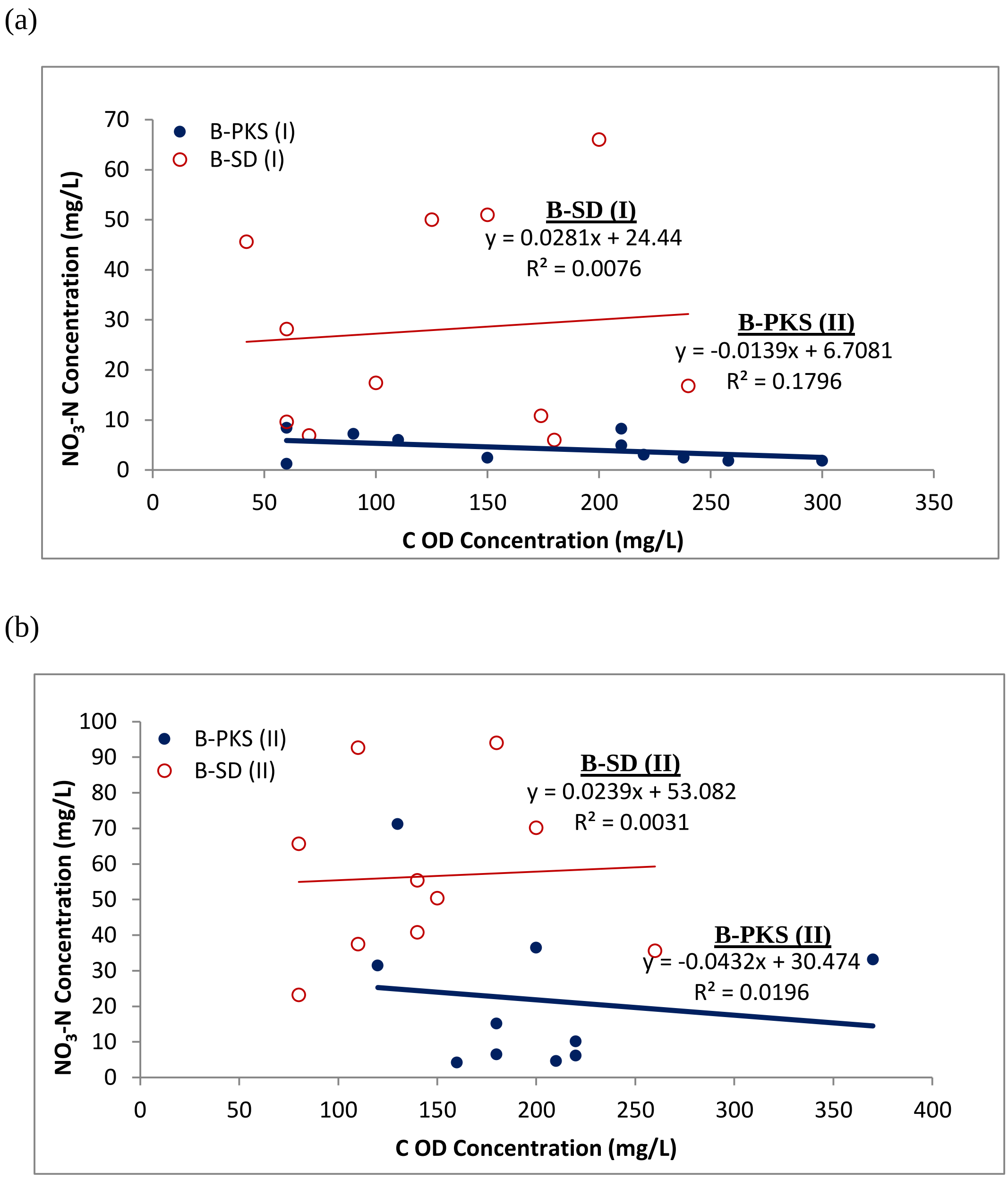
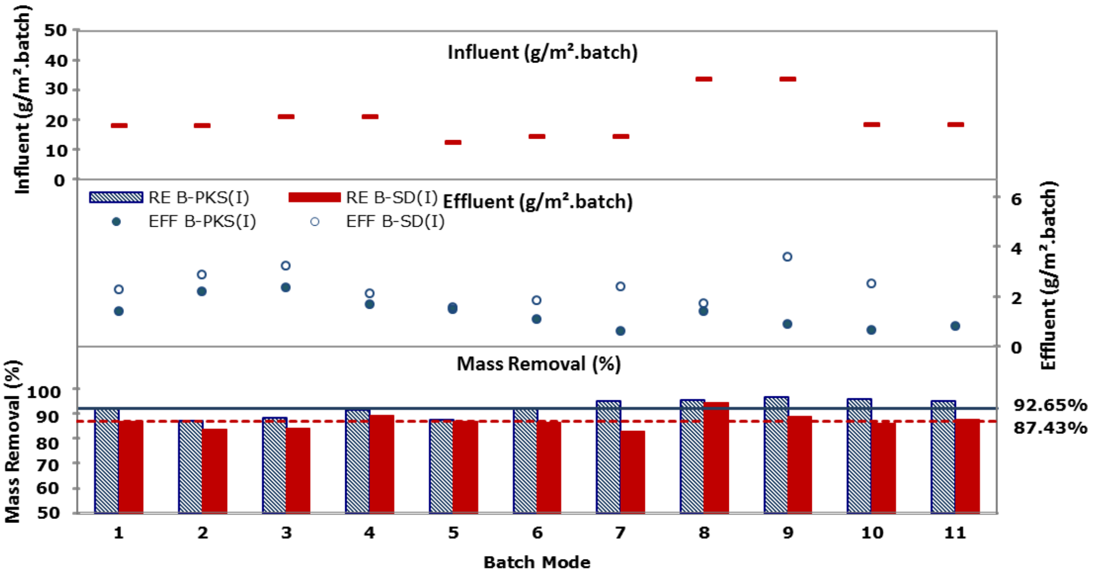


Figure 6.23 Plot of effluent COD concentration vs. effluent NO_3-N concentration for B-PKS and B-SD at (a) batch loading mode (b) intermittent loading mode

The effect of nitrate accumulation in wetland B-SD (I) due to the absence of PKS was most obvious in the batch loaded wetland, with mean NO_3-N loads and concentrations at approximately 7 times more than in the effluent of wetland B-PKS (I) due to the prolonged influent impounding time of 3 days (Table 6.14). The batch operation mode which completely drained the effluent before refilling the wetlands left the wetlands idle for 3 days following 3 days of influent ponding. This operational strategy allows wetland to have sufficient resting time before the next batch of pre-treated septage was fed onto the bed, and subsequently left ponded for another 3 days. Under the batch loading mode (P:R=3:3), the influent had longer hydraulic retention time (HRT) in the wetlands, where nitrate reduction can take place, with increased contact time between denitrifying bacteria, the electron donor and nitrate substrate during the ponding time. The maximum contact time between the material and the effluent are considered to be one of the key factors for the pollutant removal processes according to Langergraber (2011). With the presence of PKS, the batch fed wetland B-PKS (I) produced effluent with the NO_3-N level that satisfy Standard A according to Malaysia Environmental Quality Act 1974 (Environmental Quality (Sewage) Regulation 2009 for effluent discharge into enclosed water bodies) (please see Appendix A).

Aside from a sufficient supply of NO_3-N and carbon, denitrification also requires the presence of anaerobic conditions. Protracted ponding period during the cyclic batch feeding mode promoted an anaerobic environment due to oxygen deprivation, where this regulatory ponding regime was not implemented in intermittently fed beds. Figure 6.24 (a) and (b) depict the TN influent loading rates and the resulting effluent loads for wetlands B-PKS and B-SD, with their corresponding percentages (%) of mass removal for each treatment. Figure 6.25 (a) and (b) show the chart of N fractions in the wetlands influent and effluent. According to the figures, TN loads in the effluent of wetlands B-SD (I) and B-SD (II) were both dominated by NO_3−N, with relatively lesser content of organic and ammonia nitrogen. This was especially obvious in the intermittently loaded wetlands. Intermittently operated beds were constantly more aerated than the batch operated beds, resulting in a greater fraction of NO_3-N in the wetland effluent (Figure 6.25 (a) and (b)). The results from the study revealed that nitrate pooling was more evident in wetland B-SD where deficient carbon was clearly the limiting factor for the denitrification process.

(a)



(b)

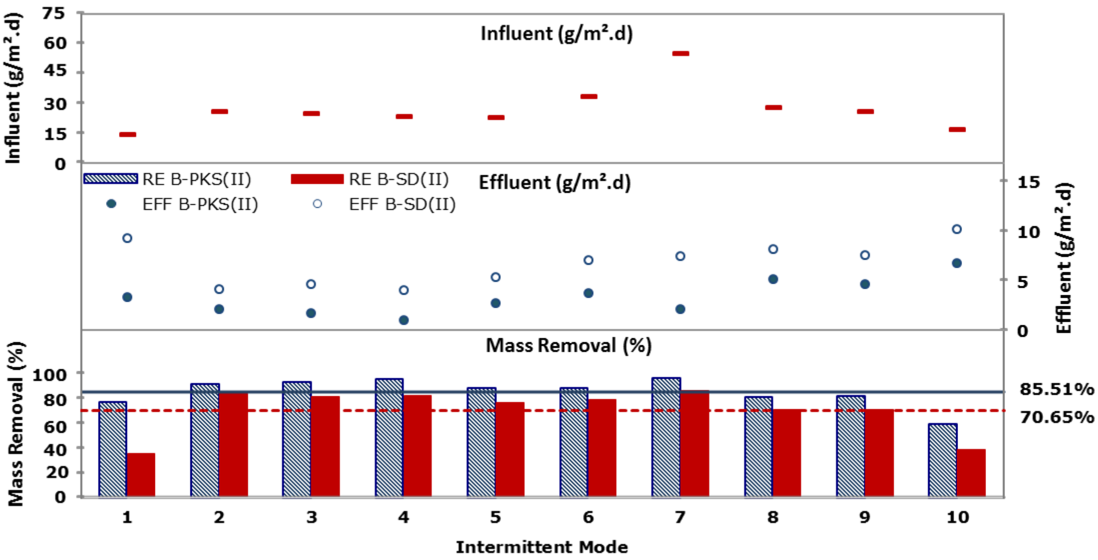
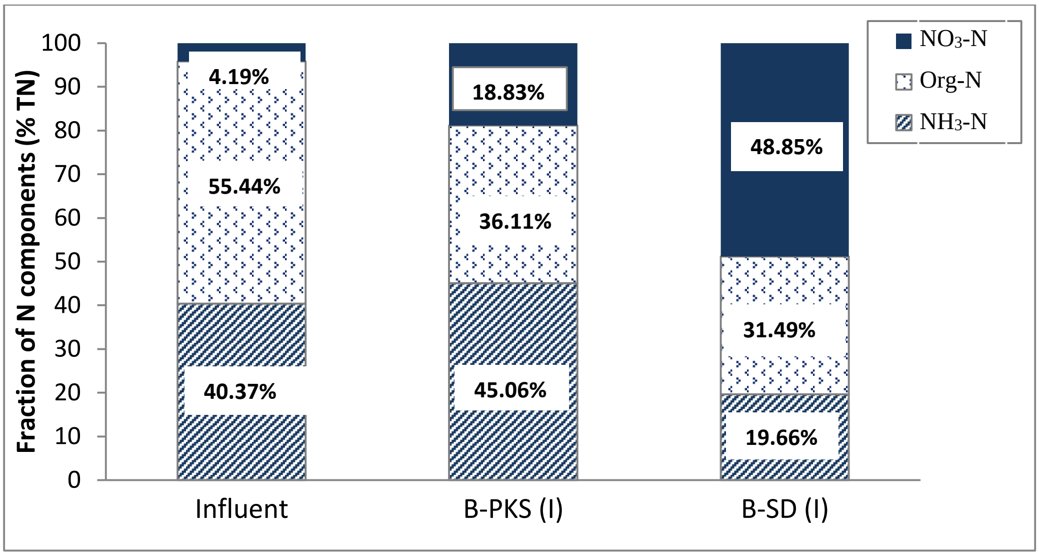


Figure 6.24 Weekly influent TN areal loading rates and the resulting effluent loads for wetland with and without PKS (B-PKS and B-SD), with the percentages (%) of mass removal for each treatment (horizontal solid line indicates mean removal efficiencies for B-PKS unit; dashed line indicates mean removal efficiencies for B-SD unit, under (a) Batch loading mode (b) Intermittent loading mode

(a)



(b)

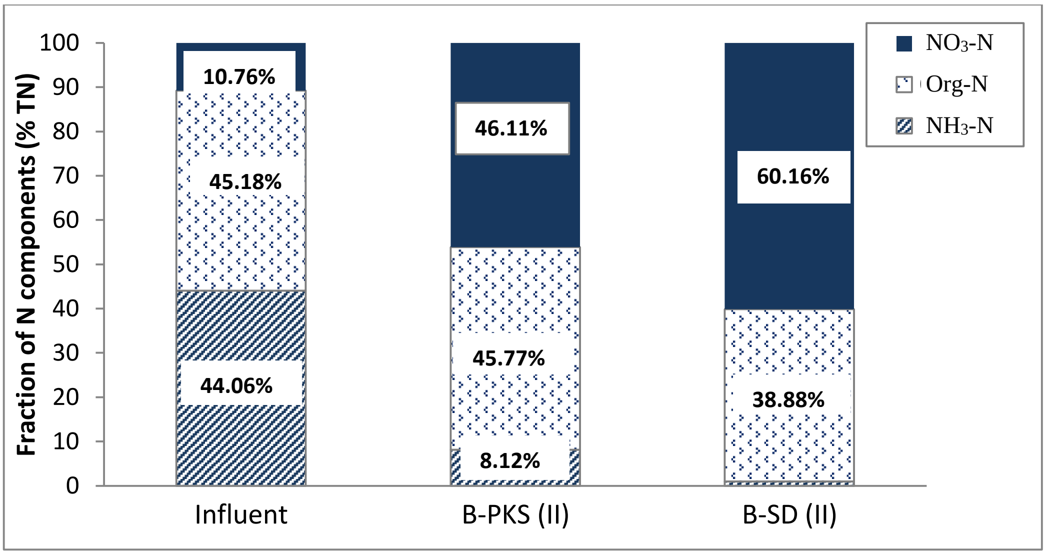


Figure 6.25 Fractions of N components in the influent pre-treated septage and effluent from B-PKS (II) and B-SD (II) under (a) batch loading mode (b) intermittent loading mode

The presence of higher nitrate contents in the effluent of wetland B-SD was also supported by the difference in the EC value recovered from the effluent of the two beds. Effluent of wetland B-SD (II) had EC ranging from 2.25 - 3.11 mS/cm which were higher compared to the effluent of wetland B-PKS (II) with EC varying between 1.95 - 2.50 mS/cm, for the intermittently fed wetlands. Similarly at the batch loaded wetlands, greater EC was also obtained in the effluent of wetland B-SD (I) with value falling in the range of 2.28 - 2.89 mS/cm against 2.12 - 2.57 mS/cm for the effluent of wetland B-PKS (I). Besides, the pH value of the effluent in wetland B-SD was also slightly lower (6.54 - 6.90 for wetland B-SD (II) and 6.23 - 6.73 for wetland B-SD (I)) than wetland B-PKS (6.77 - 7.09 for wetland B-PKS (II) and 6.41 - 6.84 for wetland B-PKS (I)) as a result of nitrate accumulation and the production of H+ ions during organic matter mineralization.

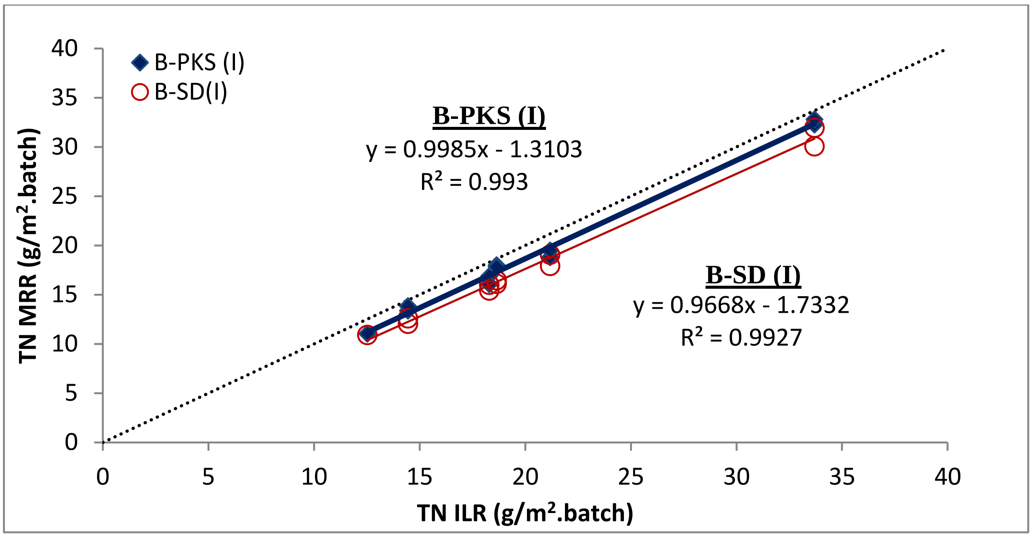
Total mass removal at wetland B-PKS (I) and B-PKS (II) was 92.9% and 85.5%, respectively for TN, accounting for 4.6 g and 5.7 g of nitrogen removed accordingly per cycle (at MRRs of 19.1 g/m^2/batch and 23.8 g/m^2/d, respectively). The wetland with inclusion of PKS and fed intermittently (B-PKS (II)) achieved significantly higher TN removal rates, when compared with other studies carried out on wetlands filled with organic substrate (7.2 – 15.8 g N/m^2 d; woodmulch substrate (Saeed and Sun 2011b)), demonstrating the efficiency of the PKS-filled vertical beds in removing the incoming N loads. High N removal rates in the pilot system could be linked to the high nitrification in the VF wetlands (which is often the limiting step for eliminating nitrogen from wastewater in treatment wetlands) and the availability of organic carbon from the PKS that foster the removal of NO_3–N via denitrification at anaerobic sites, which is an essential step to completely eliminate N from the system. However, the N removal was also highly dependent on loading rates (Tanner and Sukias 2003) and thus the high N removal efficiency of the wetlands in this study could be due to the higher influent N mass applied onto the beds compared to the other studies.

The average NH_3-N reduction efficiency was high (above 83% for concentration and more than 90% for mass) for both wetlands (B-SD and B-PKS) loaded under the feeding regimes, indicating that nitrification was not the limiting step for effective TN removal. Instead, denitrification had appeared to be the restricting factor especially in the wetlands with the absence of PKS (wetland B-SD). Besides the anoxic conditions, carbon supply is also one of the important requirements for occurrence of denitrification (Laber, Haberl and Langergraber 2003). The PKS may have played a dual role in denitrification, as it supports the heterotrophic metabolism of denitrifying bacteria (PKS effectively functioned to provide extra C for denitrifiers consumption) and also the oxygen consumption in the wetlands, with the degradation of the organic C which creates anaerobic microsites necessary for denitrification (Hamersley et al. 2001; Janke 1985; Jorgensen and Revsbech 1985).

For wetlands operated in a more aerobic state as in the intermittently loaded system (B-PKS (II)), the role of C in creating anaerobic microsites could be more important than its role as a source of C substrate for denitrifiers growth. Under sufficiently aerated system, presence of PKS helps with additional oxygen consumption which creates more anaerobic microsites for the occurrence of denitrification that yield N_2 (nitrogen gas) as the end product. On the other hand, for the batch loaded system with prolonged HRT during the effluent ponding period (anaerobic period), PKS acted as additional source of C to support denitrification and is regarded as the determining factor for N removal.

TN mass removals under the batch and intermittent feeding modes are shown in Figure 6.26 (a) and (b) as the function of substrate materials and the influent N loading rates. We found that the PKS significantly improved nitrogen removal with the considerable increment in nitrate reduction rates without devolving the removal efficiencies of NH_3-N. The strong linear correlation ($R^2 > 0.99$, $P < 0.001$) was observed between the wetlands ILRs and MRRs for TN at both wetlands B-PKS and B-SD, which suggested that the ILRs for nitrogen had a significant influence on the MRRs. The close fit of the points to the regression lines also indicate a remarkably constant areal mass removal rates for TN. In general, the MRRs of TN were constantly higher in wetland B-PKS under both loading mode, indicating the higher N removal efficiency in the wetland packed with PKS over the wetland without the presence of PKS.

(a)



(b)

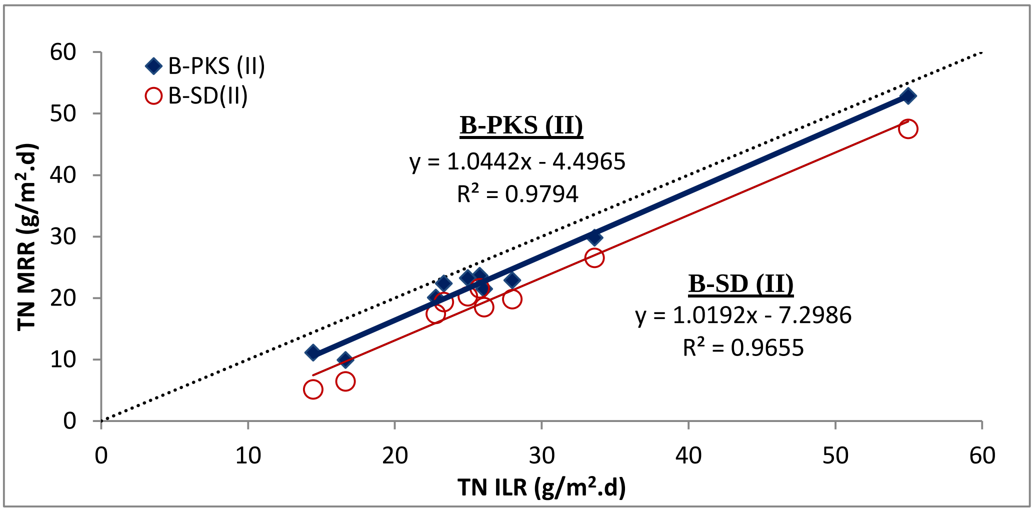


Figure 6.26 Regression graph of TN mass removal rate (MRR) against influent loading rate (ILR) B-PKS and B-SD under (a) batch loading mode (b) intermittent loading mode. The dotted line represents complete removal

6.5.3 Particulate Solids Removal

Table 6.16 and Table 6.17 show the concentration and mass statistics for wetland B-PKS and B-SD operated under batch and intermittent feeding regimes. Total Solids (TS) was observed to be the parameter with the lowest removal efficiency. The average TS mass removal of the B-PKS and B-SD beds were not significantly different, with mean value around 83% in wetland B-PKS (I) and 84% in wetland B-

SD (I), under batch feeding strategy (Table 6.16). The insignificance of the bed materials in terms of TS mass removal performance was also observed in wetlands loaded intermittently, with a mean of 72.3% and 63.6% of mass reduction efficiencies for wetlands B-PKS (II) and B-SD (II) respectively (Table 6.17). The lower TS elimination efficiency was most likely related to the non-removed TDS fraction in the effluent due to the non-biodegradable COD fraction and the inorganic (such as accumulation of NO_3-) and colloidal substances in the composition of the treated effluent. Nonetheless, the mass removal of solids was still considered very effective; removal efficiencies were stable throughout the study period and are not affected by the type of substrate used.

Table 6.16 Particulate solids concentration and mass statistics for the influent (pre-treated septage) and the resulting bed effluent of B-PKS (I) and B-SD (I) under batch loading mode (P:R=3:3)

Parameter			Range	Mean (±SD)	MRR*	RE (%)*
TS	Conc. (mg/L)	Influent	3,836 - 7,684	6,415 (±1,044)		
		Eff. B-PKS (I)	1,232 - 2,488	1,996 (±458.29)		67.87
		Eff. B-SD (I)	1,048- 2,628	1,820 (±490.76)		70.62
	Mass (g/m^2.batch)	Influent	335.65 - 672.35	561.30 (±91.34)		
		Eff. B-PKS (I)	34.71 - 129.90	92.86 (±34.65)	468.44	82.95
		Eff. B-SD (I)	35.03 - 141.60	87.52 (±32.59)	473.79	84.01
TSS	Conc. (mg/L)	Influent	950.00 - 5,083	2,345(±1,452)		
		Eff. B-PKS (I)	8.00 - 328.00	111.64 (±91.62)		94.76
		Eff. B-SD (I)	3.20 - 272.00	67.47 (±75.16)		96.71
	Mass (g/m^2.batch)	Influent	83.12 - 444.79	205.20 (±127.01)		
		Eff. B-PKS (I)	0.42 - 11.54	4.65 (±3.22)	200.55	97.33
		Eff. B-SD (I)	0.18 - 10.95	3.06 (±3.16)	202.14	98.18
VSS	Conc. (mg/L)	Influent	450.00 - 2,833	1,355 (±854)		
		Eff. B-PKS (I)	0.00 - 252.00	63.64 (±72.93)		94.89
		Eff. B-SD (I)	0.00 - 216.00	32.36 (±62.05)		97.20
	Mass (g/m^2.batch)	Influent	39.38 - 247.92	118.59 (±74.71)		
		Eff. B-PKS (I)	0.21 - 8.86	2.57 (±2.58)	116.02	97.48
		Eff. B-SD (I)	0.00 - 8.69	1.41 (±2.50)	117.18	98.54

No. of samples, N = 11

MRR= Mass removal rate

RE= Removal efficiency

* Values presented as the average REs or MRRs calculated from N samples of N experimental runs

Table 6.17 Particulate solids concentration and mass statistics for the influent (pre-treated septage) and the resulting bed effluent of B-PKS (II) and B-SD (II) under intermittent loading mode

Parameter			Range	Mean (±SD)	MRR*	RE (%)*
TS	Conc. (mg/L)	Influent	4,308 - 18,800	8,541 (±4,613)		
		Eff. B-PKS (I)	1,612 - 2,996	2,372 (±457.14)		66.81
		Eff. B-SD (I)	2,516 – 3,920	3,087 (±436.89)		55.48
	Mass (g/m^2.d)	Influent	377 - 1,645	747.36 (±403.66)		
		Eff. B-PKS (I)	122.91 - 217.85	172.81 (±32.65)	574.56	72.30
		Eff. B-SD (I)	160.49 - 298.07	221.28 (±41.36)	526.08	63.58
TSS	Conc. (mg/L)	Influent	1,560 - 5,560	2,666 (±1,139.70)		
		Eff. B-PKS (I)	10.00 - 156.00	91.90 (±51.87)		96.35
		Eff. B-SD (I)	8.00 - 145.00	76.50 (±41.60)		96.78
	Mass (g/m^2.d)	Influent	136.50 - 486.50	233.26 (±99.72)		
		Eff. B-PKS (I)	0.65 - 10.92	6.72 (±3.71)	226.54	96.92
		Eff. B-SD (I)	0.51 - 10.91	5.53 (±3.12)	227.73	97.33
VSS	Conc. (mg/L)	Influent	955 - 5,372	2,106 (±1,298)		
		Eff. B-PKS (I)	6.00 - 84.00	44.80 (±27.84)		97.32
		Eff. B-SD (I)	4.00 - 65.00	36.10 (±20.38)		97.75
	Mass (g/m^2.d)	Influent	83.56 - 470.05	184.28 (±113.54)		
		Eff. B-PKS (I)	0.39 - 5.76	3.25 (±2.00)	181.03	97.75
		Eff. B-SD (I)	0.26 - 4.89	2.61 (±1.51)	181.67	98.11

No. of samples, N = 10

MRR= Mass removal rate

RE= Removal efficiency

* Values presented as the average REs or MRRs calculated from N samples of N experimental runs

Both wetlands B-PKS and B-SD had high TSS removal efficiency up to a maximum of 99.8% in terms of mass reduction under both regimes (Figure 6.27 (a) and (b); Appendix D3). The resulting effluent from all beds was evidently clearer and free of visible suspended matter upon exit from the wetlands. This could be due to the fact that TSS removal takes place through physical processes. These results are similar to the findings of other studies (Prochaska, Zouboulis and Eskridge 2007; Kadlec and Knight 1996).

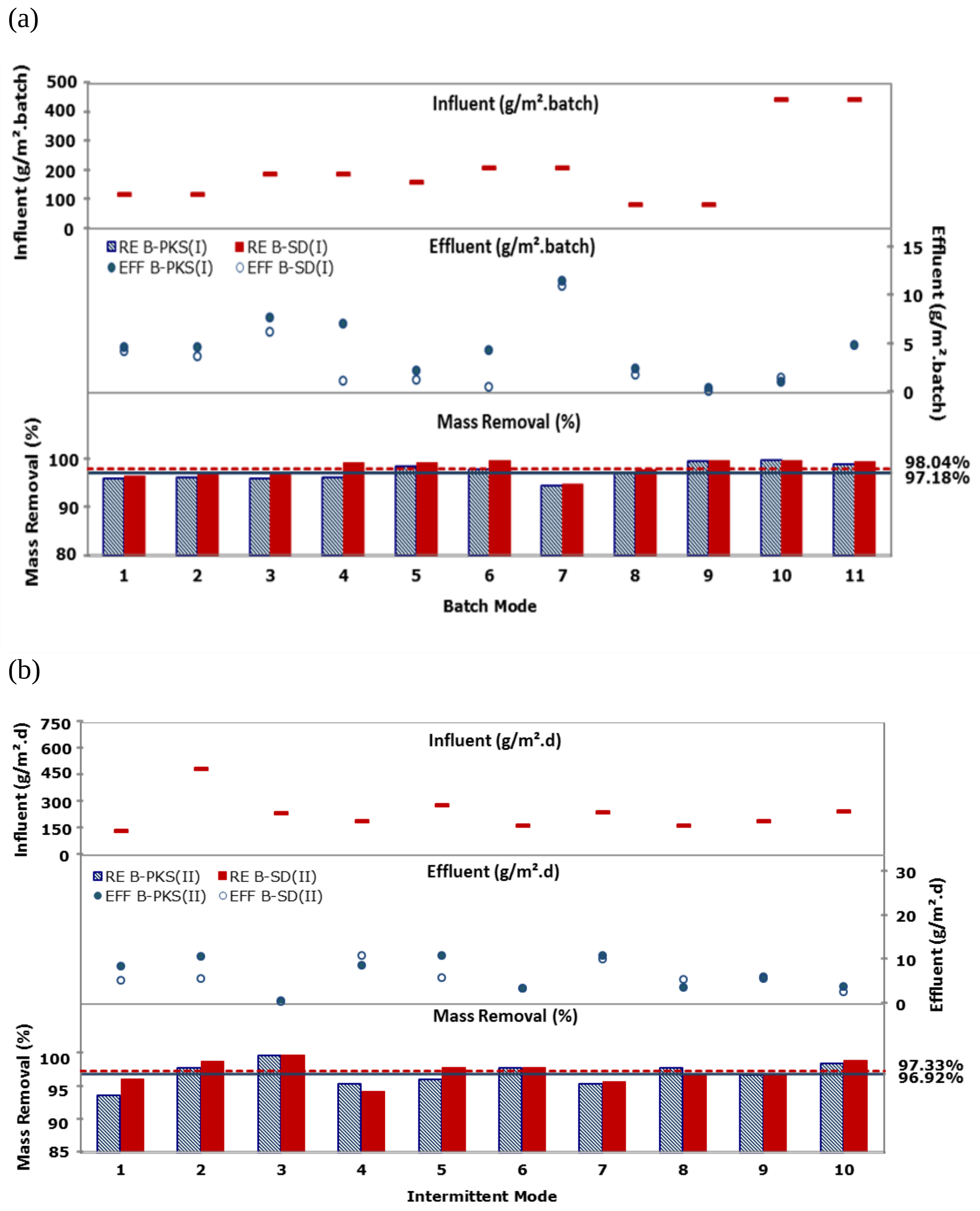
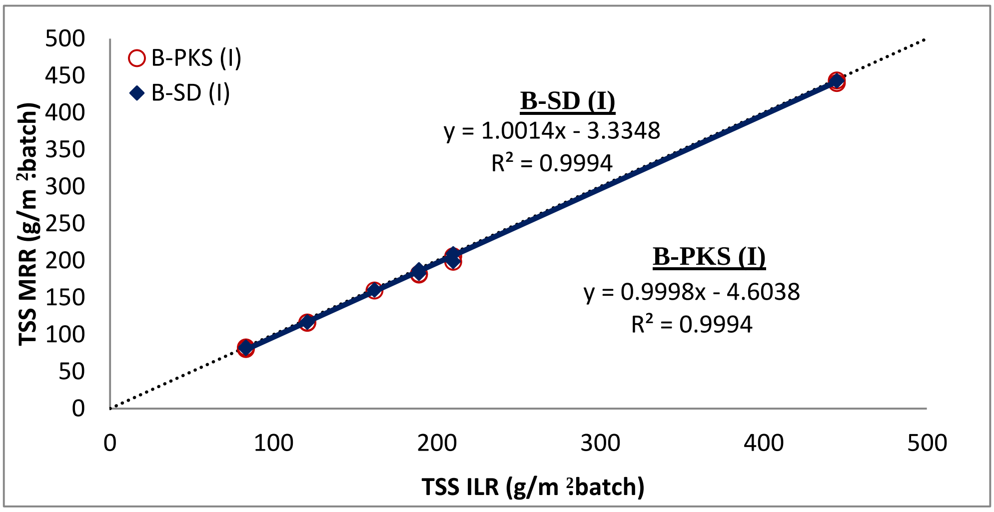


Figure 6.27 Weekly influent TSS areal loading rates and the resulting effluent loads for wetland with and without PKS (B-PKS and B-SD), with the percentages (%) of mass removal for each treatment (horizontal solid line indicates mean removal efficiencies for B-PKS unit; dashed line indicates mean removal efficiencies for B-SD unit, under (a) Batch loading mode (b) Intermittent loading mode

Although the results had generally shown that the average removal efficiency of wetland B-SD was higher than wetland B-PKS, the difference between them was not found to be statistically significant ($P>0.05$) indicating similar good performance of the two beds irrespective of the substrate material. During the period of monitoring, VSS level was also found to reduce greatly by over 97% at both wetlands B-PKS (II) and B-SD (II), giving a mean effluent mass of 0.78 g and 0.65 g, respectively with no statistical dependence of the VSS reduction performance found with the effect of PKS ($P>0.05$) (Table 6.17). The wetlands with inclusion of PKS were able to remove sufficient VSS to attain a mean positive 99.7% and 99.8% of the system overall VSS removal in terms of concentration and mass, respectively for the two-staged system as a whole.

The TSS removal performance presented in Figure 6.28 shows good correlation between the mass applied and mass treated. MRRs for TSS showed a linear relationship to mass loadings, similar to that reported by Conley, Dick, and Lion (1991). There was no discernible difference between the treatment performance of wetlands B-PKS and B-SD, with both showing similar fluctuations of the effluent TSS mass during the monitoring period. The linear regression showed that the TSS MRRs could be accurately explained by the TSS ILRs ($R^2 >0.99$, $P <0.001$). The TS and VSS regression graphs showed similar trend with positive linear relationship and high correlation between the solids ILRs and their corresponding solids MRRs (Appendix E).

(a)



(b)

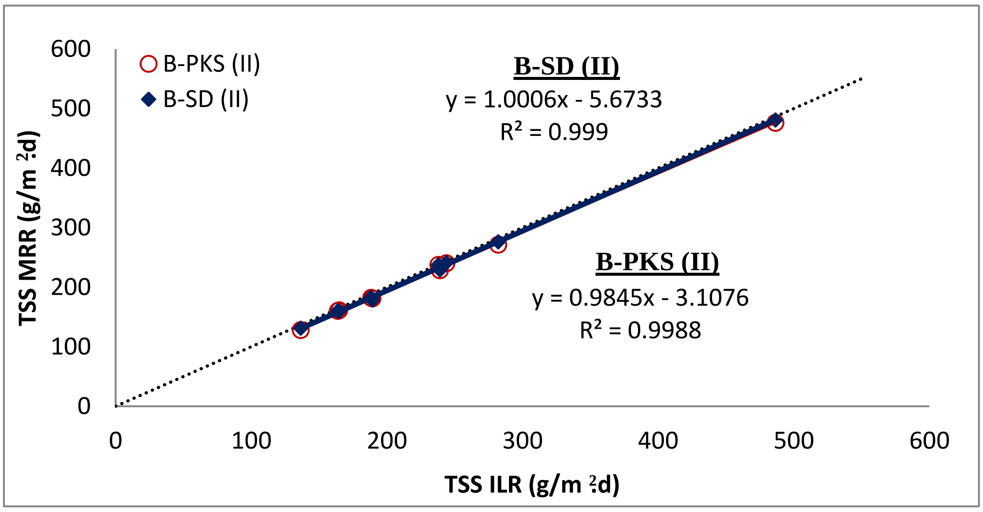


Figure 6.28 Regression graph of TSS mass removal rate (MRR) against influent loading rate (ILR) (g/m ²d) for B-PKS and B-SD under (a) batch loading mode (b) intermittent loading mode. The dotted line represents complete removal

6.6 Summary

This study has revealed that the presence of plants had a positive influence on septage effluent treatment at the second stage of the VFEWs system, where the planted unit had a significantly higher percentage of NH_3-N (mean of 97.1% against 78.3%) and TSS (mean of 96.9% against 94%) mass removal efficiencies than the unplanted wetland counterpart. The presence of plants however, did not significantly affect the treatment performance of the wetlands for COD removal, suggesting that plants played a minor role in organic carbon retention at this second stage of treatment. All the planted wetlands (B-*Phrag* and B-*Costus*) produced effluent with COD and TSS concentrations that satisfied at least Standard B according to the Environmental Quality (Sewage) Regulation 2009 for effluent discharge into inland waters and Malaysian waters.

The planted wetland was found to provide a more oxidised treatment environment in comparison with the unplanted wetland, where greater DO values and improved ORP status were observed in the treated effluent collected from the planted wetland. Higher mean DO concentration was recovered from the effluent of the planted bed (from 1.32 mg/L in the influent to 4.86 mg/L in the effluent), and it was significantly greater than that found in the effluent of the unplanted unit (1.86 mg/L). Conserved positive ORP values (118 - 403 mV) were also found in the effluent of the planted bed, which suggested aerobic conditions within the wetland substrate that stimulates bacterial activities and accelerates the nitrogen and organic compounds breakdown.

The study also suggested the possible inclusion of *Costus woodsonii* in septage effluent treatment which may potentially increase the commercial and aesthetic value of the wetland system. The B-*Phrag* system showed only marginally higher mean OM and TSS mass removal rates than the B-*Costus* beds, with no statistical importance found between the efficiency the two systems. Although significantly poorer NH_3-N removal performance was found in the *Costus*-planted wetland compared to the *Phragmites*-planted bed, it was observed that the *Costus*-planted wetland was still capable of producing effluent with a considerably low ammonia content (mean of 2.1 mg/L or 0.038 g/d) at a good rate of removal (mean of 4.7 $g/m^2 \cdot d$). All the weekly NH_3-N levels examined in the effluent of wetland B-*Phrag* and B-*Costus* met Standard A according to Malaysia Environmental Quality Act 1974 (Environmental Quality (Sewage) Regulation 2009 for effluent discharge into inland waters within catchment areas). All the wetlands studied at the second stage had demonstrated a consistent treatment performance with the pollutants removal rates accurately predictable by the incoming pollutants loading rates.

Nitrate accumulation was observed in the effluent of wetland B-SD where PKS was absent, with mean NO_3-N content at approximately 7 and 2.5 times more than that recovered in the effluent of wetland B-PKS (I) and B-PKS (II), loaded with batch and intermittent mode, respectively. Most of the weekly effluent discharge of wetland B-SD (II) with intermittent feeding (Figure 6.22(b)) did not satisfy the acceptable nitrate nitrogen limit of sewage discharge into any inland waters or Malaysia waters according to the Malaysia Environmental Quality Act 1974 (Environmental Quality (Sewage) Regulation 2009). The inclusion of PKS as part of the wetland substrate was proven to elevate the denitrification process where nitrate was greatly reduced from the wetland influent, especially at wetland B-PKS (I) operated by batch loading (with the effluent NO_3-N level satisfying Standard A (Environmental Quality (Sewage) Regulation 2009 for effluent discharge into enclosed water bodies). The study revealed satisfactory OM and NH_3-N mass removal with more than an average of 94% and 91% of reduction efficiencies, respectively at both wetland B-PKS and B-SD under the two feeding modes. Throughout the study period, no significant increment of COD concentrations and mass were observed in the effluent of wetland with the inclusion PKS. The addition of PKS for treatment of septage effluent was also shown to improve the overall TN mass removal efficiency by 6.2% and 21% for batch and intermittently fed wetlands, respectively. The study revealed that PKS had effectively functioned as an additional carbon supplier in the wetland for enhanced denitrification.

Chapter 7 Results and Discussions: Dewatering and Mineralization of Septage Deposit

7.1 Overview

Septage is characterized by high solids, organic and enteric microorganism contents and are often known to have poor settling and dewatering characteristics (Hofmann 1990). Septage treatment processes involve septage volume reduction (dewatering) and stabilization of the biodegradable fraction of the organic matter in the septage deposit (sludge reduction). VFEWs resemble what is more commonly known as sludge drying reed beds (SDRBs). Septage or sludge is introduced periodically onto the wetlands and become dewatered mainly by percolation through the sludge or septage and gravel layers, where the liquid portion will be removed from the system through draining via the bottom of the beds, and evapotranspiration from the septage or sludge layers.

The main known advantages of this wetland technology include low investment, simplicity and economy, besides having minimal septage deposit removal cost due to the efficiency of the beds in reducing septage volume and increasing its solids content. Although previously there were much research into the performance of reed bed systems, there is still need for further investigation into the design and performance of wetland systems in different countries and at specific locations. In this chapter, the effects of plant presence and solid loading rates (SLRs) on septage dewatering and mineralization are reported.

7.2 Operating Conditions

The septage stored in the septage receiving tanks was gravitationally fed once a week onto the first stage wetlands for preliminary filtration and treatment. The wetlands were designed to receive load once weekly due to the potential moisture stress of the plants. All wetlands had surface area of 2.20 m^2 and a total depth of the substrate at 800 mm, with 500 mm freeboard for septage deposit accumulation. The filter media consists of 3 layers of aggregates with varying sizes. From bottom to top, the crushed stones-packed filter consists of a 200 mm layer of coarse aggregates (50 - 60 mm diameter), a 300 mm layer of medium aggregates (30 - 45 mm diameter), and a 300 mm layer of fine aggregates (8 - 10 mm diameter). All planted beds were planted with *Phragmites karka* and loaded at solid loading rates (SLRs) of 100, 250 or 350 kg TS/m^2.yr.

At the first stage wetlands, septage was applied in batches, once weekly at a volumetric rate of 50 - 1330 L/week depending on the SLR and the septage TS content which varied greatly with every batch. This resulted in a rest period of 7 days after each weekly loading. The beds received the septage in one go in approximately 15-30 minutes, i.e. at a flow rate of around 3.6 - 44 L/min. Throughout the entire experimental period, the septage was allowed to percolate freely down the substrate layers by gravity. The septage deposit was sampled by core sampler once every fortnight and sent to the laboratory for analyses to determine the level of dewatering and mineralisation. The septage deposit core samples were thus taken from the wetlands at the end of the loading cycles at week 2, 4, 6, 8, 10, 12, 16, and 18 during Period I with SLRs of 100 and 250 kg TS/m^2.yr, and loading cycles at week 2, 4, 6, 8, and 10 during Period II with SLRs of 250 and 350 kg TS/m^2.yr.

The test methodologies were as explained in Chapter 3, section 3.6.1.1. Core samples of the septage deposit were collected from at least 3 different regions of the dried septage layer from every wetland. And at each sampling point, the collected core sample was examined at two depths, corresponding to a top layer (from the surface to mid-height of the core sample) and a bottom layer (from mid-height to the bottom of the core sample). Composite samples from each depth layer were obtained by mixing the deposit subsamples from the different points. The height of septage deposit layer of all wetlands was measured at the end of the experimental period, i.e. at 24 weeks after the first application of septage under SLRs of 100 and 250 kg TS/m^2.yr (including the acclimatization period); and 11 weeks after the first application of septage at SLR 350 kg TS/m^2.yr.

7.3 Effects of Plant Presence

Continuous plant growth in the wetland systems can be an important factor that affects the hydraulics of the substrate filter especially under Malaysia's tropical climatic conditions where plants have high growth rates throughout the year. The following sections (sections 7.3.1 and 7.3.2) present the study outcomes for the effects of plants presence on septage deposit dewatering and mineralization.

7.3.1 Dewatering of Septage Deposit

Water content from the septage deposit was mainly removed via evaporation/ evapotranspiration and by the percolation mechanism. Septage deposit dewatering is evaluated by means of an increase in total solids (TS) or the dry matter (DM) content. During the batch septage loading and bed drying cycles, the effluent was observed to start draining within half an hour after loading, depending on the solid loading rates (SLRs) and the characteristics of the septage (capillary suction time, CST). The flow rates usually increased in the next 30 minutes to an hour, and began slowing down again subsequently. The majority of the water was drained within the first 24 hours, where the infiltration was more gradual after 1 day and stopped completely 3 – 4 days later in planted beds. In unplanted wetlands, the infiltration usually ceased after about 1 - 2 days after septage loading. The remaining water in all units was progressively eliminated during storage as the septage deposit was accumulated for longer periods. Figure 7.1 (a) - (c) and Figure 7.2 (a) - (c) show the development of cracks on the surfaces of the septage deposit layers 4, 7 and 30 days after septage feeding. Noticeable cracks were observed to develop more quickly on the surface of the planted bed especially around the area near the plant stems in planted wetlands.

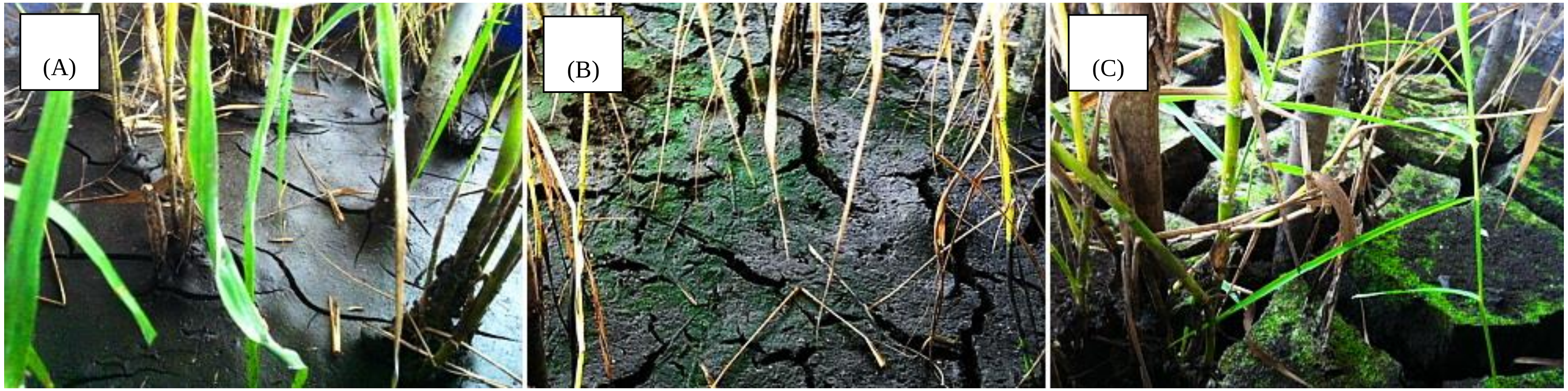


Figure 7.1 Septage deposit in planted wetland A2-350P at (a) 4 days (b) 7 days (c) 30 days after septage loading under SLR 350 kg TS/m^2/yr

Figure 7.2 Septage deposit in unplanted wetland A2-350UP at (a) 4 days (b) 7 days (c) 30 days after septage loading under SLR350 kg TS/m^2/yr

The portion of raw septage that emerged as effluent was estimated from the drained volume collected from each wetland. Evaporation and evapotranspiration rates were estimated by measuring all flows, which include the total volume of septage applied and the effluent drained, and determining the remaining water content in the septage deposit layer at the end of every other loading cycles (once in a fortnight). The dewatering process in the first stage wetlands in general was proven to be very effective, with the average septage volume reduction in all planted and unplanted units exceeding 95% after 7 days of drying as shown in Table 7.1.

Table 7.1 Depth (cm), volume reduction (%), and dry matter (DM) content (%) of septage deposit after 7 days of drying at planted (A1-250P and A2-350P) and unplanted (A1-250UP and A2-350UP) wetlands loaded with SLR 250 (Period I) and 350 kg TS/m^2.yr (Period II)

Unit	Total volume of applied septage (L)	Septage deposit volume (L)	Septage volume reduction (%)	Avg. depth of septage deposit (cm)	DM (%)
Period I					
IN					3.54
A1-250P	7526	150	98.00	6.8	21.14
A1-250UP	7526	188	97.50	8.6	17.74
Period II					
IN					5.72
A2-350P	4012	140	96.51	6.4	21.59
A2-350UP	4012	173	95.70	7.9	16.58

Generally the results had indicated that septage volume reduction in the planted units was greater compared to the unplanted ones. Septage volume reduction occurs due to drying (combination of water gravity drainage, transpiration through the leaves of the reeds and evaporation from the surface layer) and mineralization of septage residues (Kim and Smith 1997). The presence of plants appeared to have enhanced the volume lost from the wetlands, recording an average of up to 98% and 96.5% of volume reduction for Period I and II, respectively. The average height of the septage layer after the operational period of 24 weeks under SLR of 250 kg TS/m^2.yr was 6.8 cm and 8.6 cm for the planted (A1-250P) and unplanted (A1-250UP) wetlands, respectively with 7 days of bed drying at every loading cycle (Table 7.1). During Period II at wetlands loaded with higher SLR of 350 kg TS/m^2.yr, the height of the deposit layer was measured to be 6.4 cm in the planted bed (A2-350P) and a slightly greater height of 7.9 cm in the unplanted unit (A2-350UP).

The dewatering of the septage deposit resulted in the increase of DM content. The deposit DM content was found to increase as the moisture content and depth of the residual layer decreased. Drying was considered sufficient at DM of 20% (or moisture content of 80%) corresponding to the minimum dryness for spade-ability (ease of shovelling) (Cofie et al. 2006). Homogenized cores of the entire solids profile had average solids contents which varied from 16% to 27% for planted wetlands fed under both SLRs. The final average DM of more than 20% was found in the septage deposit from the planted bed A1-250P, as shown in Table 7.1. Plant presence was found to be important in improving the septage deposit dewatering efficiency, with the DM content found to be 19% and 30% greater in the planted units compared to the unplanted ones fed under SLRs of 250 and 350 kg TS/m^2.yr, respectively. Final DM content of more than 20% was also found in the septage deposit at planted wetland A2-350P after 7 days of drying time.

According to Giraldi and Iannelli (2009), drainage in wetlands happens rapidly but it can only remove the pore water, where further dewatering is achieved by the evapotranspiration of the capillary water which is strongly controlled by meteorological conditions. According to Hofmann's study in 1989 published as the "Use of *Phragmites* in sewage sludge treatment" in the book "Constructed wetlands in water pollution control" (cited in Cui et al. 2008), reeds were found to be positively impact the effluent draining, which may be caused by the change in the colloidal structure of the septage deposit. The author suggested that in the immediate vicinity of the plant roots, humic acid sols are produced from which the water is more easily removed, and the movement of the plant stems in the deposit layer and in the granular substrate improves the percolation of water.

All core samples of the septage deposit were divided at mid height to analyse the difference in dewatering efficiency between the top and bottom layer. The dewatering processes on the septage deposit had caused the difference in DM content between the deposit layers. Under SLR of 250 kg TS/m^2.yr, a rise in the DM content was observed from 0.8 – 7% in the raw septage to 15 – 25% and 18 – 28% of DM in the top and bottom layer of the deposit, respectively in the planted unit A1-250P (Figure 7.3). A lesser DM content was constantly observed at the top layer, indicative of having higher moisture content than the bottom layer. An average DM increment of 16% was observed in the top layer and 19% in the bottom layer as shown in Figure 7.4.

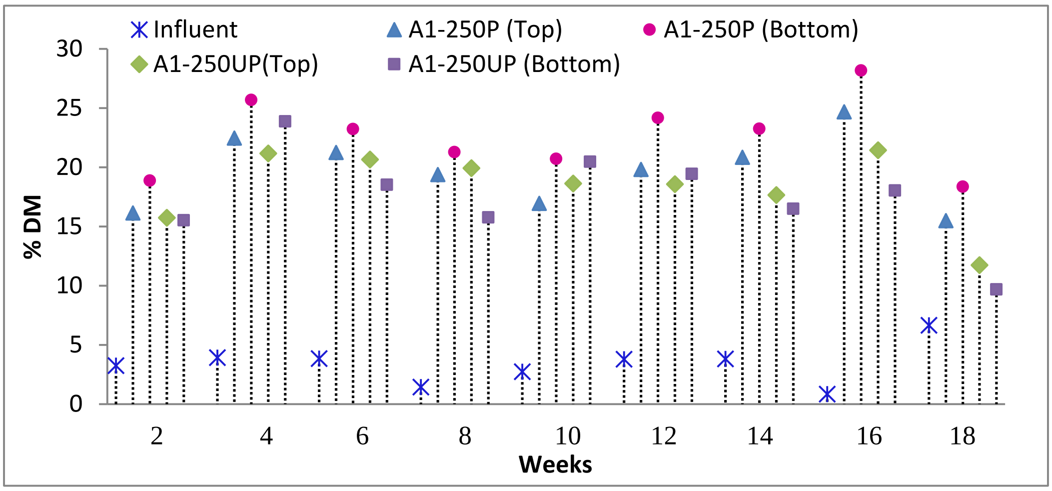


Figure 7.3 DM contents (%) in the raw septage (influent) and in the dried septage deposit (top and bottom layers) after 7 days of drying time at the planted (A1-250P) and unplanted (A1-250UP) wetlands under SLR of 250 kg TS/m^2.yr during Period I

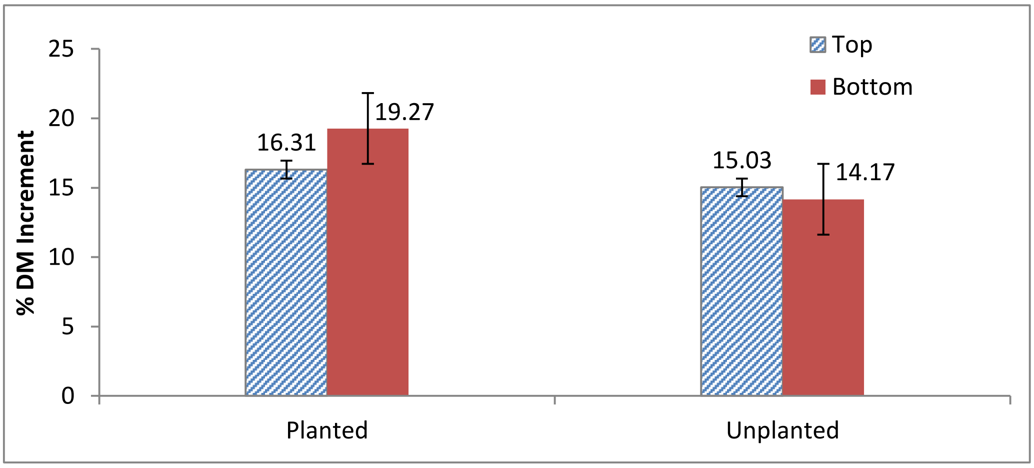


Figure 7.4 Average DM increment (%) in the top and bottom layers of the dried septage deposit after 7 days of drying time at planted (A1-250P) and unplanted (A1-250UP) under SLR of 250 kg TS/m^2.yr during Period I. Standard error bars are indicated for 18 samples.

Similarly at the planted unit fed with SLR of 350 kg TS/m^2.yr (A2-350P), the bottom layer had a slightly lesser moisture content than the top layer, as indicated by the higher percentage of DM in the bottom layer (Figure 7.5). In the planted bed, the mean influent DM contents ranged between 1.5 - 6%, and were increased to 15 - 25% in the top layer and 19 - 28% in the bottom layer of the septage deposit. The mean increment of DM in the planted unit was also about 16% in the top layer and 19% in the bottom layer as shown in Figure 7.6. Water absorption by the plant was likely to have assisted in improving the dewatering efficiency and increasing the maturity of the bottom layer, since denser plants roots system was developed in or near the bottom portion of the septage deposit.

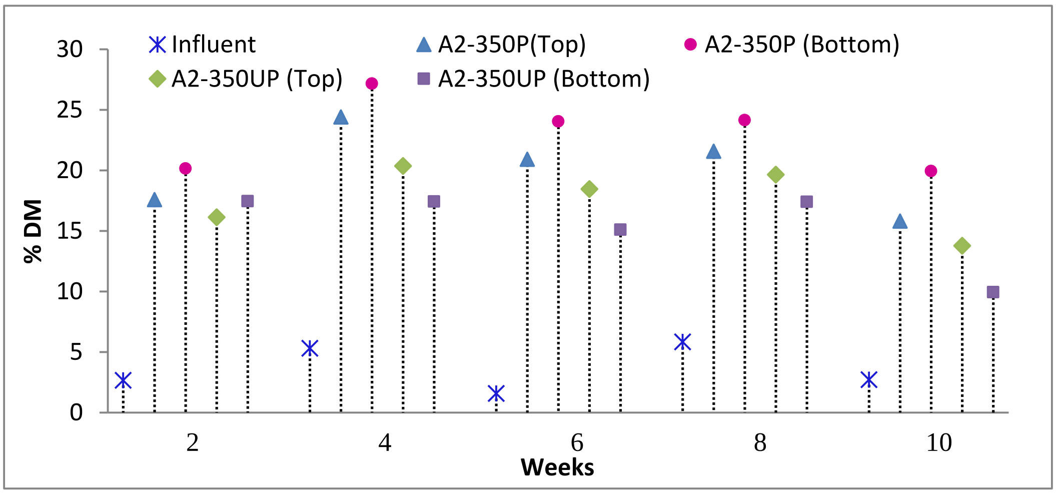


Figure 7.5 DM contents (%) in the raw septage (influent) and in the dried septage deposit (top and bottom layers) after 7 days of drying time at the planted (A2-350P) and unplanted (A2-350UP) wetlands under SLR of 350 kg TS/m^2.yr during Period II

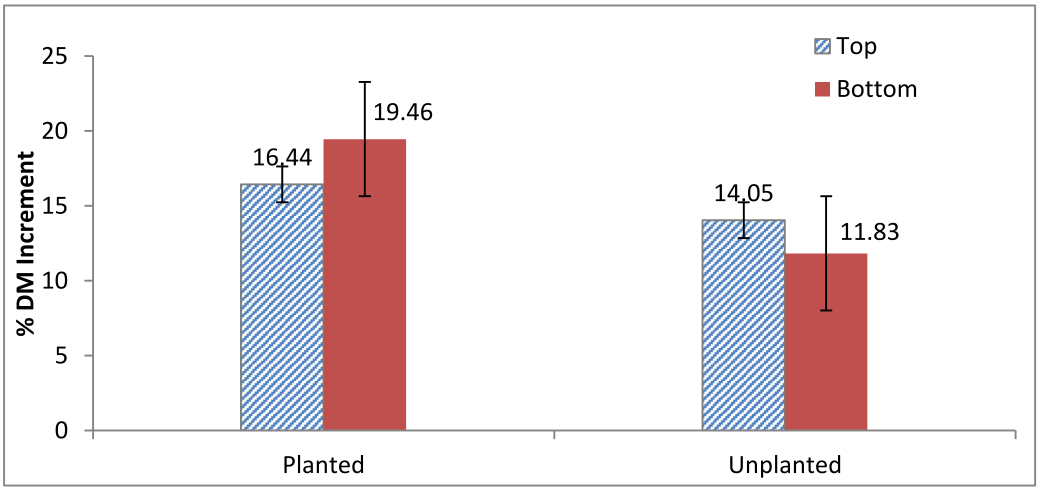


Figure 7.6 Average DM increment (%) in the top and bottom layers of the dried septage deposit after 7 days of drying time at planted (A2-350P) and unplanted (A2-350UP) under SLR of 350 kg TS/m^2.yr during Period II. Standard error bars are indicated for 18 samples.

However, with the absence of plants at wetland A2-350UP the bottom part of septage deposit was found to have lower mean DM content than that of the top layer, different to that of the planted wetlands (Figure 7.3 - Figure 7.6). The difference between the layers at the unplanted bed was more obvious during this second period of loading with higher SLR of 350 kg TS/m^2.yr. The bottom layer had an average DM content of 15%, which is about 12% lower than the top layer. The lower DM contents in the bottom layer with respect to the top layer observed towards the end of the experimental period at SLR of 250 (week 14 - 18) and 350 kg TS/m^2.yr (week 4 - 10) in the unplanted beds suggested a possible occurrence of dead zones in majority parts of the wetland substrate. Dead zones could cause reduced hydraulic performance of the wetland substrate as a result of granular clogging by the accumulation of organic solids which were retained in the substrate pores (Platzer and Mauch 1997).

As shown in Figure 7.7 and Figure 7.8, the greater water loss via percolate draining within the first day (reported as 24 hours infiltration rates, Ir) after septage feeding at the unplanted wetlands reflected the possibility of the occurrence of dead zones and thus preferential flow paths as a result of substrate clogging. An average Ir of 80.7 mm/d and 41.7 mm/d were found in the planted wetlands, and 99.6 mm/d and 65 mm/d in the unplanted wetlands, at beds fed with SLRs 250 and 350 kg TS/m^2.yr respectively. The lower influent hydraulic retention time (HRT) in the unplanted wetlands decreased the pollutants removal performance of the beds in terms of septage effluent treatment as discussed previously in Chapter 4, section 4.4. In general, the presence of the organic deposit layer formed by solids retention on the surface of the beds was found to assist with evenly distributing the septage onto the wetlands and lowering the infiltration rates for improved effluent treatment efficiency. This was especially true for the planted wetlands, with the significantly lower infiltration rates found during the study period. The presence of plant roots had ensured gradual and continuous draining of effluent from the deposit layer throughout the storage period.

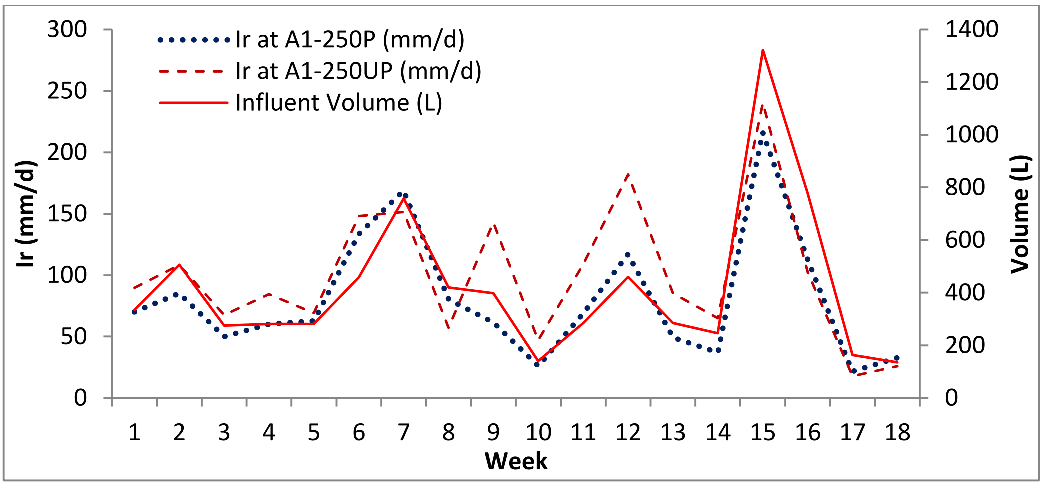


Figure 7.7 Septage influent volumes (L) and the 24 hours effluent infiltration rates (IR) (mm/d) at planted (A1-250P) and unplanted (A1-250UP) wetlands loaded with SLR of 250 kg TS/m^2.yr

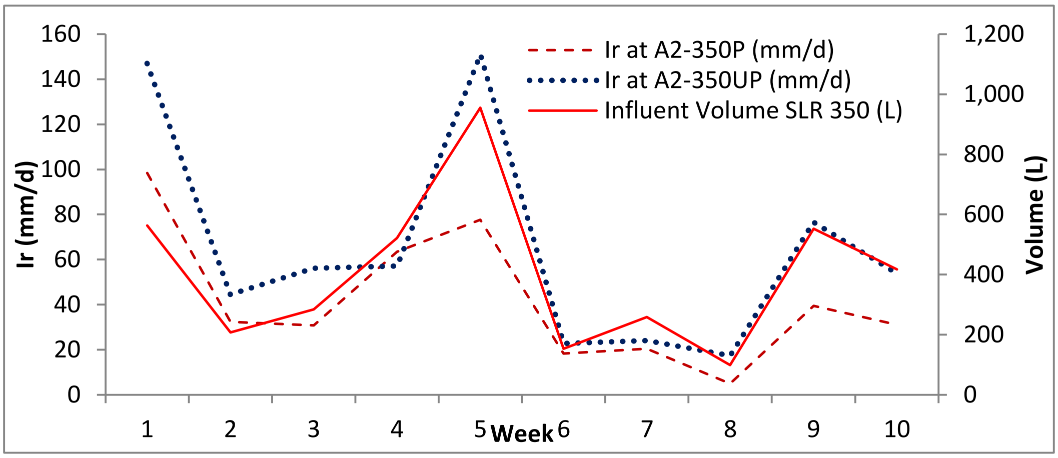


Figure 7.8 Septage influent volumes (L) and the 24 hours effluent infiltration rates (IR) (mm/d) at planted (A2-350P) and unplanted (A2-350UP) wetlands loaded with SLR of 350 kg TS/m^2.yr

As reported in Chapter 4 (section 4.4), the resulting effluent quality of the unplanted units was found to be poorer than the effluent of their planted wetland counterparts. *Phragmites* transpiration functioned as an additional dewatering mechanism in the planted wetlands to support further water loss from the deposit layer. The *Phragmites* drew and absorbed the water content from the septage deposit through their root system to support their growth. Subsequently, together with the effects of evaporation and effluent draining, the DM content in the deposit increased and the volume of the layer decreased with the bed resting time. However, while there was no presence of reed plants to transpire water from the deposit layer in the unplanted beds, there was still water loss due to evaporation from the wetland surface which played a significant role in septage drying especially with Malaysia's climatic conditions.

The results are graphically presented in Figure 7.9 and Figure 7.10, where the contribution of each process (evapotranspiration (ET) and draining) in the water loss is accounted as a percentage of the total influent water volume in both planted and unplanted beds at SLRs of 250 and 350 kg TS/m^2.yr, respectively. These measurements showed that drying due to drainage was higher in the unplanted units compared to the planted beds. Of the total water input, an average of 45% of water left the system by drainage, 53.9% by ET and 1.1% remained in the septage deposit in the planted unit loaded with SLR 250 kg TS/m^2.yr (Figure 7.9). The study findings are similar to those reported by Koottatep et al. (2004) on a pilot-scale system in Bangkok, loaded with 250 kg TS/m^2/yr and planted with cattails. The authors recorded the water loss of the system on 45% via draining and 50% via ET, leaving 5% water in their dried sludge (Koottatep et al. 2004).

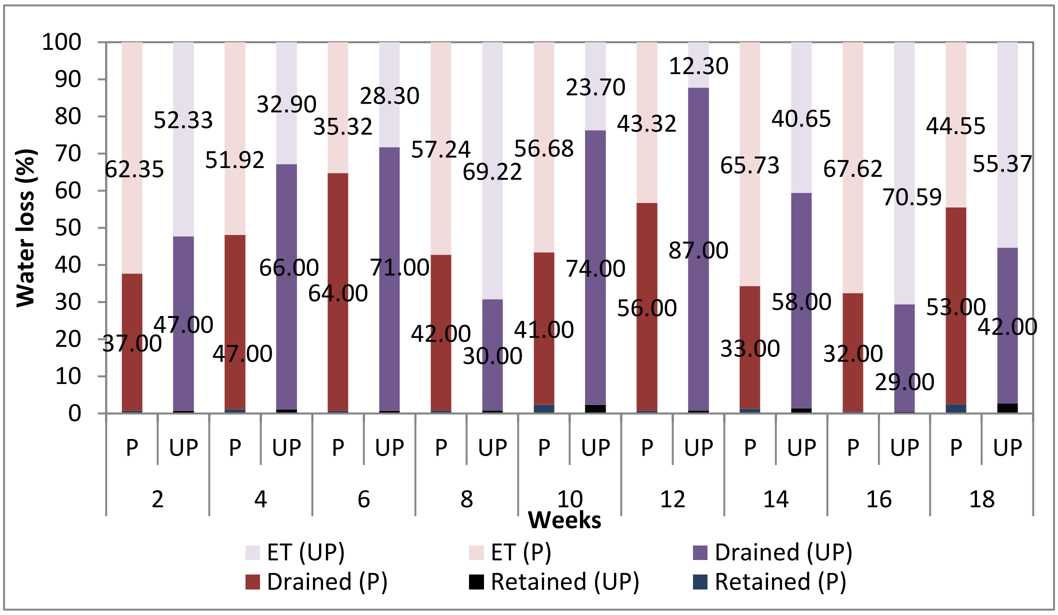


Figure 7.9 Percentages of water loss via evapotranspiration and draining, and the remaining water content in the sludge layer after 7 days of drying time at wetlands loaded under SLR of 250 kg TS/m^2.yr ('P' denotes planted wetland and 'UP' denotes unplanted wetland)

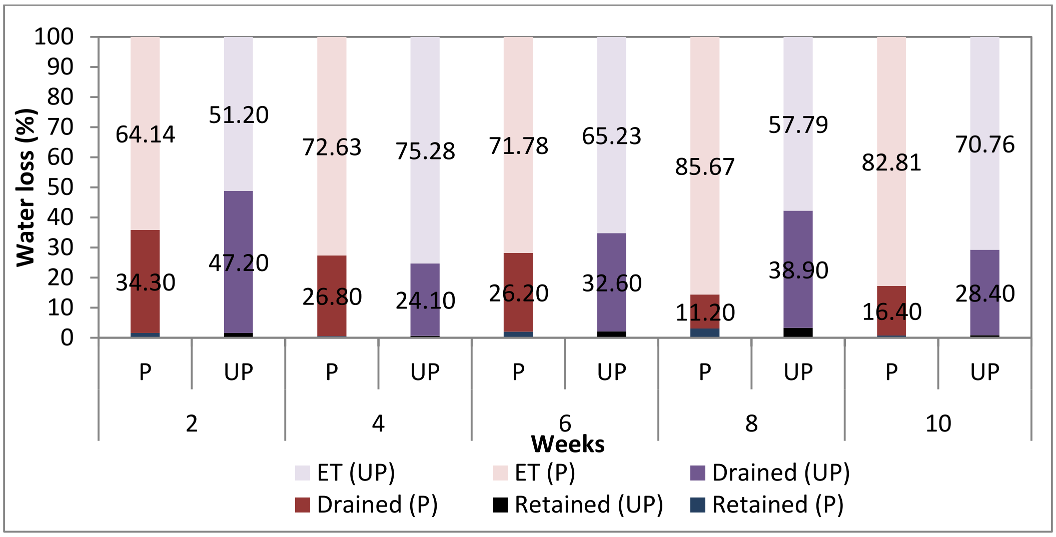


Figure 7.10 Percentages of water loss via evapotranspiration and draining, and the remaining water content in the sludge layer after 7 days of drying time at wetlands loaded under SLR of 350 kg TS/m^2.yr ('P' denotes planted wetland and 'UP' denotes unplanted wetland)

For the wetlands without presence of *Phragmites* (A1-250UP), of the total septage influent volume, the majority of the water portion left the system by drainage (56%) and followed by evaporation (42.8%), leaving 1.2% of moisture in the septage deposit. However, we could not conclude that the transpiration effect by reeds was the sole reason that contributed to the water loss difference between the planted and unplanted system. This is due to the existence of plant roots network in the planted units which led to greater retention of septage on the wetlands surfaces that subsequently encouraged the evaporation process to prevail over draining. Generally both the planted and unplanted system were very effective in septage dewatering, with septage feeding once weekly at 7 days of bed resting/drying period (up to SLR of 350 kg TS/m^2.yr). The findings suggested that evapotranspiration dominated the septage deposit dewatering process in the planted wetlands, whereas drainage appeared as the main mechanism in eliminating water content at the unplanted wetlands.

7.3.2 Mineralisation of Septage Deposit

Mineralisation of deposit is the decomposition of organic matter that is contained in the septage residual in the process of the stabilization. Drying of the septage deposit is occasionally required to enhance the mineralisation performance by maintaining aerobic conditions within the filter bed to mineralize the organic deposit. A septage loading regime with one application per week under the designed SLRs was implemented. The process of stabilization is reported as the reduction of volatile solids (VS) content in the septage deposit. Table 7.2 reports on the mean VS content (g/kg) in the raw septage and in the septage deposit of the planted and unplanted wetlands, with their corresponding VS reduction after 1 week of storage. At SLR of 250 kg/m^2.yr, the accumulated septage from the unplanted bed was found to have VS contents that ranged from 454 – 575 g/kg (average of 497 g/kg); while in the planted unit the VS contents was observed to range from 436 - 529 g/kg (average of 482 g/kg).

Table 7.2 Mean VS content (g/kg) in raw septage and in the septage deposit on the planted and unplanted wetlands with 1 week of storage per cycle (after 7 days of drying time). VS reductions are reported in terms of percentage (%).

	SLR 250			SLR 350		
	IN	A1-250P	A1-250UP	IN	A2-350P	A2-350UP
VS (g/kg)	648.71 ± 110.50	482.03 ± 33.75	496.63 ± 41.94	578.80 ± 136.37	442.94 ± 28.02	481.77 ± 15.63
VS reduction (%)		25.69	23.44		23.47	16.76

Core samples of the septage deposit were tested for the VS content in the top and lower layer of the retained septage. In the planted unit A1-250P, the VS concentrations decreased from 51 - 85% (as of %TS) in the raw septage to 44 - 55% and 42 - 52% in the top and the bottom layer, respectively (Figure 7.11). The percentage of reduction was slightly lower in the unplanted wetland A1-250UP, with the top layer having VS content ranging between 46 - 56% and the bottom layer between 44 - 59%. The reduction in the VS content in the septage deposit had suggested that significant oxidation/mineralisation occurred during storage.

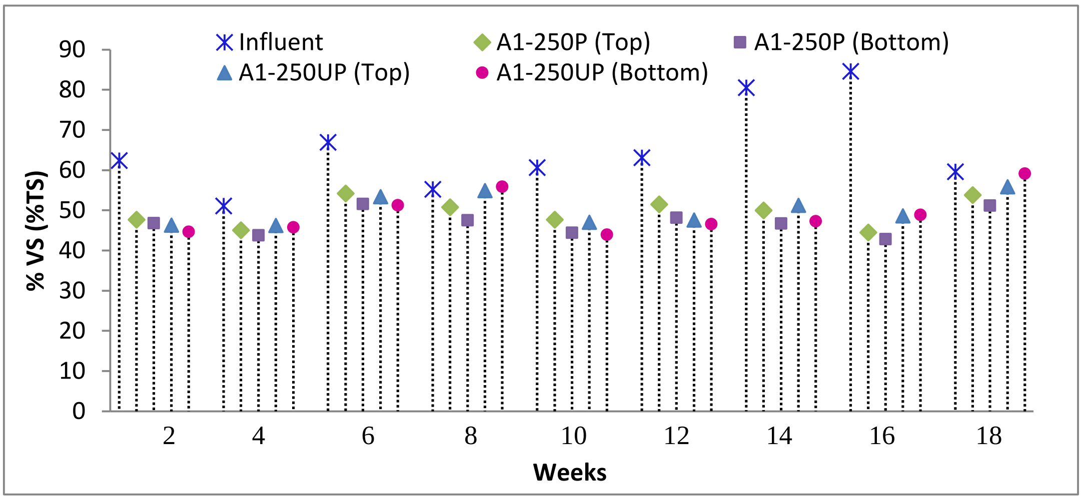


Figure 7.11 Percentage of VS contents (as % of TS) in the raw septage (influent) and in the dried septage deposit (top and bottom layers) after 7 days of drying time at the planted (A1-250P) and unplanted (A1-250UP) wetlands under SLR of 250 kg TS/m^2.yr during Period I

The VS content was higher at the top of each core and this indicated that the top deposit layer had a higher organic matter content than the bottom layer, consistent with the results reported elsewhere (Kim and Smith 1997; Melidis et al. 2010). The bottom layer was constantly more mature (less rapid changes in the organic matter composition) and stable compared to the top layer of the deposit at the planted wetlands during both experimental periods (Period I and II). This signified better oxidation/mineralization at the bottom layer as it had been oxidized for a longer period of time compared to the top layer.

However, it was observed that the difference between the layers was more evident in the planted unit A1-250P compared to its unplanted counterpart A1-250UP in terms of mineralisation as shown in Figure 7.12 The bottom layer was found to have a significantly lower VS content than the top layer. The difference between the top and bottom layers was less significant in both the planted and unplanted wetlands fed with 350 kg TS/m^2.yr (Figure 7.13 and Figure 7.14). The transformation and mineralization of degradable organic pollutants is mainly performed by microorganisms. The study results indicated that, among other factors, the presence of *Phragmites* in the planted wetland aided the stabilisation of the septage deposit, possibly via the oxygen released from the plant rhizosphere and the cracks that were developed due to the swaying of plant stem and root growth. Reed, Crims, and Middlebrooks (1988) found that reeds are capable of creating aerobic microsites (adjacent to the roots) in an otherwise anaerobic environment in the deposit, which can assist in the septage stabilization and mineralization.

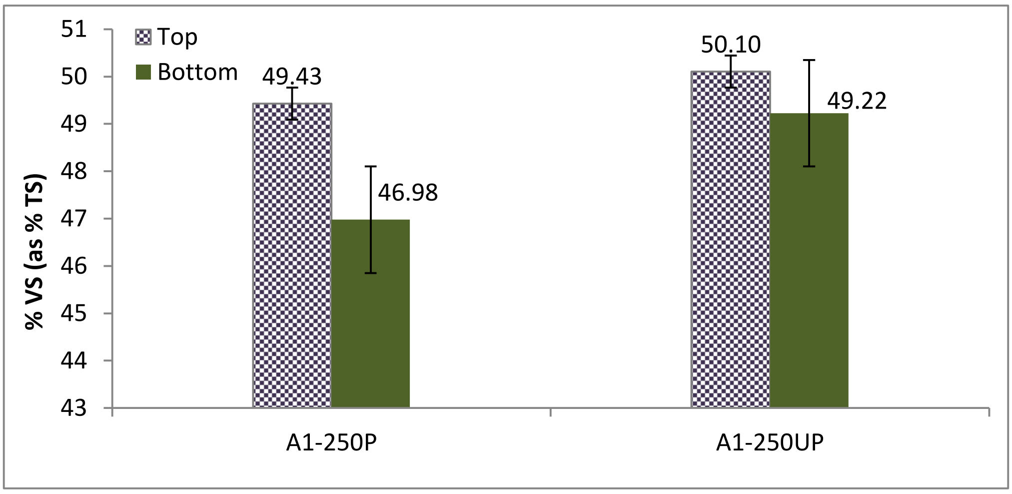


Figure 7.12 Mean VS of TS (%) with standard error in the top and bottom layer of the septage deposit after 7 days of drying at planted (A1-250P) and unplanted (A1-250UP) wetlands fed under SLR 250 kg TS/m^2.yr time during Period I. Standard error bars are indicated for 18 samples.

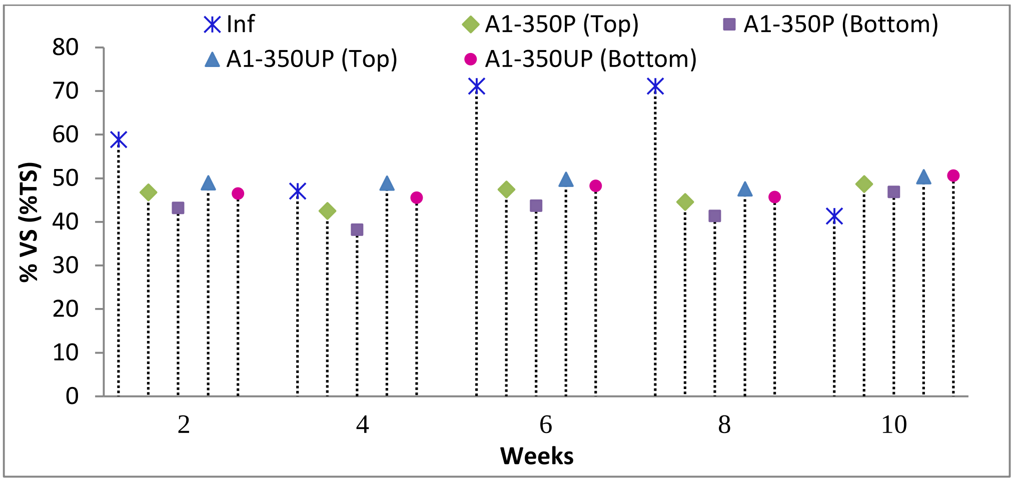


Figure 7.13 Percentage of VS contents (as % of TS) in the raw septage (influent) and in the dried septage deposit (top and bottom layers) after 7 days of drying time at the planted (A2-350P) and unplanted (A2-350UP) wetlands under SLR of 350 kg TS/m^2.yr during Period II

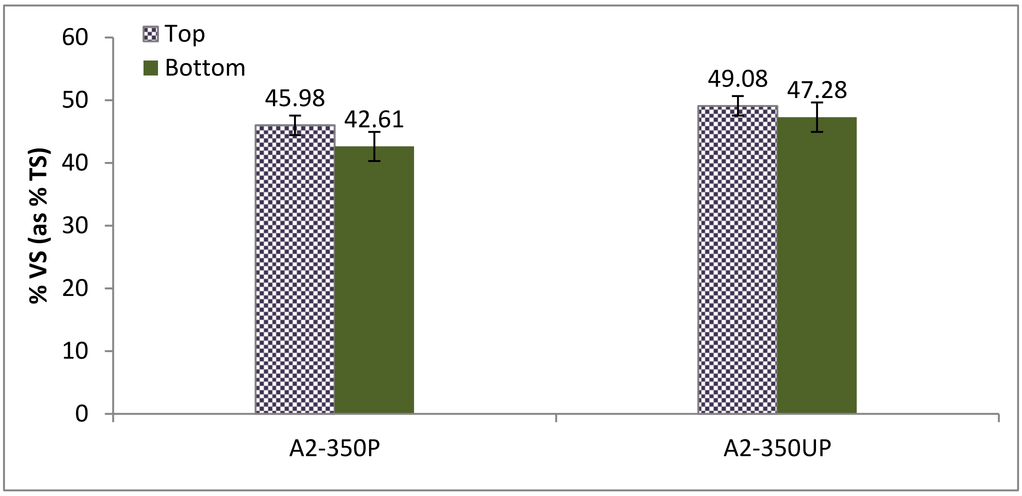


Figure 7.14 Mean VS of TS (%) with standard error in the top and bottom layer of the septage deposit after 7 days of drying time at planted (A2-350P) and unplanted (A2-350UP) wetlands fed under SLR 350 kg TS/m^2.yr during Period II. Standard error bars are indicated for 18 samples.

7.4 Effect of Solid Loading Rate (SLR)

The planted vertical wetlands designed for septage pollutants retention and treatment were loaded with solid loading rates (SLRs) of 100, 250 and 350 kg TS/m^2.yr.The following sections (sections 7.4.1 and 7.4.2) present the study outcomes on the effects of SLR on septage deposit dewatering and mineralization.

7.4.1 Dewatering of Septage Deposit

At wetland A1-100P which received the lowest SLR of 100 kg TS/m^2.yr, the septage deposit layer was reasonably observed to be much thinner compared to wetland A1-250P which was loaded with SLR of 250 kg TS/m^2.yr. All water volume was drained within 1 - 2 days after feeding and the majority of the water was removed via percolation in the unit with lower SLR. Prolonged influent ponding (more than 2 days) was very rarely observed on the surface of wetland A1-100P. Hence the thinner septage deposit had most of its depth exposed to the atmosphere for evaporation and reeds transpiration, achieving a higher final solids content. Septage volume reduction was high for all beds, with an average reduction of 98.1% achieved in bed A1-100P and 98% in bed A1-250P as shown in Table 7.3.

Table 7.3 Depth (cm), volume reduction (%), and dry matter (DM) content (%) of septage deposit after 7 days of drying time for Period I and II with SLR 100, 250 and 350 kg TS/m^2.yr

Unit	Total volume of applied septage (L)	Deposit septage volume (L)	Septage volume reduction (%)	Avg. depth of septage deposit (cm)	DM (%)
Period I					
IN					3.54
A1-100P	3010.41	55.88	98.14	2.54	24.37
A1-250P	7526.03	150.26	98.00	6.83	21.14
Period II					
IN					5.72
A2-250P	2865.88	79.64	97.22	3.62	22.98
A2-350P	4012.24	140.14	96.51	6.37	21.59

The results revealed that the water loss processes depend mainly on the applied SLR or the septage volume to be treated. As indicated in Table 7.3, all planted beds had final DM contents more than 20% in the septage deposit after 7 days of drying time, up to SLR of 350 kg TS/m^2.yr. According to Figure 7.15, the majority of the water was removed from the septage deposit via draining at wetland A1-100P, while ET was on the other hand the main water removal pathway at wetland A1-250P. Of the total water input, an average of 67% of water left the system by drainage, 30.3% by evapotranspiration (ET) and 2.7% remained in the septage deposit in the planted unit A1-100P. At solids loading of 100 kg TS/m^2.yr, the drained water volume was found to be greater than at the loading of 250 kg TS/m^2.yr, indicating that vertical drainage was the main water loss mechanism, where ET came in as the second important dewatering process.

The increase of loading rate to 250 kg TS/m^2.yr had the majority of the water portion removed via ET (53.9%), followed by draining (45%). The higher SLR implies greater applied septage volume and thus more septage was retained on the wetland surface for a longer time, which allowed the process of ET to override water drainage. Also in the wetlands fed with higher septage load, the deposit layer was comparatively thicker which subsequently reduced the rate of water drainage to the unit base. Visible cracks were noticed much later on the surface of the septage deposit at wetland A1-250P than that of wetland A1-100P.

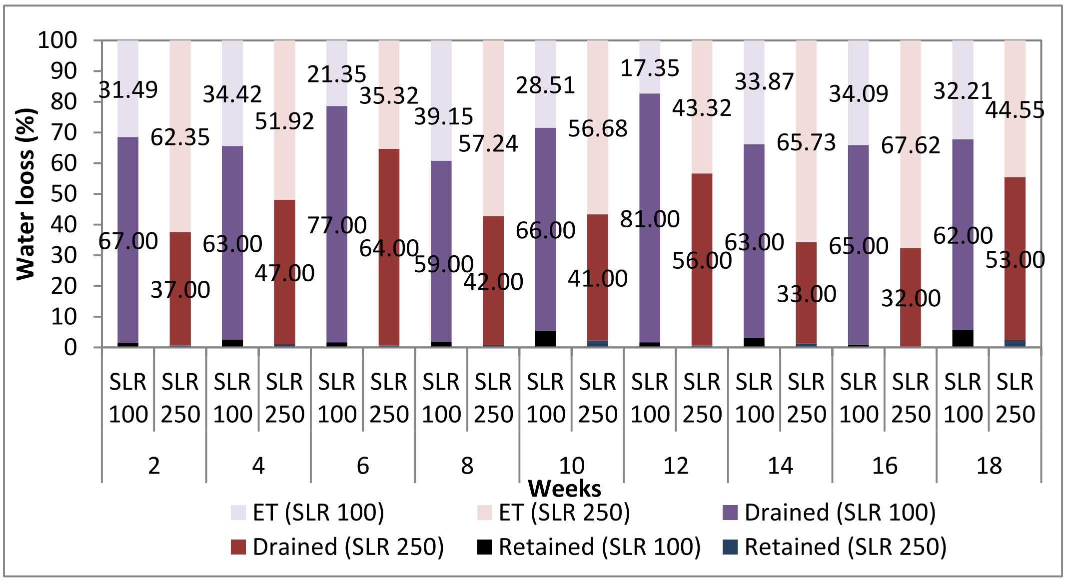


Figure 7.15 Percentages of water loss via evapotranspiration and draining, and the remaining water content in the sludge layer at wetlands loaded under SLRs of 100 and 250 kg TS/m^2.yr after 7 days of drying time during Period I

Further increment of SLR to 350 kg TS/m^2.yr at Period II had also revealed ET as the main dewatering mechanism, with the water loss via ET yielding a marginally higher percentage than the wetland fed at 250 kg TS/m^2.yr (Figure 7.16). With an average of more than 70% of the water found to be lost via ET at both wetlands, it was suggested that the increase in SLR generally increased the percentage of water loss related to ET, while the water loss via draining decreased. In a study in the North Mediterranean region (Greece) using activated sludge, a similar finding was reported by Stefanakis and Tsihrintzis (2011) such that higher ET values were accounted for with the higher amount of sludge a unit received.

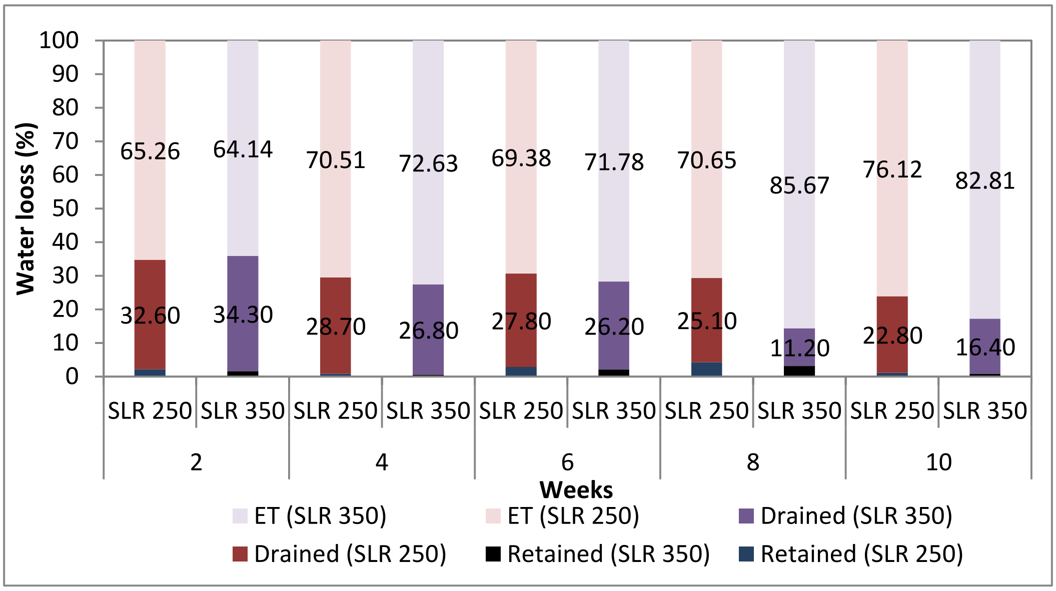


Figure 7.16 Percentages of water loss via evapotranspiration and draining, and the remaining water content in the sludge layer after 7 days of drying time at wetlands loaded under SLRs of 250 and 350 kg TS/m^2.yr during Period II

At wetland A1-250P, distinct difference between the top and bottom layer in terms of DM content (Figure 7.17 and Figure 7.18) and variation in terms of colour was observed. The top layer of the septage deposit had slightly darker shade than its bottom layer. This could be due to the difference in the moisture content between the layers, with generally higher DM content measured in the bottom layer. On average, the top layer of the septage deposit had a moisture content of 80%, and the bottom layer had a moisture content of 77% after 7 days of drying time. Correspondingly, the DM content showed an increase from an average of 3.4% in the raw septage to 17 – 27% in the final deposit after 7 days of bed resting. The difference between the layers was found to be much unobvious in wetland A1-100P. The moisture contents varied between 71 - 80% for both the layers, with an average DM content of 24.2% in the top layer and 24.5% in the bottom layer.

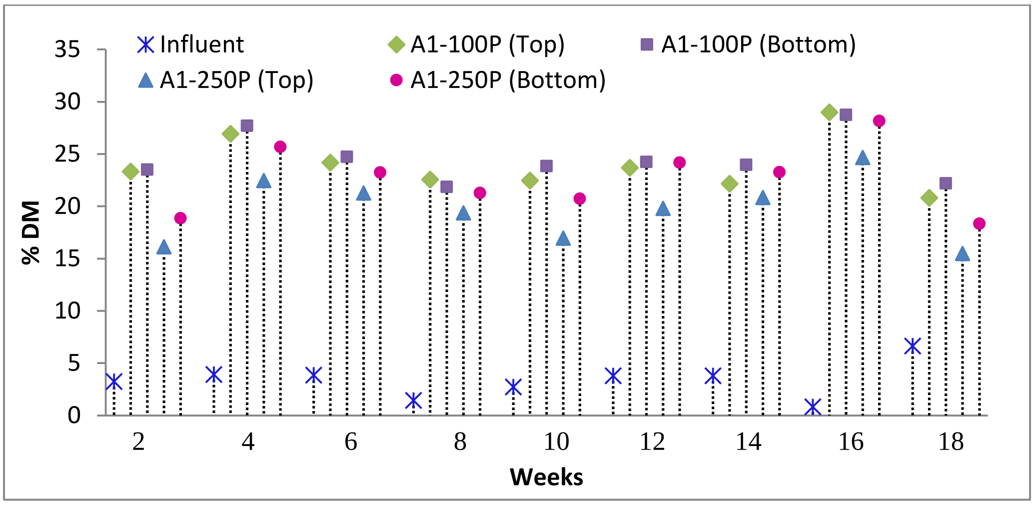


Figure 7.17 DM content (%) in the raw septage (influent) and in the dried septage deposit (top and bottom layers) after 7 days of drying time at the wetlands loaded in Period I with SLRs of 100 (A1-100P) and 250 kg TS/m^2.yr (A1-250P)

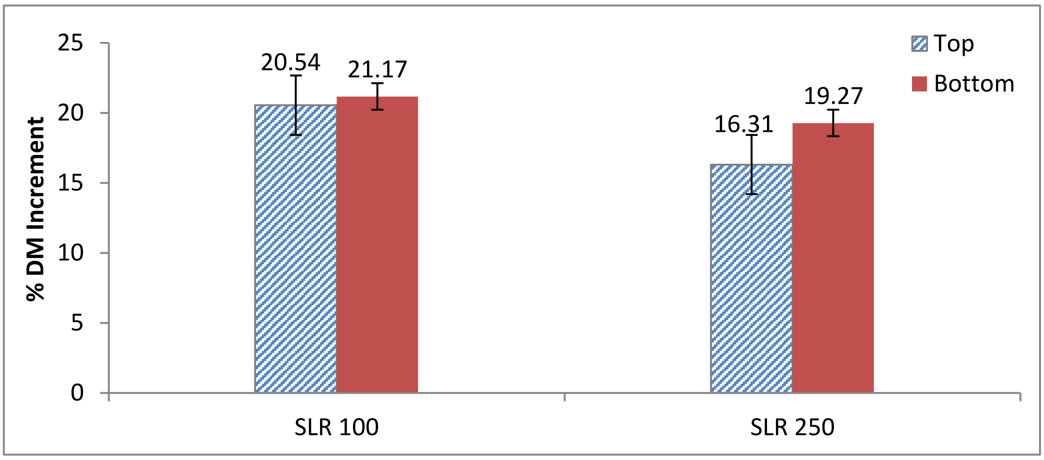


Figure 7.18 Average DM increment (%) in the top and bottom layers of the dried septage residual after 7 days of drying time at wetlands loaded in Period I with SLRs of 100 (A1-100P) and 250 kg TS/m^2.yr (A1-250P). Standard error bars are indicated for 18 samples.

In Period II with SLRs of 250 and 350 kg TS/m^2.yr, the difference in terms of DM content between the two wetlands was relatively less evident than Period I with SLRs 100 and 250 kg TS/m^2.yr (Figure 7.19 and Figure 7.20). The average DM contents the wetland fed with 250 kg TS/m^2.yr were always greater than 20%, except at the top where the deposit was most recent. Wetland A2-250P had an average of 23% of DM content in the septage deposit, which was about 6.4% greater than wetland A2-350P. Both the wetlands had difference in colour between the top and bottom layers due to the thicker septage deposit which subsequently led to variation in the moisture contents.

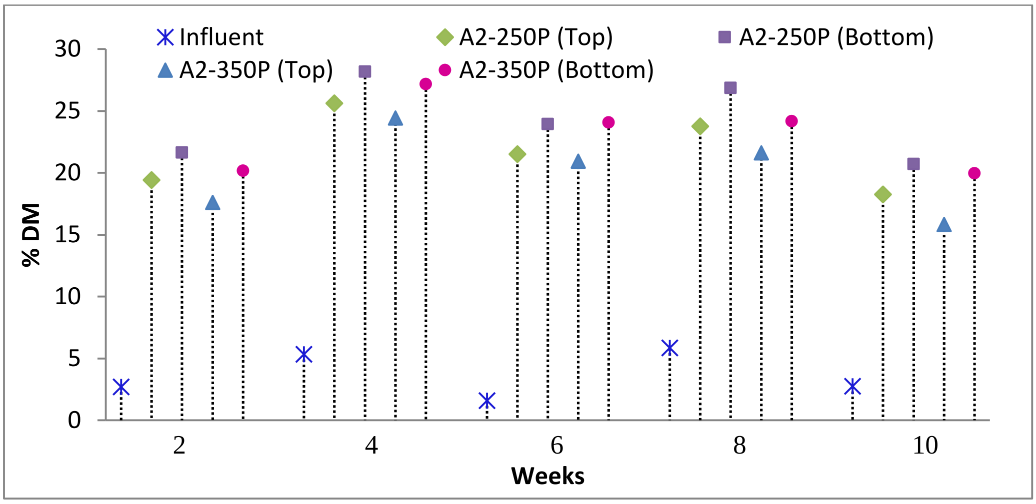


Figure 7.19 DM content (%) in the raw septage (influent) and in the dried septage deposit (top and bottom layers) after 7 days of drying time at the wetlands loaded in Period II with SLRs of 250 (A2-250P) and 350 kg TS/m^2.yr (A2-350P)

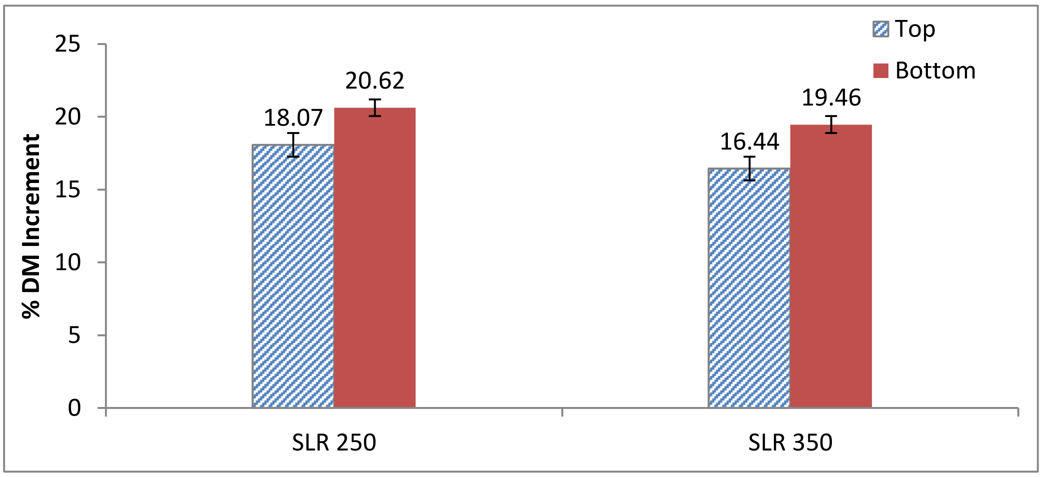


Figure 7.20 Average DM increment (%) in the top and bottom layers of the dried septage deposit after 7 days of drying time at wetlands loaded in Period II with SLRs of 250 (A2-250P) and 350 kg TS/m^2.yr (A2-350P). Standard error bars are indicated for 18 samples.

Generally, the increase in the height of the septage deposit did not drastically affect the hydraulic performance of the wetland filter. Instead, the 24 hours infiltration rates (IR) of the wetland effluent depended on the septage load that each unit received during each application, as presented in Figure 7.21 and Figure 7.22. The study results suggested that as the septage loading rate reduces, so does the percentage of water loss due to ET, while the effluent infiltration rate increases. More water was removed from the septage deposit via percolation and drained out from the unit base with the lower SLR.

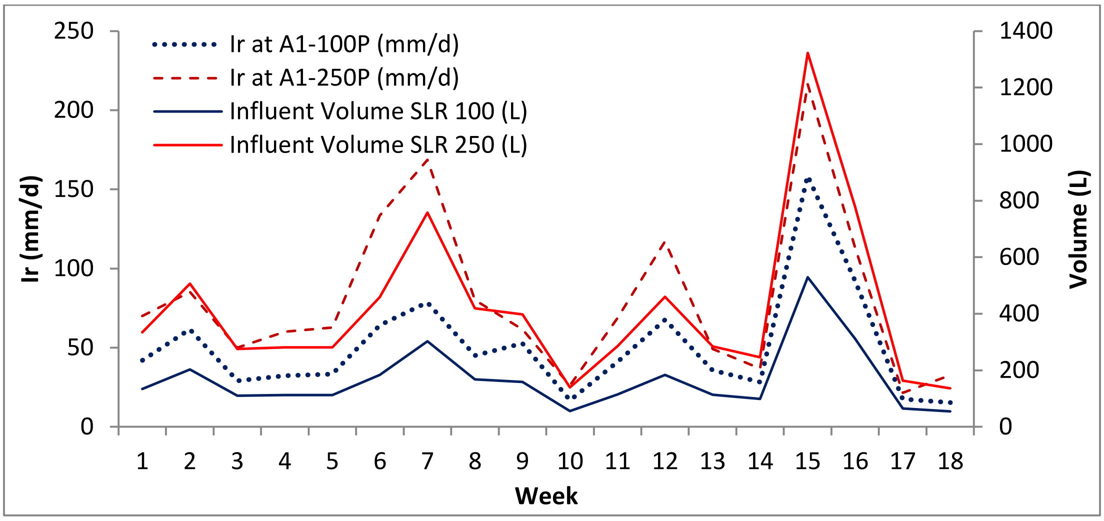


Figure 7.21 Septage influent volumes (L) and the 24 hours effluent infiltration rates (IR) (mm/d) at wetland loaded with SLRs of 100 (A1-100P) and 250 kg TS/m^2.yr (A1-250P) during Period I

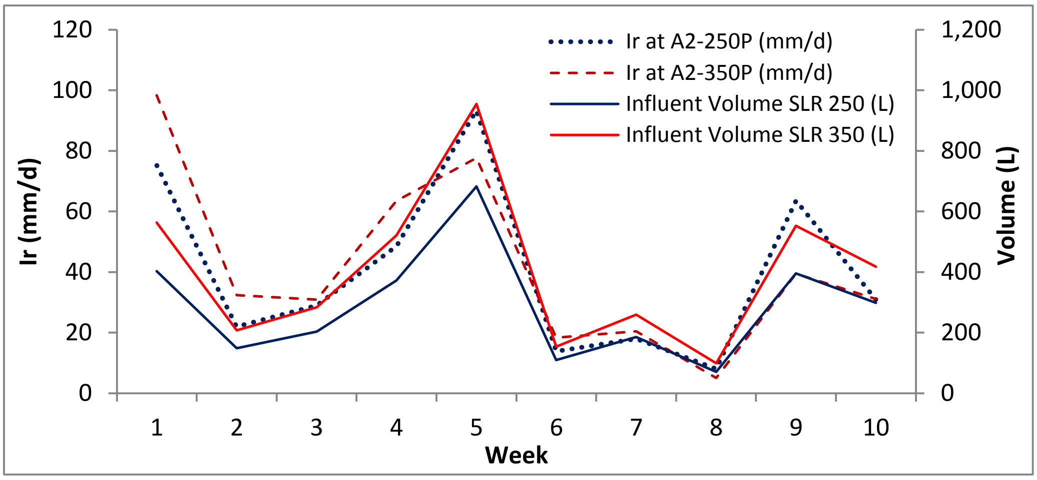


Figure 7.22 Septage influent volumes (L) and the 24 hours effluent infiltration rates (IR) (mm/d) at wetland loaded with SLRs of 250 (A1-250P) and 350 kg TS/m^2.yr (A1-350P) during Period II

7.4.2 Mineralisation of Septage Deposit

Together with septage deposit dewatering, mineralisation took place during septage storage, as indicated by the reduction in VS content. Table 7.4 presents the data on the mean VS content (g/kg) in the raw septage and in the septage deposit at wetlands loaded with SLRs of 100, 250 and 350 kg TS/m^2.yr. During study Period I, septage deposit on the bed with the lowest loading of 100 kg TS/m^2.yr had the highest mean VS elimination at 44%, i.e. with the VS content drop to 366 g/kg from 649 g/kg in the raw septage (Table 7.4). Septage deposit in the wetland loaded with 250 kg

TS/m^2.yr (A1-250P) had relatively higher VS content, with the VS reduction at 41% lower than the wetland fed at 100 kg TS/m^2.yr. The thinner septage deposit at the bed fed with lower loading rate achieved higher dewatering efficiency, and subsequently the greater performance in septage mineralisation.

A similar outcome was also recorded in Period II with SLRs of 250 and 350 kg TS/m^2.yr, where the lower loading rate was found to favour the septage deposit VS reduction efficiency. An average of 33% and 23% of VS was reduced from the raw septage in wetland A2-250P and A2-350P, respectively. At lower loading rates which equated to smaller amounts of septage being treated, organic matter decomposed at a higher rate and maturity was reached sooner compared to the wetland fed at higher SLRs. The finding is in agreement with Stefanakis, Komilis, and Tsihrintzis (2011) in their research using wastewater sludge. Besides, the lesser thickness of the deposit layer had allowed for greater depth of the septage deposit to be exposed to the atmosphere for aerobic decomposition of organic matter.

Table 7.4 Mean VS content (g/kg) in raw septage and in the septage deposit on wetlands loaded under SLRs 100, 250 and 350 kg TS/m^2.yr with 1 week of storage per cycle (after 7 days of drying time). VS reductions are reported in terms of percentage (%)

	Period I			Period II		
	IN	A1-100P	A1-250P	IN	A2-250P	A2-350P
VS (g/kg)	648.71 ± 110.5	365.57 ± 25.88	482.03 ± 33.75	578.80 ± 136.37	386.3 ± 25.75	442.94 ± 28.02
VS reduction (%)		43.65	25.69		33.25	23.47

At all beds, the mean VS concentration was found to be lower in the bottom layer compared to the top layer of the core samples, though the difference was not found to be statistically significant (Figure 7.23 and Figure 7.24) (P>0.05). This was because the bottom layer consisted of older septage that was stored for a longer period of time and had achieved a higher degree of mineralisation compared to the newer septage layer on the top. Similar findings were reported by Cui et al. (2008) where the authors studied on the dewatering and mineralisation ability of a pilot-scale vertical wetland in China using combined thickened sludge produced from cyclic activated sludge technology (CAST) process.

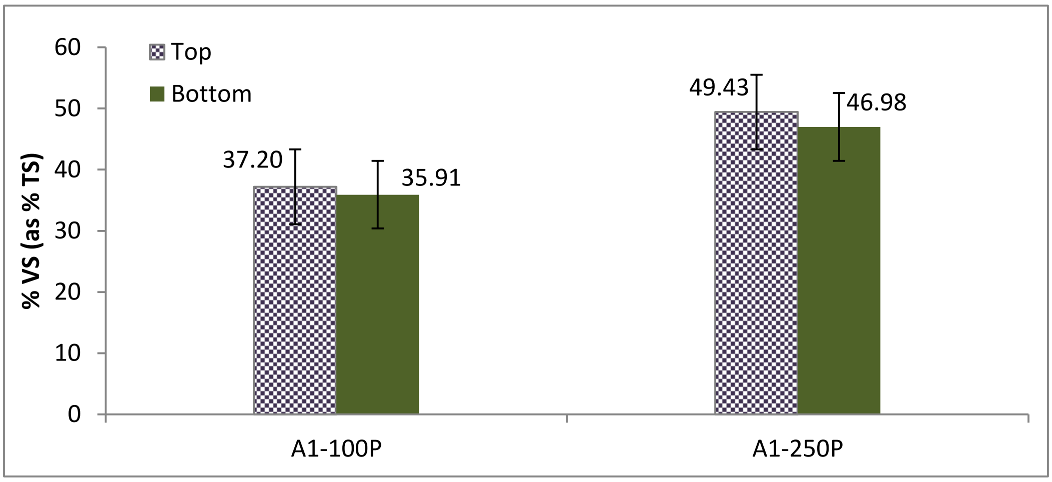


Figure 7.23 Mean VS of TS (%) with standard error in the top and bottom layer of the septage deposit after 7 days of drying time in Period I at wetlands fed under SLRs 100 (A1-100P) and 250 kg TS/m^2.yr (A1-250P). Standard error bars are indicated for 18 samples.

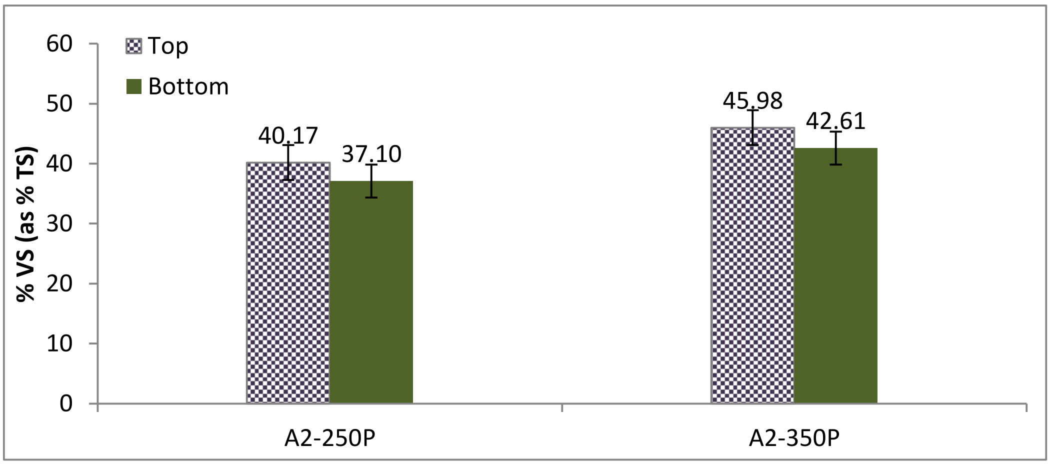


Figure 7.24 Mean VS of TS (%) with standard error in the top and bottom layer of the septage deposit after 7 days of drying time in Period II at wetlands fed under SLRs 250 (A2-250P) and 350 kg TS/m^2.yr (A2-350P). Standard error bars are indicated for 18 samples.

7.5 Summary

The study suggested that both septage reductions by dewatering and oxidation processes are favourable in the VFEWs system under the Malaysia's climatic conditions. The study reported that the presence of plants is beneficial in obtaining a more stable, mature and dry deposit sludge end-product. The planted wetlands showed important improvement over the unplanted wetlands in terms of greater efficiency in volume reduction and in producing septage deposit with a higher content of dry matter (DM). All planted beds had the final DM content of more than 20% in the septage deposit after 7 days of drying time, up to the solid loading rate (SLR) of 350 kg TS/m^2.yr. The planted wetlands also recorded 25.7% and 21.7% of volatile solids (VS) reduction efficiency, which was 9.3% and 44.7% greater than the VS removal performance observed at their unplanted wetland counterparts at SLRs of 250 and 350 TS/m^2.yr, respectively.

The presence of plants appeared to have enhanced the volume lost from the wetlands, recording an average of more than 96% of volume reduction up to an SLR of 350 kg TS/m^2.yr. The septage deposit on the planted wetlands had a higher DM content found in the bottom layer compared to the top layer as a result of water absorption by plant roots. The presence of plant roots ensure continuous draining of effluent from the deposit layer throughout the storage period. On the other hand in the unplanted wetlands, towards the end of the experimental period the bottom layer of septage deposit was observed to have a lower mean DM content than that of the top layer. Possible occurrence of preferential flow paths in the unplanted wetland substrate was reflected by a significantly greater 24 hours infiltration rates of 99.6 mm/d and 65 mm/d found in the unplanted wetlands, which were 23.4% and 55.9% greater than recorded at the planted wetland counterparts loaded with SLRs of 250 and 350 kg TS/m^2.yr respectively.

Of the total water input, an average of 45% of water left the system by drainage, 53.9% by ET and 1.1% remained in the septage deposit in the planted unit with SLR of 250 kg TS/m^2.yr. For the unplanted wetland, of the total septage influent volume, the majority of the water portion left the system by drainage (56%) and followed by evaporation (42.8%), leaving 1.2% of moisture in the septage deposit. However, the transpiration effect by reeds may not be the sole reason that contributed to the water loss difference between the planted and unplanted system, as the existence of plant roots network in the planted units had led to a greater retention of septage on the wetlands surfaces, which allowed the evaporation process to prevail over draining. The study outcomes also revealed better mineralisation of the septage deposit at the planted wetlands compared to the unplanted ones with greater decrease in the volatile solids (VS) content under all applied SLRs. The bottom deposit layer at all beds was constantly more mature and stable compared to the top layer at the planted wetlands. This signified better oxidation/mineralization at the bottom layer as it had been oxidized for a longer period of time compared to the top layer.

Comparison between the wetlands loaded with 100 and 250 kg TS/m^2.yr had suggested vertical drainage as the main water loss mechanism, where evapotranspiration (ET) came in as the second most important dewatering process in the bed fed with the lower SLR (100 kg TS/m^2.yr). Of the total water input, an average of 67% of water left the system by drainage, 30.3% by ET and 2.7% remained in the septage deposit in the planted unit loaded with SLR 100 kg TS/m^2.yr. The higher loadings of 250 and 350 kg TS/m^2.yr had had the ET as the main dewatering pathway, followed by drainage. With an average of more than 70% of the water found to be lost via ET at wetlands loaded under higher loading rates, it was suggested that the increase in SLR generally increased the percentage of water loss related to ET, while the water loss via draining decreased.

It was also revealed in the study that the increase in SLR decreased the overall septage deposit mineralisation performance of the wetlands, with the highest mean VS elimination of 44% found in wetland loaded with 100 kg TS/m^2.yr, followed by 26% and 24% in wetlands fed with 250 and 350 kg TS/m^2.yr, respectively. The thinner deposit layer at the bed loaded with lower loading rates led to more rapid and efficient drying of the layer, which subsequently improved its performance in septage deposit mineralisation.

Chapter 8 Conclusions and Recommendations

8.1 Conclusions

This study examined the efficiency and the general feasibility of a pilot-scale two-staged vertical flow engineered wetlands (VFEWs) system to treat septage in Miri, Malaysia. The effectiveness of such a system in septage deposit dewatering and stabilisation, as well as the performance on the septage effluent treatments are reported in this dissertation. With the plant operational period of approximately 16 months since the system commissioning period, the operational needs of the VFEWs system are generally low and normally restricted to cleaning of the distribution system and clearing of the plants detritus from the wetland beds. Septage screening upon delivery to the project site is important as the removal of large non-biodegradable particles from the raw septage is necessary to prevent blocking of the distribution system and accumulation of these gross solids especially condoms, sanitary napkins and plastic bags around the shaft of the mechanical mixer.

Several system and operational related factors studied were found to have important influences on the system performance, and a proper understanding on these variables will help to improve the septage treatment efficiency of this green technology. Natural treatment technologies are often considered viable because of their low capital cost and ease of maintenance; and when used with proper planning, their potentially long life-cycles and ability to recover a variety of resources make them a favourable option, especially in developing countries like Malaysia.

Throughout the experimental period, *Phragmites karka* planted in the system was found to assist in preserving the hydraulic conductivity of the wetland substrate that prevented clogging and secured subsurface flow of the septage influent. The presence of plants at the first stage wetlands was found to be favourable for septage volume reduction as a result of dewatering and mineralisation of the deposit layer. The study suggested that presence of plants is beneficial in obtaining a more stable, mature and dry sludge deposit end-product. The planted wetlands showed important improvement over the unplanted wetlands in terms of greater efficiency in volume reduction, and producing septage deposit with significantly higher content of dry matter (DM) and lower content of volatile solids (VS). All planted beds had the final DM content of more than 20% in the septage deposit after 7 days of drying time, up to solid loading rate (SLR) of 350 kg TS/m^2.yr. The planted wetlands recorded 9.6% and 41.7% greater volatile solids (VS) reduction efficiency than their unplanted wetland counterpart at SLRs of 250 and 350 TS/m^2.yr, respectively.

At the first stage wetland which was loaded with low SLR of 100 kg TS/m^2.yr, vertical drainage was found to be the main water loss mechanism, where evapotranspiration (ET) came in as the second important dewatering process. On the other hand, at the wetlands applied with higher SLRs of 250 and 350 kg TS/m^2.yr ET was found to be the main dewatering pathway, followed by drainage. Thus, the increase in septage SLR generally increased the percentage of water loss related to ET, while the drained water percentage decreased. It was also revealed in the study that the increase in SLR decreased the overall wetlands mineralisation performance, with the highest mean VS elimination found in wetland loaded with 100 kg TS/m^2.yr, and the lowest at the wetland fed with 350 kg TS/m^2.yr. The thinner deposit layer at the bed fed with lower loading rates led to more rapid and efficient drying of the layer, which subsequently improved its performance in septage mineralisation. In general, the presence of organic deposit layer formed by solids retention on the surface of the beds was found to assist with evenly distributing the septage onto the wetlands and lowering the infiltration rate for improved effluent treatment efficiency. The presence of plant roots ensure gradual and continuous draining of effluent from the deposit layer throughout the storage period with significantly lower 24 hours infiltration rates (Ir) found in the planted wetlands (by 19% and 35.8% for SLRs 250 and 350 kg TS/m^2.yr, respectively) than the unplanted ones.

Throughout the plant operational period, the first stage of the VFEWs system was the stage where majority removal of contaminants occurred, with a mean relative mass reduction of at least 92% for BOD$_5$ and COD, 80% for NH$_3$-N, 81% for total nitrogen (TN), and 93% for TSS by mass, up to the solid loading rate (SLR) of 350 kg TS/m^2.yr without presence of plants. No significant deterioration of wetland performance was found when the solid loading rate (SLR) was increased from 100 to 250 kg TS/m^2.yr in Period I and from 250 to 350 kg TS/m^2.yr in Period II. The first stage wetlands were generally very efficient in organic matter (OM) and particulate solids removal from the raw septage.

The study concluded that the presence of plants is important at both the VFEWs stages for improved pollutants removal efficiency. The wetlands treatment performance was suggested to be assessed in terms of mass reduction efficiency, as the water loss due to evapotranspiration from the septage at the planted wetlands was found to be substantial (55% and 62% at planted wetlands, which was 31% and 22.6% greater than the unplanted wetlands at SLRs of 250 and 350 kg TS/m^2.yr, respectively). Under Malaysia's tropical climatic conditions, water loss from a wetland system as a result of evapotranspiration should be taken into account when making performance comparisons between planted and unplanted beds, especially when they are loaded with septage or sludge. The planted unit had been found to outperform the unplanted one in terms of organic matter (OM), ammonia nitrogen (NH_3-N) and particulate suspended solids (TSS) removal performances at both stages. The DO contents and ORP status of the wetland influent were significantly improved after the first and second stage of treatments with planted beds, suggesting the important role of plants in promoting aerobic treatments in the wetlands.

The use of ornamentals such as *Costus woodsonii* in the research project at the second stage of the VFEWs system was found to be an alternative to the traditional wetland indigenous reeds (*Phragmites karka*) for septage treatment. This species grew very well in the gravel-based substrate and exhibited high growth rate throughout the entire year. Use of ornamental plants could help to increase aesthetic values of the treatment site, while meeting the sanitation needs. Although poorer ammonia removal performance was found in the *Costus*-planted wetland compared to the *Phragmites*-planted bed, it is interesting to note that the *Costus*-planted wetland was still capable of eliminating ammonia nitrogen at a high rate of removal (4.7 g/m^{2}d), and produced effluent with a considerably low ammonia content (2.11 mg/L) that meets Standard A of the effluent discharge limit according to the

Malaysia Environmental Quality Act 1974 (Environmental Quality (Sewage) Regulation 2009 for effluent discharge into enclosed water bodies).

Intermittent feeding mode at the second stage of the system was found to be very efficient in promoting passive aeration at the wetlands which subsequently increased aerobic degradation ability of the vertical beds. The increased of HLR from 8.75 to 17.5 cm/d was found to significantly deteriorate the overall wetland pollutants removal performance. A decrease of wetland outflow rates at bed fed with HLR 17.5 cm/d were observed, due to the occurrence of gradual bed clogging with the operational time at the high loading rates which subsequently decreased the rate of re-oxygenation of the substrate. The study outcomes also revealed that the re-oxygenation capability of the wetland units was greatly affected by the dosing frequency. At high hydraulic loading rate of 17.5 cm/d, it was not recommended to increase the number of the sequencing feeding doses with lower volume per batch (more frequent daily dosing) as it was found to reduce the ammonia nitrogen and total nitrogen removal of the wetlands. In terms of the batch feeding strategy with cyclic fill-pond-drain-rest regime, the bed operated at pond:rest period of 1:1 (day:day) was found to significantly underperform the wetland with P:R of 3:3. It was suggested that for all feeding modes, a sufficient period of resting was imperative to restore aerobic conditions within the bed and to ensure sufficient treatment of the wastewater.

A high relative nitrate (NO_3-N) removal was also achieved at the second stage with the presence of palm kernel shells (PKS), which contributed substantially to the good nitrate elimination performance. Nitrate accumulation was observed in the effluent of wetland B-SD where PKS was absent, with mean NO_3-N content at approximately 7 and 2.5 times more than observed in the effluent of wetland B-PKS (I) and B-PKS (II), loaded with batch and intermittent mode, respectively. Inclusion of PKS as part of the wetland substrate was proven to elevate nitrate removal from the septage, where the PKS had effectively functioned as an additional carbon supplier in the wetland for enhanced denitrification. The inclusion of PKS in wetlands operated by batch loading produced effluent with NO_3-N levels that met Standard A according to the Environmental Quality (Sewage) Regulation 2009 for effluent discharge into enclosed water bodies. The use of PKS which is a waste product from Malaysia's growing palm oil industry shows promise as substrate choice for engineered wetland systems to treat septage. However, further studies would be needed to get sufficient and reliable data from pilot and field-scale wetland systems to confirm the order of magnitude of the organic substrate's lifespan.

Overall, the study outcomes suggested high predictability of the pollutants removal rates according to the incoming pollutant mass at all wetlands, with remarkably near constant areal removal rates for almost all the tested pollutants under the applied regime. The findings arising from this research project have contributed to the design facets and operational guidelines of the pilot VFEWs system for septage treatment, as summarised in Table 8.1.

Table 8.1 Suggested design features and operational practices of the two-staged VFEWs system for septage treatment arising from this research project

<table>
<tr><td colspan="4">First stage wetlands</td></tr>
<tr><td>Plant type</td><td colspan="3"><i>Phragmites karka</i></td></tr>
<tr><td>Solid loading rate (SLR)</td><td colspan="3">Up to 350 kg TS/m^2.yr</td></tr>
<tr><td>Substrate type</td><td colspan="3">Aggregates</td></tr>
<tr><td>Substrate arrangement (bottom to top)</td><td colspan="3">200 mm layer of coarse aggregates (diameter 50 - 60 mm), 300 mm layer of medium aggregates (diameter 30 - 45 mm), and 300 mm layer of fine aggregates (diameter 8 - 10 mm)</td></tr>
<tr><td colspan="3">Second stage wetlands</td><td>Remarks</td></tr>
<tr><td>Plant type</td><td colspan="2"><i>Phragmites karka</i> or <i>Costus woodsonii</i></td><td></td></tr>
<tr><td>Feeding mode</td><td colspan="2">(I) Intermittent</td><td rowspan="3">Intermittent feeding promotes constant O$_2$ renewal in the wetland substrate</td></tr>
<tr><td></td><td>Hydraulic loading rate (HLR)</td><td>8.75 cm/d</td></tr>
<tr><td></td><td>Dosing frequency</td><td>4 times daily</td></tr>
<tr><td></td><td colspan="2">(II) Batch</td><td rowspan="3">Batch feeding promotes N removal</td></tr>
<tr><td></td><td>Batch volume</td><td>21 L/batch</td></tr>
<tr><td></td><td>Pond: Rest (P:R) period</td><td>3:3 (days)</td></tr>
<tr><td>Substrate type</td><td colspan="2">Palm kernel shell (PKS) and aggregates</td><td></td></tr>
<tr><td>Substrate arrangement (bottom to top)</td><td colspan="2">Medium sized aggregate (diameter 37.5 mm; 50 mm thick), fine aggregates (diameter 8 - 10 mm; 200 mm thick), pea gravels (diameter 3 mm; 200 mm thick), PKS (250 mm thick) and topped with river sand (100 mm thick)</td><td></td></tr>
</table>

This research project has confirmed that high treatment performance is achievable by the pilot VFEWs system to treat raw septage, with suitable coupling of system design and operational practices. The study has proven that the VFEWs system which utilises ecologically engineered processes can perform fairly well in treating high-strength organic wastewaters like septage to tertiary standards. The development and implementation of this naturally-based and de-centralised technology in the suburban or rural area is one of the most suitable options; while in the urban environment this eco-technology alternative has to be properly planned as the system is by their very nature, consumptive in terms of their spatial requirements. Although land is still available in plentiful abundance in Malaysia and also in other developing countries in Southeast Asia like Thailand and Indonesia, reasonable sizing of the system could further encourage inclusion of this robust green technology in sustainable urban planning.

8.2 Opportunities and Limitations

The engineered wetlands system is customisable to suit local climatic conditions, aesthetic requirements, water quality objectives, and when intended, the end uses. The outcomes of this research project reflected the opportunity to implement the two-staged VFEWs system for septage treatment in larger scale and also in other cities or suburban areas around in Malaysia. The current project scale which occupied an area of approximately 49 m^2 is applicable for septage treatment for 12 – 15 population equivalent, PE (based on a max SLR of 350 kg $TS/m^2.yr$ with once a week application). The system is scalable according to the condition of the project site and the volume of septage to be treated.

The design and study of a wetland system is often carried out using the well-known “black-box” concept (Haberl et al. 2003; Koottatep et al. 2005; Jia et al. 2010; Vymazal and Kröpfelová 2010) which is also the approach for this current project, where the focus is on the overall performance of the system and the major removal mechanisms are not taken into account. It was understood that the removal of pollutants in engineered wetlands occurs as a result of complex physico-chemical and microbial interactions. Following this project, which has demonstrated the potential and efficiency of the engineered wetlands system in septage treatment in Malaysia, an on-going research work is currently underway in Curtin University to understand the main processes and the dynamics of the VFEWs that led to the efficient treatment of septage by this system.

8.3 Recommendations for Future Work

This research project has revealed several useful outcomes that can assist in providing future guidelines for design and operation of a septage treatment wetland system. However further studies on the system are required to gain insight into the "black-box" of the wetland system to increase the reliability of this technology. The knowledge gaps in this research work were identified and the recommended directions for future research are pointed out as follow:

I. Gersberg et al. (1987) had found the potential of wetlands in removing disease-causing viruses from municipal wastewater and that the presence of plants was important in the removal of total coliforms by the wetlands. The removals of E.coli and Faecal coliforms in the engineered wetlands for septage treatment in the VFEWs system can be studied to determine the effectiveness of the beds in reducing the bacterial indicators from the influent.

II. The mechanisms of pollutants removal in the wetlands could be investigated to improve the design and operation of the system for enhanced treatment performance. Further studies could be conducted to investigate the role of plants uptake on N removal in the VFEWs which is located in the tropics, since the effects of plants assimilation on the removal of pollutants in the wetlands have been a controversy for decades. Besides, the use of PKS as an organic substrate for the wetlands could be studied for its adsorption, absorption and leaching capability which might have effects on the pollutant reduction efficiency. Also, more researches are needed to better understand the processes responsible for the transformation and removal of nitrogen. The ammonia-oxidation and denitrification potential of the engineered wetlands could be investigated.

III. During the past years, numerical modelling of subsurface flow engineered wetlands had been an interest for many researchers in the field to provide insights into the engineered wetlands 'black-box' for evaluation and improvements on the existing design criteria. However, almost all of the models developed (e.g. CW2D, CWM1, FITOVERT) focused on the treatment of domestic sewage by engineered wetlands, where to date no models have been developed for septage treatment by engineered wetlands to the best of our knowledge.

IV. Testings could be carried out on the palm kernel shells (PKS) to get sufficient and reliable data from pilot and field-scale wetland systems to confirm the order of magnitude of the organic substrate's lifespan.

V. Contact time between the septage, substrate, plant rhizomes and microorganisms is an important factor that dictates contaminant removal in wetland systems. The length of hydraulic retention time (HRT) can affect the treatment performance of the wetlands and it can be measured by conducting tracer studies to gain insights into the internal hydraulics of the beds. Thus, tracer tests are suggested to be carried out with the VFEWs to develop better understanding on the dynamics of the flow.

VI. Further investigations can be done to identify and characterize various tropical plant species to study on their tolerance to high nutrient levels, for potential use at septage treatment wetlands.

VII. The potential of using the dried septage deposit as fertilizers in agriculture, as material for soil improvement in land reclamation and as a source of energy and revenue can be investigated.

VIII. Long-term operation of the engineered wetlands system for septage treatment could be studied to examine the robustness and the reliability of the technology.

8.4 Other Recommendations

Suggestions to improve the operation and maintenance of the designed VFEWs system are suggested below:

I. A manual for the dried septage dredging methodology and dredging schedule can be prepared by monitoring the performance of the system before and after the deposit removal, to provide important guidelines for the wetland system design, operation and maintenance.

II. Provision should be made in substrate construction of the wetlands to minimise the risk of short circuiting with suitable gravel grading and adequate compaction.

III. The addition of clean-out risers along and at the end of the distributor pipes is suggested to facilitate cleaning of the pipes and removing build-ups that may clog the pipes.

IV. For a better comparison, solid loading rates (SLRs) in terms of suspended solids (SS) are suggested as a more preferable variable for the design loading over total solids (TS). This is to disregard the dissolved salts when designing for the total applicable solids on the wetlands.

References

Aalbers, H., Waste, and UWEP. 1999. *Resource Recovery from Faecal Sludge Using Constructed Wetlands: A Survey of the Literature*. Gouda, The Netherlands: WASTE.

Aik, C. L. , and G. Jia. 1998. "Preparation and Characterization of Chars from Oil Palm Waste." *Carbon* 36: 1663-1670.

Albuquerque, A., M. Arendacz, M. Gajewska, H. Obarska-Pempkowiak, P. Randerson, and P. Kowalik. 2009. "Removal of Organic Matter and Nitrogen in an Horizontal Subsurface Flow (Hssf) Constructed Wetland under Transient Loads." *Water Science and Technology* 60 (7): 1677-82.

Aluko, O. O., and M. K. C. Sridhar. 2005. "Application of Constructed Wetlands to the Treatment of Leachates from a Municipal Solid Waste Landfill in Ibadan, Nigeria." *Journal of Environmental Health* 67 (10): 58-62.

APHA. 1998. *Standard Methods for the Examination of Water and Wastewater*. 20th edn ed. Washington DC, USA: American Public Health Association, American water Works Association and Water Environment Federation.

Armstrong, W., D. Cousins, J. Armstrong, D. W. Turner, and P. M. Beckett. 2000. "Oxygen Distribution in Wetland Plant Roots and Permeability Barriers to Gas-Exchange with the Rhizosphere: A Microelectrode and Modelling Study with Phragmites Australis." *Annals of Botany* 86 (8): 687-703.

Asano, T., F.L. Burton, H.L. Leverenz, R. Tsuchihashi, and G. Tchobanoglous. 2007. *Water Reuse, Issues, Technologies and Applications*. New York, USA: McGraw-Hill.

Aslam, M. M., M. Malik, M. A. Baig, I. A. Qazi, and J. Iqbal. 2007. "Treatment Performances of Compost-Based and Gravel-Based Vertical Flow Wetlands Operated Identically for Refinery Wastewater Treatment in Pakistan " *Ecological Engineering* 30 (1): 34-42.

Avsara, Y., H. Tarabeahb, S. Kimchiec, and I. Ozturkd. 2007. "Rehabilitation by Constructed Wetlands of Available Wastewater Treatment Plant in Sakhnin." *Ecological Engineering* 29: 27-32.

Babatunde, A. O., Y. Q. Zhao, M. O'Neill, and B. O'Sullivan. 2008. "Constructed Wetlands for Environmental Pollution Control: A Review of Developments, Research and Practice in Ireland." *Environment International* 34 (1): 116-126.

Bachand, P. A. M., and A. J. Horne. 1999. "Denitrification in Constructed Free-Water Surface Wetlands: Ii. Effects of Vegetation and Temperature." *Ecological Engineering* 14: 17-32.

Badkoubi, A., H.Ghaderi Ganjidoust, A., and A. Rajabu. 1998. "Performance of Subsurface Wetland in Iran." *Water Science and Technology* 38: 345-350.

Bancole ́, A., F. Brissaud, and T. Gnagne. 2003. "Oxidation Processes and Clogging in Intermittent Unsaturated Infiltration." *Water Science and Technology* 48 (11-12): 139-146.

Begg, J. S., R. L. Lavigne, and P. L. M. Veneman. 2001. "Reed Beds: Constructed Wetlands for Municipal Wastewater Treatment Plant Sludge Dewatering." *Water Science and Technology* 44: 393-398.

Belgiorno, V., G. De Feo, and R. M. A. Napoli. 2003. "Carbonaceous Removal and Nitrification with Biological Aerated Filters." *Journal of Environmental Science Health* A38 (10): 2147-2156.

Best, E. P. H., M. Zippin, and J. H. A. Dassen. 1981. "Growth and Production of Phragmites Australis in Lake Vechten (the Netherlands)." *Hydrobiological Bulletin, Netherlands Hydrobiological Society* 15: 165-174.

Bezbaruah, A. N., and T. C. Zhang. 2004. "Ph, Redox and Oxygen Micro-Profiles in Rhizosphere of Bulrush (Scirpus Validus) in a Constructed Wetland Treating Municipal Wastewater." *Biotechnology and Bioengineering* 88: 60-70.

Boller, M., A. Schwager, J. Eugster, and V. Mottier. 1993. "Dynamic Behavior of Intermittent Buried Filters." *Water Science and Technology* 28 (10): 99-107.

Boutin, C., A. Lienard, and D. Esser. 1997. "Development of a New Generation of Reed-Bed Filters in France: First Results." *Water Science and Technology* 35 (5): 315-322.

Brix, H. 1993. *Wastewater Treatment in Constructed Wetlands: System Design, Removal Processes, and Treatment Performance*. Boca Raton: Lewis.

———. 1994. "Functions of Macrophytes in Constructed Wetlands." *Water Science and Technology* 29 (4): 71-78.

———. 1997. "Do Macrophytes Play a Role in Constructed Treatment Wetlands?" *Water Science and Technology* 35 (5): 11-17.

Brix, H., and C. A. Arias. 2005. "The Use of Vertical Flow Constructed Wetlands for on-Site Treatment of Domestic Wastewater: New Danish Guidelines." *Ecological Engineering* 25 (5): 491-500.

Bt Fuadi, N.A., A.S. Ibrahim, and K. Nor Ismail. 2012. "Review Study for Activated Carbon from Palm Shell Used for Treatment of Wastewater " *Journal of Purity, Utility Reaction and Environment* 1 (5): 252-266.

Bulc, T. G. 2006. "Long Term Performance of a Constructed Wetland for Landfill Leachate Treatment." *Ecological Engineering* 26 (4): 365-374.

Burgoon, P. S., K. Frank Kirkbride, M.E. Henderson, and E. Landon. 1997. "Reed Beds for Biosolids Drying in the Arid Northwestern United States." *Water Science and Technology* 35: 287-292.

Burgoon, P. S., K. R. Reddy, and T. A DeBusk. 1989. "Domestic Wastewater Treatment Using Emergent Plants Cultured in Gravel and Plastic Substrate." In*: Hammer, D.A.*

(Ed.), Constructed Wetlands for Wastewater Treatment, 536–541. Chelsea, MI, USA: Lewis Publishers.

Burgoon, P. S., K. R. Reddy, and T. A. DeBusk. 1995. "Performance of Subsurface Flow Wetlands with Batch-Load and Continuous-Flow Conditions." *Water Environmental Research* 67 (5): 855-862.

Calheiros, C., A. Rangel, and P. Castro. 2007. "Constructed Wetland Systems Vegetated with Different Plants Applied to the Treatment of Tannery Wastewater." *Water Research* 41: 1791-1798.

Calhound, A., and G. M. King. 1997. "Regulation of Root-Associatedmethanotrophybyoxy-Gen Availability in the Rhizosphere of Two Aquatic Macrophytes." *Applied and Environmental Microbiology* 63 (7): 3051-3058.

Cameron, S. G., and L. A. Schipper. 2010. "Nitrate Removal and Hydraulic Performance of Organic Carbon for Use in Denitrification Beds." *Ecological Engineering* 36 (11): 1588-1595.

Chazarenc, F., and G. Merlin. 2005. "Influence of Surface Layeronhydrologyandbiology of Gravel Bed Verticalflowconstructed Wetlands." *Water Science and Technology* 51 (9): 91-97.

Chimney, M. J., and K. C. Pietro. 2006. "Decomposition of Macrophyte Litter in a Subtropical Constructed Wetland in South Florida (USA)." *Ecological Engineering* 27 (4): 301-321.

Chitzi, I., P. Melidis, C. Akratos, J. N. E. Papaspyros, and V. A. Tsihrintzis. 2007. "Study of Activated Sludge Dewatering in Pilot-Scale Reed-Planted Sdb's" *10th International Conference on Environmental Science and Technology, Kos island, Greece,*

Chung, A. K. C. , Y. Wu, N. F. Y. Tam, and M. H. Wong. 2008. "Nitrogen and Phosphate Mass Balance in a Sub-Surface Flow Constructed Wetland for Treating Municipal Wastewater." *Ecological Engineering* 32: 81-89.

Cofie, O. O., S. Agbottah, M. Strauss, H. Esseku, a. Montangero, E. Awuah, and D. Kone. 2006. "Solid-Liquid Separation of Faecal Sludge Using Drying Beds in Ghana: Implications for Nutrient Recycling in Urban Agriculture." *Water Research* 40 (1): 75-82.

Comin, F.A., L.A. Romero, V. Astorga, and C. Garcia. 1997. "Nitrogen Removal and Cycling in Restored Wetlands Used as Filters of Nutrients for Agricultural " *Water Science and Technology* 35 (5): 255-261.

Conley, L. M., R. I. Dick, and L. W. Lion. 1991. "An Assessment of the Root Zone Method of Wastewater Treatment." *Journal of the Water Pollution Control Federation* 63 (3): 239-247.

Cooper, P. 1999. "A Review of the Design and Performance of Vertical-Flow and Hybrid Reed Bed Treatment Systems." *Water Science and Technology* 40 (3): 1-9.

Cooper, P. F., and A. G. Boon. 1987. "The Use of Phragmites for Wastewater Treatment by the Root Zone Method: The Uk Approach." In *Aquatic Plants for Water Treatment* *and Resource Recovery*, eds Reddy K.R. and Smith W.H., 153-74. Orlando, USA: Magnolia Publishing.

Cooper, P. F., G. D. Job, M. B. Green, and R. B. E. Shutes. 1996. *Reed Beds and Constructed Wetlands for Wastewater Treatment*. Swindon, UK: WRc Publications.

Cooper, P., P. Griffin, S. Humphries, and A. Pound. 1999. "Design of a Hybrid Reed Bed System to Achieve Complete Nitrification and Denitrification of Domestic Sewage " *Water Science and Technology* 40 (3): 283-289.

Cui, Y., T. Sun, L. Zhao, T. Jiang, and L. Zhang. 2008. "Performance of Wastewater Sludge Ecological Stabilization." *Journal of Environmental Science (China)* 20 (4): 385-9.

Dabadghao, P. M., and K. A. Shankarnarayan. 1973. *The Grass Cover of India*. New Delhi Indian Council of Agricultural Research.

Dakora, F. D. , and D. A. Phillips. 2002. "Root Exudates as Mediators of Mineral Acquisition in Low-Nutrient Environments." *Plant and Soil* 245: 35-47.

Delabie, J. H. C. 2001. "Trophobiosis between Formicidae and Hemiptera (Sternorrhyncha and Auchenorrhyncha): An Overview." *Neotropical Entomology* 30 (4): 501-516. http://www.scielo.br/scielo.php?script=sci_arttext&pid=S1519-566X2001000400001&nrm=iso.

Delaune, R. D., S. R. Pezeshki, and J. H. Pardue. 1990. "An Oxidation-Reduction Buffer for Evaluating Physiological Response of Plants to Root Oxygen Stress." *Environmental and Experimental Botany* 30: 243-247.

Denny, P. 1997. "Implementation of Constructed Wetlands in Developing Countries." *Water Science and Technology* 35 (5): 27-34.

Department of Environment, DOE. 2009. "Malaysia Environmental Quality (Sewage) Regulations " In *PU(A) 432*.

Domingos, S. 2011. "Vertical Flow Constructed Wetlands for the Treatment of Inorganic Industrial Wastewater." PhD thesis in Environmental Engineering, Murdoch University.

Donnell, C., A. Privett, and L.L. Behrends. 2003. "Reciprocating Constructed Wetlands for Treating Industrial, Municipal and Agricultural Wastewater." *Small Flows Quarterly* 4 (2): 24-27.

Dornelas, F. L., M. B. Machado, and M. von Sperling. 2009. "Performance Evaluation of Planted and Unplanted Subsurface-Flow Constructed Wetlands for the Post-Treatment of Uasb Reactor Effluents." *Water Science and Technology* 60 (12): 3025-33.

Drizo, A. , C.A. Frost, K.A. Smith, and J. Grace. 1997. "Phosphate and Ammonium Removal by Constructed Wetlands with Horizontal Subsurface Flow, Using Shale as a Substrate." *Water Science and Technology* 35: 95-102.

Dunbabin, J. S., J. Pokorny, and K. H. Bowmer. 1988. "Rhizosphere Oxygenation by Typha Domingensis Pers. In Miniature Artificial Wetland Filters Used for Metal Removal from Wastewaters." *Aquatic Botany* 29 (4): 303-317.

Dzakpasu, M., O. Hofmann, M. Scholz, R. Harrington, S. N. Jordan, and V. McCarthy. 2011. "Nitrogen Removal in an Integrated Constructed Wetland Treating Domestic Wastewater." *Journal of environmental science and health. Part A, Toxic/hazardous substances & environmental engineering* 46 (7): 742-750.

Economopoulou, M. A., and V. A. Tsihrintzis. 2003. "Design Methodology and Area Sensitivity Analysis of Horizontal Subsurface Flow Constructed Wetlands." *Water Resources Management* 17: 147-174.

Edwards, J. K., K. R. Gray, D. J. Cooper, A. J. Biddlestone, and N. Willoughby. 2001. "Reed Bed Dewatering of Agricultural Sludges and Slurries." *Water Science and Technology* 44 (11-12): 551-558.

Fan, J. L., S. Liang, B. Zhang, and J. Zhang. 2012. "Enhanced Organics and Nitrogen Removal in Batch-Operated Vertical Flow Constructed Wetlands by Combination of Intermittent Aeration and Step Feeding." *Environmental Science and Pollution Research International* 20 (4): 2448-2455.

Forquet, N., A. Wanko, P. Molle, R. Mosé, and A.-G. Sadowski. 2009. "Two-Phase Flow Modelling for Oxygen Renewal Estimation in Vertical Flow Filter: Luxury or Necessity?" *Water Science and Technology* 59: 2311-2319.

Gale, P. M., K. R. Reddy, and D. A. Graetz. 1993. "Nitrogen Removal from Reclaimed Water Applied to Constructed and Natural Wetlands Microcosms." *Water Environmental Research* 65 (2): 162-168.

García, J., P. Aguirre, R. Mujeriego, Y. Huang, L. Ortiz, and J.M. Bayona. 2004. "Initial Contaminant Removal Performance Factors in Horizontal Flow Reedbeds Used for Treating Urban Wastewater." *Water Research* 38 (7): 1669-1678.

Gersberg, R. M., B. V. Elkins, and C. R. Goldman. 1983. "Nitrogen Removal in Artificial Wetlands." *Water Research* 17 (9): 1009-1014.

Gersberg, R. M., S. R. Lyon, R. Brenner, and B. V. Elkins. 1987. "Fate of Viruses in Artificial Wetlands." *Applied and Environmental Microbiology* 53 (4): 731-736.

Giraldi, D., and R. Iannelli. 2009. "Short-Term Water Content Analysis for the Optimization of Sludge Dewatering in Dedicated Constructed Wetlands (Reed Bed Systems)." *Desalination* 246: 92-99.

Gopal, B., and D. Ghosh. 2008. "Natural Wetlands." *Encyclopedia of Ecology*: 2493-2504.

Green, M., E. Friedler, Y. Ruskol, and I. Safrai. 1997. "Investigation of Alternative Method for Nitrification in Constructed Wetlands." *Water Science and Technology* 35 (5): 63-70.

Haberl, R. 1999. "Constructed Wetlands: A Chance to Solve Wastewater Problems in Developing Countries." *Water Science and Technology* 40 (3): 11-17.

Haberl, R., S. Grego, G. Langergraber, R. H. Kadlec, A. R. Cicalini, S. M. Martins Dias, J. M. M. Novais et al. 2003. "Constructed Wetlands for the Treatment of Organic Pollutants " *Journal of Soils and Sediments* 3 (2): 109 - 124.

HACH. 2007. *Procedures Manual*. 2nd ed. Loveland, CO, USA: HACH Company.

Hamersley, M. R., B. L. Howes, D. S. White, S. Johnke, D. Young, S. B. Peterson, and J. M. Teal. 2001. "Nitrogen Balance and Cycling in an Ecologically Engineered Septage Treatment System." *Ecological Engineering* 18 (1): 61-75.

Hammer, D.A. 1989. *Constructed Wetlands for Wastewater Treatment: Municipal, Industrial,and Agricultural.* Lewis Publishers: Chelsea, MI. .

———. 1992. *Creating Freshwater Wetland*. Chelsea, MI: Lewis Publishers.

Hara, I., J. van der Toorn, and J. H. Mook. 1993. "Growth Dynamics and Size Structure of Shoots of Phragmites Australis, a Clonal Plant." *Journal of Ecology* 81: 47-60.

Haslam, S. M. 1971. "The Development and Establishment of Young Plants of Phragmites Communis Trin." *Annals of Botany* 35 (5): 1059-1072.

Headley, T. R., E. Herity, and L. Davison. 2005. "Treatment at Different Depths and Vertical Mixing within a 1-M Deep Horizontal Subsurface-Flow Wetland." *Ecological Engineering* 25 (5): 567-582.

Healy, M. G., M. Rodgers, and J. Mulqueen. 2006. "Denitrification of a Nitrate-Rich Synthetic Wastewater Using Various Wood-Based Media and Materials." *Journal of Environmental Science Health* 41: 779–788.

Heinss, U., S. A. Larmie, and M. Strauss. 1998. *Solids Seperation and Pond Systems for the Treatment of Faecal Sludges in the Tropics*. EAWAG.

———. 1999. *Characteristics of Faecal Sludges and Their Solids-Liquid Separation*. Duebendorf, Switzerland: EAWAG/SANDEC.

Higginsa, J. P., S. Hurdb, and C. Weilb. 2000. "The Use of Engineered Wetlands to Treat Recalcitrant Wastewaters." *Journal of Environmental Science and Health. Part A, Toxic/hazardous substances & environmental engineering, Part A: Toxic/Hazardous Substances and Environmental Engineering* 35 (8): 1309-1334.

Hinsinger, P., C. Plassard, C. X. Tang, and B. Jaillard. 2003. "Origins of Root-Mediated Ph Changes in the Rhizosphere and Their Responses to Environmenta Constraints." *Plant and Soil* 248 (1-2): 43-59.

Hoa, N. T., and T. Koottatep. 2007. "Effects of Different Substrate on Nitrogen Removal in Constructed Wetlands Treating Faecal Sludge." In *International Conference on Sustainable Architectural Design and Urban Planning, Hanoi, Vietnam*. Hanoi Architectural University.

Hofmann, K. 1990. "Use of Phragmites in Sewage Sludge Treatment." In *Constructed Wetlands in Water Pollution Control (Adv. Wat. Pollut. Control No. 11)* ed. Findlater B. C. Cooper P. F., 269-277. New York: Pergamon Press.

Horne, A. J. 1995. "Nitrogen Removal from Waste Treatment Pond or Activated Sludge Plant Effluents with Free Surface Wetlands." *Water Science and Technology* 31 (12): 341-351.

Hu, C. W., and Y. J. Zhao. "Effects of Plants Development and Pollutant Loading on Performance of Vertical Subsurface Flow Constructed Wetlands." *International Journal of Environmental Science and Technology* 8 (1): 177-186.

Hu, Y. S., Y. Q. Zhao, and A. Rymszewicza. 2014. "Robust Biological Nitrogen Removal by Creating Multiple Tides in a Single Bed Tidal Flow Constructed Wetland." *Science of The Total Environment* 470-471: 1197-1204.

Hu, Y. S., Y. Q. Zhao, X. H. Zhao, and J. L. G. Kumar. 2012. "Comprehensive Analysis of Step-Feeding Strategy to Enhance Biological Nitrogen Removal in Alum Sludge-Based Tidal Flow Constructed Wetlands." *Biosource Technology* 111: 27-35.

Huang, J., R.B. Reneau Jr., and C. Hagedorn. 2000. "Nitrogen Removal in Constructedwetlands Employed to Treat Domesticwastewater." *Water Research* 34 (9): 2582–2588.

Huisman, M. , and W.G.M. Van Kesteren. 1998. "Consolidation Theory Applied to the Capillary Suction Time (Cst) Apparatus." *Water Science and Technology* 37 (6-7): 117-124.

Hunt, R. J., D. P. Krabbenhoft, and M. P. Anderson. 1997. "Assessing Hydrogeochemical Heterogeneity in Natural and Constructed Wetlands." *Biogeochemistry* (39): 271-93.

Interstate Technology & Regulatory Council, ITRC. 2003. "Technical and Regulatory Guidance Document for Constructed Treatment Wetlands." edited by The Interstate Technology & Regulatory Council Wetlands Team.

IWA. 2000. *Constructed Wetlands for Pollution Control: Processes, Performance, Design, and Operation. Scientific and Technical Report No. 8*. London, UK: IWA Publishing.

Janke, R. 1985. "A Model of Microenvironments in Deep-Sea Sediment: Formation and Effects on Porewater Profiles. ." *Limnology and Oceanography* 30: 956-965.

Jia, W. L., J. Zhang, H. J. Xie, and B. Zhang. 2010. "Effect of Intermittent Operation on Contaminant Removal and Plant Growth in Vertical Flow Constructed Wetlands: A Microcosm Experiment." *Desalination* (262): 202-208.

Jing, S. H., Y. F. Lin, T. W. Wang, and D. Y. Lee. 2002. "Microcosm Wetland for Wastewater Treatment with Different Hydraulic Loading Rates and Macrophytes." *Journal of Environmental Quality* 31: 690-696.

Jorgensen, B. B., and N. P. Revsbech. 1985. "Diffusive Boundary Layers and the Oxygen Uptake of Sediments and Detritus." *Limnology and Oceanography* 30: 111-122.

Kadlec, R. H., and R. L. Knight. 1996. *Treatment Wetlands*. Boca Raton, FL, USA.: CRC Press.

Kadlec, R. H., R. L. Knight, J. Vymazal, H. Brix, P. Cooper, and R. Haberl. 2000. *Constructed Wetlands for Pollution Control – Processes, Performance, Design and*

Operation. Iwa Scientific and Technical Report No. 8. London, UK.: IWA Publishing.

Kadlec, R. H., and S. Wallace. 2009. *Treatment Wetlands*. 2nd ed: CRC Press, Taylor and Francis Group.

Kantawanichkul, S., S. Kladprasert, and H. Brix. 2009. "Treatment of High-Strength Wastewater in Tropical Vertical Flow Constructed Wetland Planted with Typha Angustifolia and Cyperus Involucratus." *Ecological Engineering* 35 (2): 238-247.

Kantawanichkul, S., S. Somprasert, U. Aekasin, and R. B. E. Shutes. 2003. "Treatment of Agricultural Wastewater in Two Experimental Combined Constructed Wetland Systems in a Tropical Climate." *Water Science and Technology* 48 (5): 199-205.

Kaseva, M.E. 2004. "Performance of a Subsurface Flow Constructed Wetland in Polishing Pre-Treated Wastewater-a Tropical Case Study." *Water Research* 38 (681-87).

Kayser, K., and S. Kunst. 2005. "Processes in Vertical-Flow Reed Beds: Nitrification, Oxygen Transfer and Soil Clogging." *Water Science and Technology* 51 (9): 177-184.

Keffala, C., and A. Ghrabi. 2005. "Nitrogen and Bacterial Removal in Constructed Wetlands Treating Domestic Wastewater." *Desalination* 185: 383-389.

Kengne, I. M., P. H. Dodane, A. Akoa, and D. Koné 2009. "Vertical-Flow Constructed Wetlands as Sustainable Sanitation Approach for Faecal Sludge Dewatering in Developing Countries." *Desalination* 248 (1-3): 291-297.

Kengne, I.M., A. Amougou, E.K. Soh, V. Tsama, M.M. Ngoutane, P.-H. Dodane, and D. Koné 2008. "Effects of Faecal Sludge Application on Growth Characteristics and Chemical Composition of Echinochloa Pyramidalis (Lam.) Hitch. And Chase and Cyperus Papyrus L." *Ecological Engineering* 34: 233-242.

Kim, B. J., and E. D. Smith. 1997. "Evaluation of Sludge Dewatering Reed Beds: A Niche for Small Systems." *Water Science and Technology* 35 (6): 21-28.

Kivaisi, A. K. 2001. "The Potential for Constructed Wetlands for Wastewater Treatment and Reuse in Developing Countries: A Review." *Ecological Engineering* 16: 545–560.

Kjeldsen, P., M.A. Barlaz, A.P. Rooker, A. Baun, A. Ledin, and T.H. Christensen. 2002. "Present and Long-Term Composition of Msw Landfill Leachate: A Review." *Environmental Science and Technology* 32 (4): 297-336.

Koottatep, T. 2004. *Executive Summary Report of Technical Guidelines Development and Demonstration of Constructed Wetland Treatment System Project.* Bangkok (Thailand).

Koottatep, T., D. Konnerup, and H. Brix. 2009. "Treatment of Domestic Wastewater in Tropical, Subsurface Flow Constructed Wetlands Planted with Canna and Heliconia." *Ecological Engineering* 35 (2): 248-257.

Koottatep, T., and C. Polprasert. 1997. "Role of Plant Uptake on Nitrogen Removal in Constructed Wetlands Located in the Tropics." *Water Science and Technology* 36 (12): 1-8.

Koottatep, T., C. Polprasert, and S. Hadsoi. 2006. "Integrated Faecal Sludge Treatment and Recycling through Constructed Wetlands and Sunflower Plant Irrigation." *Water Science and Technology* 54 (11-12): 155-164.

Koottatep, T., C. Polprasert, N.T.K. Oanh, U. Heinss, A. Montangero, and M. Strauss. 2001a. "Potentials of Vertical-Flow Constructed Wetlands for Septage Treatment in Tropical Regions." *Advances in Water and Wastewater Treatment Technology*: 315-323.

———. 2001b. "Septage Dewatering in Vertical-flow Constructed Wetlands Located in the Tropics." *Water Science and Technology* 44 (2-3): 181-188.

Koottatep, T., N. Surinkul, A.S.M. Kamal, C. Polprasert, A. Montangero, K. Doulaye, and M. Strauss. 2004. "Material Fluxes in Constructed Wetlands Treating Septage and Their Polishing Systems." In *9th International IWA Specialist Group Conference on Wetland Systems for Water Pollution Control and 6th International IWA Specialist Group Conference on Waste Stabilization Ponds*, *Avignon, France*.

Koottatep, T., N. Surinkul, C. Polprasert, A.S.M. Kamal, D. Kone ́, A. Montangero, U. Heinss, and M. Strauss. 2005. "Treatment of Septage in Constructed Wetlands in Tropical Climate: Lessons Learnt from Seven Years of Operation." *Water Science and Technology* 51: 119-126.

Korboulewsky, N., R. Wang, and V. Baldy. 2012. "Purification Processes Involved in Sludge Treatment by a Vertical Flow Wetland System: Focus on the Role of the Substrate and Plants on N and P Removal." *Bioresource technology* 105: 9-14.

Korkusuz, E. A., M. Beklioğlu, and G. N. Demirer. 2005. "Comparison of the Treatment Performances of Blast Furnace Slag-Based and Gravel-Based Vertical Flow Wetlands Operated Identically for Domestic Wastewater Treatment in Turkey " *Ecological Engineering* 24 (3): 185-198.

Kroiss, H. 2004. "What Is the Potential for Utilizing the Resources in Sludge? ." *Water Science and Technology* 49: 1-10.

Kröpfelová, L., J. Vymazal, J. Švehla, and J. Štíchová. 2009. "Removal of Trace Elements in Three Horizontal Sub-Surface Flow Constructed Wetlands in the Czech Republic." *Environmental Pollution* 157 (4): 1186-1194.

Kyambadde, J., F. Kansiime, L. Gumaelius, and G. Dalhammer. 2004. "A Comparative Study of Cyperus Papyrus and Miscanthidium Violaceum-Based Constructed Wetlands for Wastewater Treatment in a Tropical Climate." *Water Research* 38: 475-485.

Laber, J., R. Haberl, and G. Langergraber. 2003. "Treatment of Hospital Wastewater with a 2-Stage Constructed Wetland System." In *Haberl, R., Langergraber, G. (Eds.), Achievements and Prospects of Phytoremediation in Europe. Book of Abstracts*, eds R. Haberl and G. Langergraber, 85. University of Natural Resources and Applied Life Sciences, Vienna, Austria.

Laber, J., R. Haberl, and R. Shrestha. 1999. "Two-Stage Constructed Wetland for Treating Hospital Wastewater in Nepal." *Water Science and Technology* 40 (3): 317-324.

Laber, J., R. Perfler, and R. Haberl. 1997. "Two Strategies for Advanced Nitrogen Elimination in Vertical flow Constructed Wetlands." *Water Science and Technology* 35 (5): 71-78.

Langergraber, G. 2011. "Numerical Modelling: A Tool for Better Constructed Wetland Design?" *Water Science and Technology* 64 (1): 14-21.

Langergraber, G., D. Giraldi, J. Mena, D. Meyer, M. Peña, and A. Toscano. 2009. "Recent Developments in Numerical Modelling of Subsurface Flow Constructed Wetlands." *The Science of Total Environment* 407 (13): 3931-43.

Langergraber, G., R. Haberl, J. Laber, and A. Pressl. 2003. "Evaluation of Substrate Clogging Processes in Vertical flow Constructed Wetlands." *Water Science and Technology* 48: 25-34.

Langergraber, G., C. Prandtstetten, A. Press, R. Rohrhofer, and R. Haberl. 2007. "Removal Efficiency of Subsurface Vertical Flow Constructed Wetlands for Different Organic Loads." *Water Science and Technology* 56 (3): 75-84.

Lee, B. H., and M. Scholz. 2007. "What Is the Role of Phragmites Australis in Experimental Constructed Wetland Filters Treating Urban Runoff?" *Ecological Engineering* 29: 87-95.

Lee, C. G., T. D. Fletcher, and G. Z. Sun. 2009. "Nitrogen Removal in Constructed Wetland Systems." *Engineering in Life Sciences* 9 (1): 11-12.

Lin, Y.F., S.R. Jing, T.W. Wang, and D.Y. Lee. 2002. "Effects of Macrophytes and External Carbon Sources on Nitrate Removal from Groundwater in Constructed Wetlands." *Environmental Pollution* 119: 413-420.

Lowrance, R., J.C. Johnson Jr., G.L. Newton, and R.G. Williams. 1998. "Denitrification from Soils of a Year-Round Forage Production System Fertilized with Liquid Dairy Manure." *Journal of Environmental Quality* 27: 1504-1511.

Maeseneer, J. L. De. 1997. "Constructed Wetlands for Sludge Dewatering." *Water Science and Technology* 35 (5): 279-285.

Mara, D. D. 1978. *Sewage Treatment in Hot Climates*. Chichester: John Wiley & Sons.

———. 2004. *Domestic Wastewater Treatment in Developing Countries*: Earthscan.

Marks, M., B. Lapin, and J. Randall. 1994. "Phragmites Australis (P. Communis): Threats, Management and Monitoring." *Natural Areas Journal* 14: 285-294.

Martin, C., K. Johnson, and G.A. Moshiri. 1999. "Performance of a Constructed Wetland Leachate Treatment System at the Chunchula Landfill, Mobile County, Alabama." *Water Science and Technology* 40 (3): 67-74.

Masi, F., G. Bendoricchio, G. Conte, G. Garuti, A. Innocenti, D. Franco, L. Pietrelli, G. Pineschi, B. Pucci, and F. Romagnolli. "Constructed Wetlands for Wastewater

Treatment in Italy: State-of-the Art and Obtained Results." http://www.iridra.com/pubblicazioni/Masi_WaterPollution_ORAL.pdf.

Mbuligwe, S. E. 2004. "Comparative Effectiveness of Engineered Wetland Systems in the Treatment of Anaerobically Pre-Treated Domestic Wastewater." *Ecological Engineering* 23 (4-5): 269-284.

Mbuligwe, S. E. 2005. "Comparative Treatment of Dye-Rich Wastewater in Engineered Wetland Systems (Ewss) Veg- Etated with Different Plants." *Water Research* 39: 271-280.

Melidis, P., G. D. Gikas, C. S. Akratos, and V. A. Tsihrintzis. 2010. "Dewatering of Primary Settled Urban Sludge in a Vertical Flow Wetland." *Desalination* 250 (1): 395-398.

Merlin, G., J. L. Pajean, and T. Lissolo. 2002. "Performance of Constructed Wetlands for Municipal Wastewater Treatment in Rural Mountainous Area." *Hydrobiologia* 469: 87-98.

Metcalf, and Eddy. 1991. *Wastewater Engineering; Treatment, Disposal and Reuse*: McGraw-Hill.

Mitchell, C., and D. McNevin. 2001. "Alternative Analysis of Bod Removal in Subsurface Flow Constructed Wetlands Employing Monod Kinetics." *Water Research* 35 (5): 1295-1303.

Mitterer-Reichmann, G.M. 2002. "Data Evaluation of Constructed Wetlands for Treatment of Domestic Wastewater." In *8th international conference on wetland treatment for water pollution control, Arusha, Tanzania*.

Molle, P., A. Liénard, A. Grasmick, and A. Iwema. 2004. "French Vertical Flow Constructed Wetlands : Reed Bed Behaviour and Limits Due to Hydraulic Overloading on First Stage Filters." In *9ème conférence sur les marais artificiels et 6ème conférence sur le lagunage naturel, Avignon, France*.

———. 2006. "Effect of Reeds and Feeding Operations on Hydraulic Behaviour of Vertical Flow Constructed Wetlands under Hydraulic Overloads." *Water Research* 40 (3): 606-612.

Molle, P., S. Prost-Boucle, and A. Lienard. 2008. "Potential for Total Nitrogen Removal by Combining Vertical Flow and Horizontal Flow Constructed Wetlands: A Full-Scale Experiment Study." *Ecological Engineering* 34: 23-29.

Morgan, J. A., G. D. Bending, and P. J. White. 2005. "Biological Costs and Benefits to Plant-Microbe Interactions in the Rhizosphere." *Journal of Experimental Botany* 56 (417): 1729-1739.

Moshiri, G.A. 1993. *Constructed Wetlands for Water Quality Improvement*. Boca Raton: Lewis Publishers.

Moustafa, M. Z., M Chimney, J., T. D. Fontaine, G. Shid, and S. Davies. 1996. "The Response of a Freshwater Wetland to Long-Term "Low Level" Nutrient Loads - Marsh Efficiency." *Ecological Engineering* 7: 15-33.

Mulingbayan, M. T. Q. 2005. "Treatment of Laundry Wastewater Using Horizontal Flow Engineered Reed Beds." Master Thesis, College of Engineering, University of the Philippines.

Nassar, A., Smith M., and S. Afifi. 2006. "Sludge Dewatering Using the Reed Bed System in the Gaza Strip, Palestine." *Water and Environmental Journal* 20: 27-34.

Nassar, A. M., M. Smith, and S. Afifi. 2009. "Palestinian Experience with Sewage Sludge Utilizing Reed Beds." *Water and Environmental Journal* 23 (1): 75-82.

Nguyen, L. 2001. "Accumulation of Organic Matter Fractions in a Gravel-Bed Constructed Wetland." *Water Science and Technology* 44 (11-12): 281-287.

Nielsen, S. 2003. "Sludge Drying Reed Beds." *Water Science and Technology* 48: 101-109.

O.O. Cofie, S. Agbottah, M. Strauss, H. Esseku, A. Montangero, E. Awuah, and D. Kone. 2006. "Solid–Liquid Seperation of Faecal Sludge Using Drying Beds in Ghana: Implications for Nutrient Recycling in Urban Agriculture." *Water Research* 40 (1): 75-82.

O'Hogain, S. 2003. "The Design, Operation and Performance of a Municipal Hybrid Reed Bed Treatment System." *Water Science and Technology* 48 (5): 119-126.

Ong, S., K. Uchiyama, D. Inadama, Y. Ishida, and K. Yamagiwa. 2010. "Performance Evaluation of Laboratory Scale up-Flow Constructed Wetlands with Different Designs and Emergent Plants." *Bioresource Technology* 101: 7239-7244.

Oovel, M., A. Tooming, T. Mauring, and Ulo. Mander. 2007. "Schoolhouse Wastewater Purification in a Lwa-Filled Hybrid Constructed Wetland in Estonia." *Ecological Engineering* 29: 17-26.

Paing, J., and J. Voisin. 2005. "Vertical Flow Constructed Wetlands for Municipal Wastewater and Septage Treatment in French Rural Area." *Water Science and Technology* 51 (9): 145-55.

Panuvatvanich, A., T. Koottatep, and D. Kone. 2009. "Influence of Sand Layer Depth and Percolate Impounding Regime on Nitrogen Transformation in Vertical-Flow Constructed Wetlands Treating Faecal Sludge." *Water Research* 43 (10): 2623-2630.

Panuvatvanich, A., Thammarat Koottatep, and D. Koné. 2009. "Hydraulic Behaviour of Vertical-Flow Constructed Wetland under Different Operating Conditions." *Environmental Technology* 30 (10): 1031-1040.

Pescod, M. B. . 1971. "Sludge Handling and Disposal in Tropical Developing Countries." *Journal of Water Pollution Control Federation* 43 (4): 555-570.

Peters, J., S. M. Combs, B. Hoskins, J. Jarman, J. L. Kovar, M. E. Watson, A. M. Wolf, and N. Wolf. 2003. *Recommended Methods of Manure Analysis*. United States: Cooperative Extension Publishing.

Platzer, C 1999. "Design Recommendations for Subsurface Flow Constructed Wetlands for Nitrification and Denitrification." *Water Science and Technology* 40 (3): 257–263.

Platzer, C., and K. Mauch. 1997. "Soil Clogging in Vertical Flow Reed Beds – Mechanisms, Parameters, Consequences and Solutions." *Water Science and Technology* 35 (5): 175-181.

Poach, M. E., P. G. Hunt, and G. B. Reddy. 2004. "Ammonia Volatilization Frommarsh-Pond-Marsh Constructed Wetlands Treating Swine Wastewater." *Journal of Environmental Quality* 33 (3): 844-851.

Põldverea, E., K. Karabelnika, A. Noorveea, M. Maddisona, K. Nurka, I. Zaytseva, and Ü. Mandera. 2009. "Improving Wastewater Effluent Filtration by Changing Flow Regimes—Investigations in Two Cold Climate Pilot Scale Systems." *Ecological Engineering* 35: 193-203.

Prochaska, C. A., A. I. Zouboulis, and K. M. Eskridge. 2007. "Performance of Pilot-Scale Vertical-Flow Constructed Wetlands, as Affected by Season, Substrate, Hydraulic Load and Frequency of Application of Simulated Urban Sewage." *Ecological Engineering* 31 (1): 57-66.

Randall, C.W. 2003. "Changing Needs for Appropriate Excreta Disposal and Small Wastewater Treatment Methodologies or the Future Technology for Small Wastewater Treatment Systems." *Water Science and Technology* 48: 1-6.

Rao, T. P., K. Yano, M. Iijima, A. Yamauchi, and J. Tatsumi. 2002. "Regulation of Rhizosphere Acidification by Photosynthetic Activity in Cowpea (Vigna Unguiculata L. Walp.) Seedlings." *Annals of Botany* 89 (2): 213-220.

Reddy, K. R., and E. M D' Angelo. 1997. "Biogeochemical Indicators to Evaluate Pollutant Removal Efficiency in Constructed Wetlands." *Water Science and Technology* 35: 1-10.

Reddy, K. R., E. M. D'Angelo, and T. A. DeBusk. 1989. "Oxygen Transport through Aquatic Macrophytes, the Role in Wastewater Treatment." *Journal of Environmental Quality* 19: 261-267.

Reddy, K. R., W. H. Patrick Jr., and C. W. Lindau. 1989. "Nitrification–Denitrification at the Plant Root–Sediment Interface in Wetlands." *American Society of Limnology and Oceanography* 34 (6): 1004-1013.

Reddy, K. R., and W. H. Smith. 1987. *Aquatic Plants for Water Treatment and Resource Recovery*. Orlando, FL, USA: Magnolia Publishing.

Reed, S. C., and D. S. Brown. 1992. "Constructed Wetland Design - the First Generation." *Water Environmental Research* 64 (6): 776.

Reed, S. C., R. W. Crims, and E. J. Middlebrooks. 1988. "Natural Systems for Waste Management and Treatment." McGraw Hill Book Co.

Reed, S. C., R. W. Crites, and E. J. Middlebrooks. 1995. *Natural Systems for Waste Management and Treatment*. New York: McGraw Hill.

Roberts, M., M. J. Reiss, and G. Monger. 2000. *Advanced Biology*: Nelson.

Romero, J .A., R.A. Comin, and C. Garcia. 1999. "Restored Wetlands as Filters to Remove Nitrogen." *Chemosphere* 39 (2): 323-332.

Rousseau, D. P. L., P. A. Vanrolleghem, and N. De Pauw. 2004. "Model Baased Design of Horizontal Subsurface Flow Constructed Treatment Wetlands: A Review." *Water Research* 38: 1484-1493.

Ruppe, L.M. 2005. "Effects of Dosing Frequency on the Performance of Intermittently Loaded Packed Bed Wastewater Filters." University of California, Davis.

Saeed, T., and G. Sun. 2011a. "A Comparative Study on the Removal of Nutrients and Organic Matter in Wetland Reactors Employing Organic Media." *Chemical Engineering Journal* 171 (2): 439-447.

———. 2011b. "Enhanced Denitrification and Organics Removal in Hybrid Wetland Columns: Comparative Experiments." *Bioresource Technology* 102 (2): 967-974.

———. 2011c. "Kinetic Modelling of Nitrogen and Organics Removal in Vertical and Horizontal Flow Wetlands." *Water Research* 45 (10): 3137-3152.

Sarawak, Government. 2013. The Geography of Sarawak. 12/3/2014 Accessed 15/3/2013, http://www.sarawak.gov.my/en/about-sarawak/geography.

Sartoris, J. J., J. S. Thullen, L. B. Barber, and D. E. Salas. 2000. " Investigation of Nitrogen Transformations in a Southern California Constructed Wastewater Treatment Wetland." *Ecological Engineering* 14: 49-65.

Scholz, M., and B-H. Lee. 2005. "Constructed Wetlands: A Review." *International Journal of Environmental Study* 62 (4): 421-47.

Seo, D. C., J. S. Cho, H. J. Lee, and J. S. Heo. 2005. "Phosphorus Retention Capacity of Filter Media for Estimating the Longevity of Constructed Wetland." *Water Research* 39 (11): 2445-2457.

Sirianuntapiboon, S., M. Kongchum, and S. Jitvimolnimit. 2006. "Effects of Hydraulic Retention Time and Media of Constructed Wetland for Treatment of Domestic Wastewater." *African Journal of Agricultural Research* 1: 27-37.

Sleytr, K., A. Tietz, G. Langergraber, R. Haberl, and A. Sessitsch. 2009. "Diversity of Abundant Bacteria in Subsurface Vertical Flow Constructed Wetlands." *Ecological Engineering* 35 (6): 1021-1025.

Spieles, D. J., and W. J. Mitsch. 2000. "The Effects of Season and Hydrologic and Chemical Loading on Nitrate Retention in Constructed Wetlands: A Comparison of Low- and High- Nutrient Riverine Systems." *Ecological Engineering* 14: 77-91.

Stefanakis, A. I., C. S. Akratos, P. Melidis, and V. A. Tsihrintzis. 2009. "Surplus Activated Sludge Dewatering in Pilot-Scale Sludge Drying Reed Beds." *Journal of Hazardous Materials* 172 (2-3): 1122-1130.

Stefanakis, A. I., D. P. Komilis, and V. A. Tsihrintzis. 2011. "Stability and Maturity of Thickened Wastewater Sludge Treated in Pilot-Scale Sludge Treatment Wetlands." *Water Research* 45 (19): 6441-6452.

Stefanakis, A. I., and V. A. Tsihrintzis. 2011. "Dewatering Mechanisms in Pilot-Scale Sludge Drying Reed Beds: Effect of Design and Operational Parameters." *Chemical Engineering Journal* 172 (1): 430-443.

———. 2012. "Effects of Loading, Resting Period, Temperature, Porous Media, Vegetation and Aeration on Performance of Pilot-Scale Vertical Flow Constructed Wetlands." *Chemical Engineering Journal* 181-182: 416-430.

Stein, O. R., P. B. Hook, J. A. Biederman, W. C. Allen, and D. J. Borden. 2003. "Does Batch Operation Enhance Oxidation in Subsurface Constructed Wetlands?" *Water Science and Technology* 48 (5): 149-156.

Strauss, M., S. A. Larmie, and U. Heinss. 1997. "Treatment of Sludges from on-Site Sanitation: Low-Cost Options." *Water Science and Technology* 35 (6): 129-136.

Su, C., and R. W. Puls. 2007. "Removal of Added Nitrate in Cotton Burr Compost, Mulch Compost, and Peat: Mechanisms and Potential Use for Groundwater Nitrate Remediation." *Chemosphere* 66: 91-98.

Sun, G., and D. Austin. 2007. "Completely Autotrophic Nitrogen-Removal over Nitrite in Lab-Scale Constructed Wetlands: Evidence from a Mass Balance Study." *Chemosphere* 68: 1120-1128.

Suthersan, S. S. 2002. *Natural and Enhanced Remediation Systems*. Washington, DC: Lewis Publisher.

Tanner, C. C. 2001. "Plants as Ecosystem Engineers in Subsurface-Flow Treatment Wetlands." *Water Science and Technology* 44 (11-12): 9-17.

Tanner, C. C., J. S. Clayton, and M. P. Upsdell. 1995a. "Effect of Loading Rate and Planting on Treatment of Dairy Farm Wastewaters in Constructed Wetlands - 1. Removal of Oxygen Demand, Suspended Solids and Fecal Coliforms." *Water Research* 29 (1): 17-26.

Tanner, C. C., J. D'Eugenio, G. B. McBride, J. P. S. Sukias, and K. Thompson. 1999. "Effect of Water Level Fluctuation on Nitrogen Removal from Constructed Wetland Mesocosms." *Ecological Engineering* 12: 67-92.

Tanner, C. C., and J. P. S. Sukias. 2003. "Linking Pond and Wetland Treatment: Performance of Domestic and Farm Systems in New Zealand." *Water Science and Technology* 48: 331-339.

Tanner, C.C., J.S. Clayton, and M.P. Upsdell. 1995b. "Effect of Loading Rate and Planting on Treatment of Dairy Farmwastewaters in Constructed Wetland-2. Removal of Nitrogen and Phosphorus." *Water Research* 29 (1): 27-34.

Tao, W. D., and J. Wang. 2009. "Effects of Vegetation, Limestone and Aeration on Nitrification, Annamox and Denitrifcation in Wetland Systems." *Ecological Engineering* 35 (5): 836-842.

Teal, J. M., and S. B. Peterson. 1991. "The Next Generation of Septage Treatment." *Research Journal of the Water Pollution Control Federation* 63 (1): 84-89.

Tietz, A., G. Langergraber, A. Watzinger, R. Haberl, and A. K. T. Kirschner. 2008. "Bacterial Carbon Utilization in Vertical Subsurface Flow Constructed Wetlands." *Water Research* 42 (6-7): 1622-1634.

Toet, S., R. S. P. Van Logtestijn, R. Kampf, M. Schreijer, and J. T. A. Verhoeven. 2005. "The Effect of Hydraulic Retention Time on the Removal of Pollutants from Sewage Treatment Plant Effluent in a Surface-Flow Wetland System." *Wetlands* 25: 375-391.

Torrens, A., P. Molle, C. Boutin, and M. Salgot. 2009. "Impact of Design and Operation Variables on the Performance of Vertical-Flow Constructed Wetlands and Intermittent Sand Filters Treating Pond Effluent." *Water Research* 43 (7): 1851-1858.

Trang, N. T. D., D. Konnerup, H. H. Schierup, N. H. Chiem, L. A. Tuan, and H. Brix. 2010. "Kinetics of Pollutant Removal from Domestic Wastewater in a Tropical Horizontal Subsurface Flow Constructed Wetland System: Effects of Hydraulic Loading Rate." *Ecological Engineering* 36 (4): 527-535.

Troesch, S., A. Liénard, P. Molle, G. Merlin, and D. Esser. 2009a. "Sludge Drying Reed Beds: Full- and Pilot-Scale Study for Activated Sludge Treatment." *Water Science Technology* 60 (5): 1145-1154.

———. 2009b. "Treatment of Septage in Sludge Drying Reed Beds: A Case Study on Pilot-Scale Beds." *Water Science and Technology* 60 (3): 643-653.

Tropical, Stokes. Costus Woodsonii. Accessed 13/6/2014, http://stokestropicals.plants.com/Costus-woodsonii-Dwarf-Lipstick-P77.aspx.

Tunçsiper, B., S. Ayaz, L. Akça, and K. Gunes. 2009. "Performance of a Pilot-Scale, Three-Stage Constructed Wetland System for Domestic Wastewater Treatment." *Environmental Technology* 30 (11): 1187-1194.

U.S. Environmental Protection Agency, U.S.EPA. 2002. *Onsite Wastewater Treatment Systems Manual*.

U.S. Environmental Protection Agency, USEPA. 1988. *Design Manual: Constructed Wetlands and Aquatic Plant Systems for Municipal Wastewater Treatment*. Cincinnati, OH.: U.S. EPA.

U.S.EPA. 1999. *Decentralized Systems Technology Fact Sheet, Septage Treatment/ Disposal*. Washington DC, USA.

U.S.EPA. 2000. *Constructed Wetlands Treatment of Municipal Wastewaters*. Cincinnati, OH.

Uggetti, E., I. Ferrer, E. Llorens, and J. García. 2011. "Technical, Economic and Environmental Assessment of Sludge Treatment Wetlands." *Water Research* 45 (2): 573-582.

Uggetti, E., E. Llorens, A. Pedescoll, I.Ferrer, R. Castellnou, and J. García. 2009. "Sludge Dewatering and Stabilization in Drying Reed Beds: Characterization of Three Full-Scale Systems in Catalonia, Spain." *Bioresource Technology* 100 (17): 3882-3890.

United States Department of Agriculture , USDA. 1995. *Handbook of Constructed Wetlands. A Guide to Creating Wetlands For: Agricultural Wastewater, Domestic Wastewater, Coal Mine Drainage, Storm Water in the Mid-Atlantic Region*. Vol. 1, *General Considerations*. Washington, D.C.

Vázquez, M. A., D. de la Varga, R. Plana, and M. Soto. 2013. "Vertical Flow Constructed Wetland Treating High Strength Wastewater from Swine Slurry Composting." *Ecological Engineering* 50: 37-43.

Vincent, J., P. Molle, C. Wisniewski, and A. Liénard. 2011. "Sludge Drying Reed Beds for Septage Treatment: Towards Design and Operation Recommendations." *Bioresource Technology* 102 (17): 8327-30.

von Felde, K., and S. Kunst. 1997. "N- and Cod-Removal in Vertical-flow Systems." *Water Science and Technology* 35 (5): 79-85.

Vymazal, J. 1999. "Removal of Bod in Constructed Wetlands with Horizontal Subsurface flow: Czech Experience." *Water Science and Technology* 40 (13): 133-138.

———. 2002. "The Use of Sub-Surface Constructed Wetlands for Wastewater Treatment in the Czech Republic: 10 Years Experience." *Ecological Engineering* 18 (5): 633-646.

———. 2005. "Horizontal Sub-Surface Flow and Hybrid Constructed Wetlands Systems for Wastewater Treatment." *Ecological Engineering* 25: 478-490.

———. 2007. "Removal of Nutrients in Various Types of Constructed Wetlands." *Science of The Total Environment* 380 (1-3): 48-65.

Vymazal, J., H. Brix, P. F. Cooper, M. B. Green, and R. Haberl. 1998. *Constructed Wetlands for Wastewater Treatment in Europe*. Leiden, The Netherlands: Backhuys Publishers.

Vymazal, J., and L. Kröpfelová. 2005. "Growth of Phragmites Australis and Phalaris Arundinacea in Constructed Wetlands for Wastewater Treatment in the Czech Republic." *Ecological Engineering* 25: 606-621.

———. 2008a. "Environmental Polution." In *Wastewater Treatment in Constructed Wetlands with Horizontal Sub-Surface Flow*.

———. 2008b. "Is Concentration of Dissolved Oxygen a Good Indicator of Processes in Filtration Bedsof Horizontal-Flow Constructed Wetlands." In *Vymazal, J. (Ed.). Wastewater Treatment, Plant Dynamics and Management in Constructed and Natural Wetlands*, Berlin: Springer Science + Business Media.

———. 2010. "A Three-Stage Experimental Constructed Wetland for Treatment of Domestic Sewage: First 2 Years of Operation." *Ecological Engineering*.

Wang, R., V. Baldy, C. Périssol, and N. Korboulewsky. 2001. "Influence of Plants on Microbial Activity in a Vertical-Downflow Wetland System Treating Waste Activated Sludge with High Organic Matter Concentrations." *Journal of environmental management* 95 Suppl: 158-164.

Wang, R., N. Korboulewsky, P. Prudent, V. Baldy, and G. Bonin. 2009. "Can Vertical-Flow Wetland Systems Treat High Concentrated Sludge from a Food Industry? A

Mesocosm Experiment Testing Three Plant Species." *Ecological Engineering* 35: 230-237.

Williams, J. B., E. May, M. G. Ford, and J. E. Butler. 1994. "Nitrogen Transformations in Gravel Bed Hydroponic Beds Used as a Tertiary Treatment Stage for Sewage Effluents." *Water Science and Technology* 29 (4): 29-36.

Wood, A. 1995. "Constructed Wetlands in Water Pollution Control: Fundamentals to Their Understanding." *Water Science and Technology* 32 (3): 21-29.

Wu, H., J. Zhang, P. Li, J. Zhang, H. Xie, and B. Zhang. 2011. "Nutrient Removal in Constructed Microcosm Wetlands for Treating Polluted River Water in Northern China." *Ecological Engineering* 37 (4): 560-568.

Wu, S. Q., J. J. Chang, Y. R. Dai, Z. B. Wu, and W. Liang. 2013. "Treatment Performance and Microorganism Community Structure of Integrated Vertical-Flow Constructed Wetland Plots for Domestic Wastewater." *Environmental Science and Pollution Research International* 20 (6): 2789-2798.

Yang, L., H.T. Chang, and M.N.L. Huang. 2001. "Nutrient Removal in Gravel- and Soil-Based Wetland Microcosms with and without Vegetation. ." *Ecological Engineering* 18: 91-105.

Zhang, D. Q., S. K. Tan, R. M. Gersberg, J. F. Zhu, S.Sadreddini, Y. F. Li, and A. Liénard. 2012. "Nutrient Removal in Tropical Subsurface flow Constructed Wetlands under Batch and Continuous flow Conditions." *Journal of Environmental Management* 96: 1-6.

Zhang, J., X. Huang, C. X. Liu, H. C. Shi, and H. Y. Hu. 2005. "Nitrogen Removal Enhanced by Intermittent Operation in a Subsurface Wastewater Infiltration System." *Ecological Engineering* 25 (4): 419-428.

Zhao, L. F., W. Zhu, and W. Tong. 2009. "Clogging Processes Caused by Biofilm Growth and Organic Particle Accumulation in Lab- Scale Vertical Flow Constructed Wetlands." *Journal of Environmental Science* 21: 750-757.

Zhao, Y. Q., G. Sun, C. Lafferty, and S. J. Allen. 2004. "Optimising the Performance of a Lab-Scale Tidal Flow Reed Bed System Treating Agricultural Wastewater." *Water Science and Technology* 50 (8): 65-72.

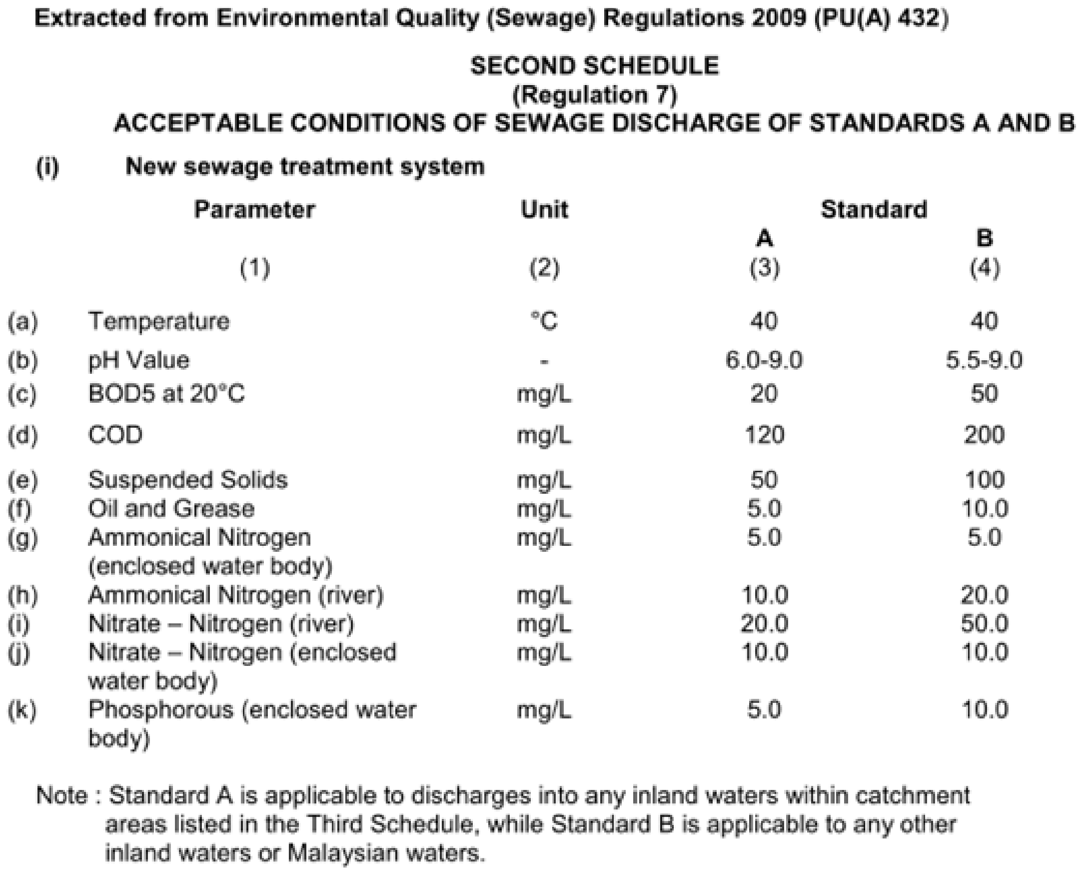
Zurita, F., J. De Anda, and M.A. Belmont. 2009. "Treatment of Domestic Wastewater and Production of Commercial Flowers in Vertical and Horizontal Subsurface-Flow Constructed Wetlands." *Ecological Engineering* 35 (5): 861-869.

Zurita, F., M. A. Belmont, J. De Anda, and J. R. White. 2011. "Seeking a Way to Promote the Use of Constructed Wetlands for Domestic Wastewater Treatment in Developing Countries." *Water Science and Technology* 63 (4): 654–659

Every reasonable effort has been made to acknowledge the owners of copyright material. I would be pleased to hear from any copyright owner who has been omitted or incorrectly acknowledged.

Appendices

Appendix A: Malaysia Environmental Quality Act 1974 (Environmental Quality (Sewage) Regulation 2009)



Extracted from Environmental Quality (Sewage) Regulations 2009 (PU(A) 432)

SECOND SCHEDULE
(Regulation 7)
ACCEPTABLE CONDITIONS OF SEWAGE DISCHARGE OF STANDARDS A AND B

(i) New sewage treatment system

	Parameter (1)	Unit (2)	Standard A (3)	 B (4)
(a)	Temperature	°C	40	40
(b)	pH Value	-	6.0-9.0	5.5-9.0
(c)	BOD5 at 20°C	mg/L	20	50
(d)	COD	mg/L	120	200
(e)	Suspended Solids	mg/L	50	100
(f)	Oil and Grease	mg/L	5.0	10.0
(g)	Ammonical Nitrogen (enclosed water body)	mg/L	5.0	5.0
(h)	Ammonical Nitrogen (river)	mg/L	10.0	20.0
(i)	Nitrate – Nitrogen (river)	mg/L	20.0	50.0
(j)	Nitrate – Nitrogen (enclosed water body)	mg/L	10.0	10.0
(k)	Phosphorous (enclosed water body)	mg/L	5.0	10.0

Note : Standard A is applicable to discharges into any inland waters within catchment areas listed in the Third Schedule, while Standard B is applicable to any other inland waters or Malaysian waters.

Appendix B : First Stage wetlands

(B1) Effect SLR

100 kg TS/m^2.yr and 250 kg TS/m^2.yr

COD

Raw
mg/L
31875.00
20740.00
38080.00
46410.00
45450.00
23490.00
15930.00
33686.67
12400.00
51678.00
24021.00
22440.00
54870.00
47120.00
8990.00
55180.00
21930.00
20400.00
31927.26
±15081.28

A1-100P		A1-250P	
mg/L	RE %	mg/L	RE %
3180.00	90.02	3270.00	89.74
1260.00	93.92	1440.00	93.06
570.00	98.50	1140.00	97.01
510.00	98.90	980.00	97.89
540.00	98.81	403.33	99.11
440.00	98.13	1246.67	94.69
440.00	97.24	1155.00	94.69
183.33	99.46	3440.00	89.79
1130.00	90.89	2040.00	83.55
990.00	98.08	15300.00	70.39
1140.00	95.25	1740.00	92.76
1140.00	94.92	1440.00	93.58
2280.00	95.84	3780.00	93.11
2160.00	95.42	5040.00	89.30
1020.00	88.65	1800.00	79.98
600.00	98.91	1020.00	98.15
480.00	97.81	1500.00	93.16
408.00	98.00	1200.00	94.12
1026.19	***96.04***	***2663.06***	***91.34***
±788.14	***±3.28***	***±3371.77***	***±7.14***

		A1-100P			A1-250P		
Raw (kg TS/m2.yr)		kg TS/m2.yr		RE %	kg TS/m2.yr		RE (%)
SLR 100	SLR 250	Eff. Mass	MRR		Eff. Mass	MRR	
1938.59	4846.46	133.45	1805.14	93.12	228.71	4617.76	95.28
1908.35	4770.89	77.68	1830.68	95.93	122.56	4648.33	97.43
1907.00	4767.50	16.56	1890.45	99.13	57.09	4710.41	98.80
2373.67	5934.18	16.43	2357.24	99.31	58.89	5875.28	99.01
2324.57	5811.43	17.95	2306.62	99.23	25.27	5786.16	99.57
1959.62	4899.04	28.26	1931.35	98.56	166.40	4732.64	96.60
2194.14	5485.36	34.54	2159.60	98.43	194.88	5290.48	96.45
2570.51	6426.28	8.25	2562.26	99.68	275.62	6150.66	95.71
896.54	2241.35	59.64	836.90	93.35	125.37	2115.98	94.41
1314.56	3286.40	16.62	1297.94	98.74	398.92	2887.48	87.86
1246.74	3116.85	46.74	1200.00	96.25	119.66	2997.19	96.16
1876.25	4690.64	77.21	1799.05	95.89	168.56	4522.07	96.41
2836.54	7091.35	81.33	2755.21	97.13	185.64	6905.71	97.38
2107.33	5268.34	60.86	2046.48	97.11	185.96	5082.38	96.47
2161.06	5402.64	161.83	1999.23	92.51	389.42	5013.22	92.79
7802.60	19506.50	55.15	7747.45	99.29	115.38	19391.12	99.41
648.82	1622.04	8.38	640.44	98.71	32.17	1589.87	98.02
502.96	1257.40	6.24	496.72	98.76	39.20	1218.20	96.88
2142.77	***5356.93***	***50.40***	***2092.38***	***97.29***	***160.54***	***5196.39***	***96.37***
±1600.08	***±4000.19***	***±39.83***	***±1593.85***	***±2.13***	***±112.27***	***±3998.93***	***±2.82***

BOD

Raw
mg/L
3600.00
2900.00
4830.00
3060.00
8740.00
1720.00
3200.00
1690.00
1410.00
7630.00
1938.00
2472.00
3912.00

A1-100P		A1-250P	
mg/L	RE %	mg/L	RE %
590.00	83.61	620.00	82.78
531.00	81.69	550.00	81.03
312.00	93.54	410.00	91.51
141.00	95.39	216.00	92.94
390.00	95.54	540.00	93.82
60.00	96.51	336.00	80.47
240.00	92.50	420.00	86.88
23.40	98.62	50.70	97.00
114.60	91.87	172.80	87.74
402.00	94.73	684.00	91.04
66.00	96.59	46.50	97.60
31.35	98.73	64.20	97.40
88.50	97.74	98.55	97.48

4374.00	112.20	97.43	112.20	97.43
2538.00	47.70	98.12	106.80	95.79
3936.00	92.85	97.64	102.15	97.40
894.00	97.80	89.06	99.45	88.88
1044.00	103.50	90.09	116.10	88.88
3327.11	***191.33***	***93.86***	***263.64***	***91.45***
±2172.29	***±151.16***	***±4.42***	***±204.80***	***±5.65***

		A1-100P			A1-250P		
Raw (kg TS/m2.yr)		kg TS/m2.yr		RE %	kg TS/m2.yr		RE %
SLR 100	SLR 250	Eff. Mass	MRR		Eff. Mass	MRR	
218.95	547.37	24.76	194.19	88.69	43.36	504.00	92.08
266.84	667.10	32.74	234.10	87.73	46.81	620.28	92.98
241.88	604.70	9.06	232.82	96.25	20.53	584.17	96.60
156.51	391.26	4.54	151.96	97.10	12.98	378.28	96.68
447.01	1117.53	12.97	434.05	97.10	33.83	1083.70	96.97
143.49	358.72	3.85	139.63	97.31	44.85	313.87	87.50
440.76	1101.89	18.84	421.91	95.73	70.87	1031.03	93.57
128.96	322.40	1.05	127.90	99.18	4.06	318.33	98.74
101.95	254.86	6.05	95.90	94.07	10.62	244.24	95.83
194.09	485.22	6.75	187.34	96.52	17.83	467.39	96.32
100.59	251.47	2.71	97.88	97.31	3.20	248.27	98.73
206.69	516.72	2.12	204.57	98.97	7.52	509.21	98.55
202.23	505.58	3.16	199.08	98.44	4.84	500.74	99.04
195.62	489.04	3.16	192.46	98.38	4.14	484.90	99.15
610.10	1525.24	7.57	602.53	98.76	23.11	1502.13	98.49
556.56	1391.40	8.53	548.03	98.47	11.56	1379.85	99.17
26.45	66.12	1.71	24.74	93.55	2.13	63.99	96.77
25.74	64.35	1.58	24.16	93.85	3.79	60.56	94.11
236.91	***592.28***	***8.40***	***228.51***	***95.97***	***20.34***	***571.94***	***96.18***
±174.33	***±435.81***	***±8.00***	***±171.00***	***±2.86***	***±19.49***	***±427.23***	***±3.03***

NH_3-N

Raw
mg/L
406.35
677.25
234.78
695.31
504.18

A1-100P		A2-250P	
mg/L	RE %	mg/L	RE %
82.62	79.67	94.35	76.78
109.65	83.81	132.09	80.50
55.59	76.32	68.85	70.67
95.45	86.27	116.54	83.24
55.59	88.97	74.97	85.13

386.79		79.05	79.56	107.36	72.24
216.72		70.95	67.26	64.90	70.05
336.96		72.40	78.51	88.20	73.82
178.20		90.60	49.16	101.00	43.32
153.90		40.70	73.55	30.60	80.12
408.00		43.20	89.41	78.00	80.88
326.40		40.80	87.50	91.80	71.88
186.00		14.40	92.26	15.00	91.94
198.40		82.80	58.27	124.20	37.40
167.40		70.20	58.06	99.60	40.50
254.20		87.60	65.54	109.80	56.81
295.80		147.00	50.30	139.20	52.94
260.10		94.80	63.55	114.06	56.15
327.04		***74.08***	***73.78***	***91.70***	***68.02***
±163.00		***±30.24***	***±13.76***	***±32.65***	***±16.30***

		A1-100P			A1-250P		
Raw (kg TS/m2.yr)		kg TS/m2.yr		RE %	kg TS/m2.yr		RE %
SLR 100	SLR 250	Eff. Mass	MRR		Eff. Mass	MRR	
24.71	61.78	3.47	21.25	85.97	6.60	55.18	89.32
62.32	155.79	6.76	55.56	89.15	11.24	144.55	92.78
11.76	29.39	1.61	10.14	86.27	3.45	25.95	88.27
35.56	88.91	3.08	32.49	91.35	7.00	81.90	92.12
25.79	64.47	1.85	23.94	92.83	4.70	59.77	92.71
32.27	80.67	5.08	27.19	84.26	14.33	66.34	82.24
29.85	74.63	5.57	24.28	81.34	10.95	63.68	85.33
25.71	64.28	3.26	22.45	87.32	7.07	57.21	89.01
12.88	32.21	4.78	8.10	62.89	6.21	26.00	80.73
3.91	9.79	0.68	3.23	82.55	0.80	8.99	91.85
21.18	52.94	1.77	19.40	91.64	5.36	47.58	89.87
27.29	68.23	2.76	24.53	89.88	10.75	57.48	84.25
9.62	24.04	0.51	9.10	94.66	0.74	23.30	96.94
8.87	22.18	2.33	6.54	73.71	4.58	17.60	79.34
40.24	100.60	11.14	29.10	72.32	21.55	79.05	78.58
35.94	89.86	8.05	27.89	77.60	12.42	77.44	86.18
8.75	21.88	2.57	6.19	70.68	2.99	18.89	86.35
6.41	16.03	1.45	4.96	77.40	3.73	12.31	76.76
23.50	***58.76***	***3.71***	***19.80***	***82.88***	***7.47***	***51.29***	***86.81***
±14.92	***±37.31***	***±2.77***	***±13.10***	***±8.82***	***±5.26***	***±33.61***	***±5.64***

TN

Raw
mg/L
969.00
1,479.00
714.00
1,190.00
1,616.00
1,660.50
1,053.00
526.50
372.00
1,271.00
638.00
539.00
1,302.00
1,085.00
1,479.00
765.00
1,085.00
1,116.00
1047.78
±388.44

A1-100P		A2-250P	
mg/L	RE %	mg/L	RE %
243.10	74.91	267.30	72.41
277.20	81.26	287.10	80.59
253.00	64.57	264.00	63.03
253.00	78.74	288.00	75.80
209.00	87.07	220.00	86.39
227.33	86.31	231.00	86.09
132.00	87.46	198.00	81.20
102.00	80.63	197.00	62.58
126.00	66.13	156.00	58.06
90.00	92.92	126.00	90.09
138.00	78.37	150.00	76.49
198.00	63.27	282.00	47.68
144.00	88.94	108.00	91.71
264.00	75.67	510.00	53.00
258.00	82.56	318.00	78.50
126.00	83.53	168.00	78.04
270.00	75.12	342.00	68.48
282.00	74.73	432.00	61.29
199.59	***79.01***	***252.47***	***72.86***
±67.57	***±8.42***	***±104.58***	***±12.89***

		A1-100P			A1-250P		
Raw (kg TS/m2.yr)		kg TS/m2.yr		RE %	kg TS/m2.yr		RE %
SLR 100	SLR 250	Eff. Mass	MRR		Eff. Mass	MRR	
58.93	147.33	10.20	48.73	82.69	18.70	128.64	87.31
136.09	340.22	17.09	119.00	87.44	24.44	315.78	92.82
35.76	89.39	7.35	28.41	79.45	13.22	76.17	85.21
60.86	152.16	8.15	52.71	86.61	17.31	134.85	88.63
82.65	206.63	6.95	75.70	91.59	13.78	192.84	93.33
138.52	346.31	14.60	123.92	89.46	30.83	315.48	91.10
145.04	362.59	10.36	134.67	92.85	33.41	329.18	90.79
40.18	100.44	4.59	35.58	88.57	15.78	84.65	84.28
26.90	67.24	6.65	20.25	75.27	9.59	57.65	85.74
32.33	80.83	1.51	30.82	95.33	3.29	77.54	95.94
33.11	82.78	5.66	27.46	82.91	10.32	72.47	87.54
45.07	112.67	13.41	31.66	70.24	33.01	79.66	70.70

67.31	168.27	5.14	62.17	92.37	5.30	162.97	96.85
48.52	121.31	7.44	41.09	84.67	18.82	102.49	84.49
355.53	888.82	40.93	314.60	88.49	68.80	820.02	92.26
108.17	270.43	11.58	96.59	89.29	19.00	251.43	92.97
32.10	80.25	4.71	27.39	85.32	7.34	72.92	90.86
27.51	68.79	4.31	23.20	84.33	14.11	54.67	79.48
81.92	***204.80***	***10.04***	***71.89***	***85.94***	***19.84***	***184.97***	***88.35***
±79.16	***±197.89***	***±8.69***	***±71.06***	***±6.30***	***±15.09***	***±184.49***	***±6.28***

TS

Raw	A1-100P		A2-250P	
mg/L	mg/L	RE %	mg/L	RE %
31620.00	4551.00	85.61	4734.00	85.03
20900.00	3624.00	82.66	3941.00	81.14
38401.00	4555.00	88.14	4952.00	87.10
37600.00	2400.00	93.62	2400.00	93.62
37600.00	1885.00	94.99	2668.00	92.90
23052.00	1200.00	91.41	2044.00	91.13
13962.00	1200.00	91.41	1436.00	89.71
25202.00	2040.00	91.91	2552.00	89.87
26598.00	2012.00	92.44	2124.00	92.01
75600.00	4800.00	93.65	16400.00	78.31
37052.00	3092.00	91.65	1512.00	95.92
23000.00	3240.00	85.91	1540.00	93.30
37200.00	3440.00	90.75	4552.00	87.76
43000.00	2992.00	93.04	4248.00	90.12
8000.00	3304.00	58.70	1552.00	80.60
13600.00	2796.00	79.44	2080.00	84.71
65000.00	2152.00	96.69	2152.00	96.69
78000.00	1748.00	97.76	2176.00	97.21
35299.28	***2835.06***	***88.88***	***3503.50***	***89.29***
±19980.91	***±1101.46***	***±8.89***	***±3431.26***	***±5.58***

		A1-100P			A1-250P		
Raw (kg TS/m2.yr)		kg TS/m2.yr		RE %	kg TS/m2.yr		RE %
SLR 100	SLR 250	Eff. Mass	MRR		Eff. Mass	MRR	
1,923.08	4,807.69	190.98	1,732.10	90.07	331.10	4,476.59	93.11
1,923.08	4,807.69	223.42	1,699.66	88.38	335.43	4,472.26	93.02
1,923.08	4,807.69	132.30	1,790.77	93.12	247.99	4,559.70	94.84
1,923.08	4,807.69	77.33	1,845.74	95.98	144.23	4,663.46	97.00
1,923.08	4,807.69	62.67	1,860.41	96.74	167.16	4,640.53	96.52

1,923.08	4,807.69	77.08	1,845.99	95.99	272.83	4,534.86	94.33
1,923.08	4,807.69	94.21	1,828.87	95.10	242.29	4,565.40	94.96
1,923.08	4,807.69	91.84	1,831.23	95.22	204.47	4,603.22	95.75
1,923.08	4,807.69	106.19	1,816.88	94.48	130.53	4,677.16	97.28
1,923.08	4,807.69	80.59	1,842.49	95.81	427.60	4,380.09	91.11
1,923.08	4,807.69	126.78	1,796.30	93.41	103.98	4,703.71	97.84
1,923.08	4,807.69	219.43	1,703.65	88.59	180.27	4,627.42	96.25
1,923.08	4,807.69	122.70	1,800.37	93.62	223.55	4,584.14	95.35
1,923.08	4,807.69	84.30	1,838.78	95.62	156.74	4,650.96	96.74
1,923.08	4,807.69	524.19	1,398.88	72.74	335.77	4,471.92	93.02
1,923.08	4,807.69	256.99	1,666.09	86.64	235.29	4,572.40	95.11
1,923.08	4,807.69	37.56	1,885.51	98.05	46.16	4,761.53	99.04
1,923.08	4,807.69	26.72	1,896.36	98.61	71.08	4,736.61	98.52
1923.08	***4807.69***	***140.85***	***1782.23***	***92.68***	***214.25***	***4593.44***	***95.54***
±0.00	***±0.00***	***±115.57***	***±115.57***	***±6.01***	***±101.20***	***±101.20***	***±2.10***

TSS

Raw
mg/L
22,560.00
19,662.00
31,710.00
26,890.00
30,000.00
5,200.00
12,500.00
25,333.33
24,400.00
50,500.00
11,300.00
9,100.00
26,800.00
38,300.00
6,700.00
12,500.00
60,900.00
31,300.00
24758.63
±14844.84

A1-100P		A2-250P	
mg/L	RE %	mg/L	RE %
260.00	98.85	580.00	97.43
375.00	98.09	250.00	98.73
736.00	97.68	1,228.00	96.13
280.00	98.96	1,680.00	93.75
335.00	98.88	875.00	97.08
35.00	99.33	80.00	98.46
96.00	99.23	850.00	93.20
48.00	99.79	1,730.00	92.28
250.00	98.98	1,400.00	94.26
1,810.00	96.42	4,940.00	90.22
587.50	94.80	1,600.00	85.84
340.00	96.26	360.00	96.04
700.00	97.39	2,000.00	92.54
680.00	98.22	2,800.00	92.69
463.64	93.08	1,233.33	81.59
475.00	96.20	825.00	93.40
1,000.00	98.36	1,550.00	97.45
500.00	98.40	1,975.00	93.69
498.40	***97.72***	***1442.02***	***93.60***
±414.76	***±1.76***	***±1116.33***	***±4.37***

		A1-100P			A1-250P		
Raw (kg TS/m2.yr)		kg TS/m2.yr		RE %	kg TS/m2.yr		RE %
SLR 100	SLR 250	Eff. Mass	MRR		Eff. Mass	MRR	
1,372.06	3,430.16	10.91	1,361.15	99.20	40.57	3,389.59	98.82
1,809.16	4,522.91	23.12	1,786.05	98.72	21.28	4,501.63	99.53
1,588.00	3,970.00	21.38	1,566.62	98.65	61.50	3,908.50	98.45
1,375.31	3,438.27	9.02	1,366.28	99.34	100.96	3,337.31	97.06
1,534.37	3,835.92	11.14	1,523.23	99.27	54.82	3,781.10	98.57
433.80	1,084.50	2.25	431.55	99.48	10.68	1,073.83	99.02
1,721.71	4,304.27	7.54	1,714.17	99.56	143.42	4,160.85	96.67
1,933.10	4,832.75	2.16	1,930.94	99.89	138.61	4,694.14	97.13
1,764.16	4,410.40	13.20	1,750.96	99.25	86.04	4,324.36	98.05
1,284.60	3,211.49	30.39	1,254.21	97.63	128.80	3,082.68	95.99
586.49	1,466.23	24.09	562.40	95.89	110.03	1,356.20	92.50
760.87	1,902.17	23.03	737.84	96.97	42.14	1,860.03	97.78
1,385.44	3,463.61	24.97	1,360.47	98.20	98.22	3,365.38	97.16
1,712.88	4,282.20	19.16	1,693.72	98.88	103.31	4,178.89	97.59
1,610.58	4,026.44	73.56	1,537.02	95.43	266.83	3,759.62	93.37
1,767.53	4,418.83	43.66	1,723.88	97.53	93.33	4,325.51	97.89
1,801.78	4,504.44	17.46	1,784.32	99.03	33.25	4,471.19	99.26
771.70	1,929.24	7.64	764.05	99.01	64.52	1,864.72	96.66
1400.75	***3501.88***	***20.26***	***1380.49***	***98.44***	***88.80***	***3413.09***	***97.31***
±459.75	***±1149.39***	***±16.93***	***±457.25***	***±1.27***	***±59.62***	***±1134.62***	***±1.87***

250 kg TS/m2.yr and 350 kg TS/m2.yr

COD

Raw
mg/L
8030.00
55180.00
33790.00
20770.00
8990.00
58280.00
39370.00
109120.00
50840.00
35650.00
42002.00
±29497.59

A2-250P		A2-350P	
mg/L	RE %	mg/L	RE %
1860.00	76.84	2100.00	73.85
240.00	99.57	3300.00	94.02
420.00	98.76	1440.00	95.74
960.00	95.38	1740.00	91.62
1140.00	87.32	1380.00	84.65
420.00	99.28	600.00	98.97
588.00	98.51	1080.00	97.26
450.00	99.59	810.00	99.26
780.00	98.47	1020.00	97.99
360.00	98.99	1080.00	96.97
721.80	***95.27***	***1455.00***	***93.03***
±490.75	***±7.47***	***±783.49***	***±8.03***

		A2-250P			A2-350P		
Raw (kg TS/m2.yr)		kg TS/m2.yr		RE %	kg TS/m2.yr		RE %
SLR 250	SLR 350	Eff. Mass	MRR		Eff. Mass	MRR	
1,469.24	2,056.94	139.87	1,329.37	90.48	206.56	1,850.37	89.96
3,717.19	5,204.07	5.27	3,711.92	99.86	106.75	5,097.32	97.95
3,113.54	4,358.95	12.15	3,101.39	99.61	44.40	4,314.56	98.98
3,515.80	4,922.12	46.64	3,469.16	98.67	110.51	4,811.61	97.75
2,787.02	3,901.83	106.38	2,680.64	96.18	107.21	3,794.62	97.25
2,901.92	4,062.69	5.81	2,896.11	99.80	10.96	4,051.73	99.73
3,308.15	4,631.40	10.57	3,297.57	99.68	22.11	4,609.30	99.52
3,491.29	4,887.81	3.61	3,487.68	99.90	4.06	4,883.74	99.92
9,125.71	12,776.00	49.56	9,076.15	99.46	40.24	12,735.75	99.69
4,834.00	6,767.60	11.13	4,822.87	99.77	33.62	6,733.97	99.50
3826.39	***5356.94***	***39.10***	***3787.29***	***98.34***	***68.64***	***5288.30***	***98.03***
±2043.60	***±2861.04***	***±47.94***	***±2055.12***	***±2.98***	***±63.24***	***±2886.19***	***±2.99***

BOD

Raw
mg/L
455.40
2466.00
3644.00
4264.00
4326.00
2790.00
2886.00
4182.00
3951.00
4693.00
3365.74
±1200.75

A2-250P		A2-350P	
mg/L	RE %	mg/L	RE %
28.09	93.83	26.66	94.15
76.35	96.90	101.10	95.90
54.00	98.52	43.65	98.80
42.00	99.02	88.20	97.93
176.40	95.92	175.80	95.94
77.40	97.23	113.70	95.92
50.10	98.26	99.60	96.55
8.10	99.81	72.75	98.26
157.80	96.01	262.20	93.36
97.80	97.92	147.60	96.85
76.80	***97.34***	***113.13***	***96.37***
±51.44	***±1.67***	***±64.98***	***±1.64***

		A2-250P			A2-350P		
Raw (kg TS/m2.yr)		kg TS/m2.yr		RE %	kg TS/m2.yr		RE %
SLR 250	SLR 350	Eff. Mass	MRR		Eff. Mass	MRR	
83.32	116.65	2.11	81.21	97.47	2.62	114.03	97.75
166.12	232.57	1.68	164.44	98.99	3.27	229.30	98.59
335.77	470.08	1.56	334.21	99.53	1.35	468.73	99.71
721.78	1,010.49	2.04	719.74	99.72	5.60	1,004.89	99.45
1,341.12	1,877.57	16.46	1,324.66	98.77	13.66	1,863.91	99.27
138.92	194.49	1.07	137.85	99.23	2.08	192.41	98.93
242.50	339.50	0.90	241.60	99.63	2.04	337.46	99.40
133.80	187.32	0.07	133.74	99.95	0.36	186.96	99.81
709.20	992.88	10.03	699.17	98.59	10.34	982.53	98.96
636.35	890.89	3.02	633.33	99.52	4.60	886.30	99.48
450.89	***631.24***	***3.89***	***447.00***	***99.14***	***4.59***	***626.65***	***99.14***
±399.69	***±559.56***	***±5.22***	***±395.14***	***±0.73***	***±4.26***	***±555.69***	***±0.61***

NH$_3$-N

Raw
mg/L
129.80
223.20
158.10
105.40
62.00

A2-250P		A2-350P	
mg/L	RE %	mg/L	RE %
42.60	67.18	49.20	62.10
61.80	72.31	76.20	65.86
27.00	82.92	31.20	80.27
21.60	79.51	40.80	61.29
30.60	50.65	41.40	33.23

204.60
232.50
406.10
365.80
260.40
214.79
±109.40

34.20	83.28	63.60	68.91
45.60	80.39	50.40	78.32
29.40	92.76	40.80	89.95
50.40	86.22	66.60	81.79
68.40	73.73	94.20	63.82
41.16	***76.90***	***55.44***	***68.55***
±15.48	***±11.78***	***±19.44***	***±15.77***

		A2-250P			A2-350P		
Raw (kg TS/m2.yr)		kg TS/m2.yr		RE %	kg TS/m2.yr		RE %
SLR 250	SLR 350	Eff. Mass	MRR		Eff. Mass	MRR	
23.75	33.25	3.20	20.55	86.51	4.84	28.41	85.44
15.04	21.05	1.36	13.68	90.97	2.46	18.59	88.29
14.57	20.40	0.78	13.79	94.64	0.96	19.43	95.28
17.84	24.98	1.05	16.79	94.12	2.59	22.39	89.63
19.22	26.91	2.86	16.37	85.14	3.22	23.69	88.05
10.19	14.26	0.47	9.71	95.35	1.16	13.10	91.86
19.54	27.35	0.82	18.72	95.80	1.03	26.32	96.23
12.99	18.19	0.24	12.76	98.18	0.20	17.99	98.87
65.66	91.92	3.20	62.46	95.12	2.63	89.30	97.14
35.31	49.43	2.11	33.19	94.01	2.93	46.50	94.07
23.41	***32.77***	***1.61***	***21.80***	***92.98***	***2.20***	***30.57***	***92.49***
±16.40	***±22.96***	***±1.14***	***±15.66***	***±4.19***	***±1.37***	***±22.54***	***±4.50***

TN

Raw
mg/L
275.00
1209.00
806.00
651.00
341.00
775.00
1054.00
1240.00
1426.00
1023.00
880.00
±381.83

A2-250P		A2-350P	
mg/L	RE %	mg/L	RE %
108.00	60.73	126.00	54.18
210.00	82.63	162.00	86.60
180.00	77.67	186.00	76.92
135.00	79.26	120.00	81.57
102.00	70.09	138.00	59.53
72.00	90.71	108.00	86.06
168.00	84.06	198.00	81.21
96.00	92.26	120.00	90.32
108.00	92.43	162.00	88.64
144.00	85.92	216.00	78.89
132.30	***81.58***	***153.60***	***78.39***
±43.18	***±10.16***	***±37.12***	***±12.18***

		A2-250P			A2-350P		
Raw (kg TS/m2.yr)		kg TS/m2.yr		RE %	kg TS/m2.yr		RE %
SLR 250	SLR 350	Eff. Mass	MRR		Eff. Mass	MRR	
50.32	70.44	8.12	42.19	83.86	12.39	58.05	82.41
81.44	114.02	4.61	76.83	94.34	5.24	108.78	95.40
74.27	103.98	5.21	69.06	92.99	5.73	98.24	94.48
110.20	154.28	6.56	103.64	94.05	7.62	146.65	95.06
105.71	148.00	9.52	96.20	91.00	10.72	137.28	92.76
38.59	54.03	1.00	37.59	97.42	1.97	52.05	96.35
88.56	123.99	3.02	85.54	96.59	4.05	119.94	96.73
39.67	55.54	0.77	38.90	98.06	0.60	54.94	98.92
255.97	358.35	6.86	249.10	97.32	6.39	351.96	98.22
138.71	194.20	4.45	134.26	96.79	6.72	187.48	96.54
98.34	***137.68***	***5.01***	***93.33***	***94.24***	***6.14***	***131.54***	***94.69***
±64.08	***±89.70***	***±2.87***	***±62.95***	***±4.30***	***±3.59***	***±89.02***	***±4.67***

TS

Raw
mg/L
26276.00
71368.00
52176.00
28402.00
15508.00
96554.00
57216.00
150264.00
26784.00
35456.00
56000.40
±41288.96

A2-250P		A2-350P	
mg/L	RE %	mg/L	RE %
1896.00	92.78	2308.00	91.22
4508.00	93.68	5132.00	92.81
3824.00	92.67	3824.00	92.67
3104.00	89.07	2664.00	90.62
2152.00	86.12	3384.00	78.18
1864.00	98.07	1500.00	98.45
1772.00	96.90	2344.00	95.90
2440.00	98.38	1204.00	99.20
2824.00	89.46	3512.00	86.89
3524.00	90.06	3784.00	89.33
2790.80	***92.72***	***2965.60***	***91.53***
±935.82	***±4.13***	***±1189.52***	***±6.09***

		A2-250P			A2-350P		
Raw (kg TS/m2.yr)		kg TS/m2.yr		RE %	kg TS/m2.yr		RE %
SLR 250	SLR 350	Eff. Mass	MRR		Eff. Mass	MRR	
4,807.69	6,730.77	142.58	4,665.11	97.03	227.02	6,503.74	96.63
4,807.69	6,730.77	99.00	4,708.69	97.94	166.01	6,564.76	97.53
4,807.69	6,730.77	110.64	4,697.05	97.70	117.90	6,612.87	98.25
4,807.69	6,730.77	150.80	4,656.90	96.86	169.19	6,561.58	97.49
4,807.69	6,730.77	200.81	4,606.88	95.82	262.90	6,467.87	96.09

4,807.69	6,730.77	25.80	4,781.89	99.46	27.40	6,703.37	99.59
4,807.69	6,730.77	31.86	4,775.83	99.34	47.98	6,682.79	99.29
4,807.69	6,730.77	19.59	4,788.10	99.59	6.04	6,724.73	99.91
4,807.69	6,730.77	179.44	4,628.25	96.27	138.56	6,592.21	97.94
4,807.69	6,730.77	108.95	4,698.74	97.73	117.81	6,612.96	98.25
4807.69	***6730.77***	***106.95***	***4700.74***	***97.77***	***128.08***	***6602.69***	***98.10***
±0.00	***±0.00***	***±64.29***	***±64.28***	***±1.34***	***±83.57***	***±83.57***	***±1.24***

TSS

Raw		A2-250P		A2-350P	
mg/L		mg/L	RE %	mg/L	RE %
24766.67		1500.00	93.94	1683.33	93.20
69160.00		290.00	99.58	2333.33	96.63
51400.00		193.33	99.62	340.00	99.34
23850.00		820.00	96.56	420.00	98.24
12600.00		1233.33	90.21	1330.00	89.44
92250.00		65.00	99.93	265.00	99.71
56600.00		1500.00	97.35	1640.00	97.10
119900.00		245.00	99.80	370.00	99.69
23700.00		825.00	96.52	1025.00	95.68
34400.00		1015.00	97.05	1305.00	96.21
50862.67		***768.67***	***97.06***	***1071.17***	***96.52***
±34529.55		***±545.85***	***±3.09***	***±708.31***	***±3.22***

		A2-250P			A2-350P		
Raw (kg TS/m2.yr)		kg TS/m2.yr		RE %	kg TS/m2.yr		RE %
SLR 250	SLR 350	Eff. Mass	MRR		Eff. Mass	MRR	
4,531.53	6,344.14	112.80	4,418.73	97.51	165.58	6,178.56	97.39
4,658.95	6,522.53	6.37	4,652.58	99.86	75.48	6,447.05	98.84
4,736.19	6,630.66	5.59	4,730.60	99.88	10.48	6,620.18	99.84
4,037.16	5,652.03	39.84	3,997.32	99.01	26.67	5,625.35	99.53
3,906.17	5,468.64	115.09	3,791.09	97.05	103.33	5,365.31	98.11
4,593.38	6,430.74	0.90	4,592.48	99.98	4.84	6,425.90	99.92
4,755.93	6,658.30	26.97	4,728.96	99.43	33.57	6,624.74	99.50
3,836.20	5,370.68	1.97	3,834.23	99.95	1.86	5,368.82	99.97
4,254.12	5,955.77	52.42	4,201.70	98.77	40.44	5,915.33	99.32
4,664.50	6,530.30	31.38	4,633.12	99.33	40.63	6,489.68	99.38
4397.41	***6156.38***	***39.33***	***4358.08***	***99.08***	***50.29***	***6106.09***	***99.18***
±356.84	***±499.58***	***±42.98***	***±372.35***	***±1.04***	***±51.38***	***±501.56***	***±0.84***

VSS

Raw
mg/L
16966.67
53640.00
31150.00
16550.00
8300.00
47550.00
44450.00
81200.00
16600.00
27300.00
34370.67
±22400.15

A2-250P		A2-350P	
mg/L	RE %	mg/L	RE %
1100.00	93.52	833.33	95.09
145.00	99.73	1716.67	96.80
86.67	99.72	320.00	98.97
510.00	96.92	320.00	98.07
1083.33	86.95	1020.00	87.71
30.00	99.94	180.00	99.62
1280.00	97.12	1520.00	96.58
195.00	99.76	300.00	99.63
675.00	95.93	750.00	95.48
895.00	96.72	1195.00	95.62
600.00	***96.63***	***815.50***	***96.36***
±472.14	***±4.00***	***±543.60***	***±3.48***

		A2-250P			A2-350P		
Raw (kg TS/m2.yr)		kg TS/m2.yr		RE %	kg TS/m2.yr		RE %
SLR 250	SLR 350	Eff. Mass	MRR		Eff. Mass	MRR	
3,104.37	4,346.12	82.72	3,021.65	97.34	81.97	4,264.15	98.11
3,613.45	5,058.83	3.18	3,610.26	99.91	55.53	5,003.30	98.90
2,870.28	4,018.39	2.51	2,867.77	99.91	9.87	4,008.52	99.75
2,801.47	3,922.06	24.78	2,776.69	99.12	20.32	3,901.73	99.48
2,573.11	3,602.36	101.09	2,472.02	96.07	79.24	3,523.12	97.80
2,367.65	3,314.71	0.42	2,367.23	99.98	3.29	3,311.42	99.90
3,735.00	5,229.00	23.02	3,711.99	99.38	31.11	5,197.89	99.40
2,597.99	3,637.19	1.57	2,596.43	99.94	1.51	3,635.68	99.96
2,979.68	4,171.55	42.89	2,936.79	98.56	29.59	4,141.96	99.29
3,701.77	5,182.48	27.67	3,674.10	99.25	37.20	5,145.28	99.28
3034.48	***4248.27***	***30.99***	***3003.49***	***98.95***	***34.96***	***4213.31***	***99.19***
±495.36	***±693.50***	***±35.32***	***±499.72***	***±1.30***	***±29.07***	***±685.74***	***±0.73***

(B2) Effects of Plant Presence

SLR 250 kg TS/m^2.yr

COD

Raw
mg/L
31875.00
20740.00
38080.00
46410.00
45450.00
23490.00
15930.00
33686.67
12400.00
51678.00
24021.00
22440.00
54870.00
47120.00
8990.00
55180.00
21930.00
20400.00
31927.26
±15081.28

A1-250P		A1-250UP	
mg/L	RE %	mg/L	RE %
3180.00	90.02	3270.00	89.74
1260.00	93.92	1440.00	93.06
570.00	98.50	1140.00	97.01
510.00	98.90	980.00	97.89
540.00	98.81	403.33	99.11
440.00	98.13	1246.67	94.69
440.00	97.24	1155.00	94.69
183.33	99.46	3440.00	89.79
1130.00	90.89	2040.00	83.55
990.00	98.08	15300.00	70.39
1140.00	95.25	1740.00	92.76
1140.00	94.92	1440.00	93.58
2280.00	95.84	3780.00	93.11
2160.00	95.42	5040.00	89.30
1020.00	88.65	1800.00	79.98
600.00	98.91	1020.00	98.15
480.00	97.81	1500.00	93.16
408.00	98.00	1200.00	94.12
1026.19	***96.04***	***2663.06***	***91.34***
±788.14	***±3.28***	***±3371.77***	***±7.14***

	A1-250P			A1-250UP		
Raw	kg TS/m2.yr		RE %	kg TS/m2.yr		RE %
kg TS/m2.yr	Eff. Mass	MRR		Eff. Mass	MRR	
4846.46	228.71	4617.76	95.28	484.42	4362.05	90.00
4770.89	122.56	4648.33	97.43	190.28	4580.60	96.01
4767.50	57.09	4710.41	98.80	126.42	4641.08	97.35
5934.18	58.89	5875.28	99.01	337.56	5596.61	94.31
5811.43	25.27	5786.16	99.57	241.66	5569.76	95.84
4899.04	166.40	4732.64	96.60	293.19	4605.85	94.02
5485.36	194.88	5290.48	96.45	258.32	5227.03	95.29
6426.28	275.62	6150.66	95.71	318.91	6107.37	95.04
2241.35	125.37	2115.98	94.41	325.00	1916.35	85.50

3286.40	398.92	2887.48	87.86	816.01	2470.39	75.17
3116.85	119.66	2997.19	96.16	255.05	2861.80	91.82
4690.64	168.56	4522.07	96.41	829.26	3861.37	82.32
7091.35	185.64	6905.71	97.38	706.27	6385.08	90.04
5268.34	185.96	5082.38	96.47	486.36	4781.98	90.77
5402.64	389.42	5013.22	92.79	692.31	4710.34	87.19
19506.50	115.38	19391.12	99.41	184.53	19321.97	99.05
1622.04	32.17	1589.87	98.02	38.34	1583.70	97.64
1257.40	39.20	1218.20	96.88	48.15	1209.25	96.17
5356.93	***160.54***	***5196.39***	***96.37***	***368.45***	***4988.48***	***91.86***
±3882.85	***±110.24***	***±3882.22***	***±2.75***	***±248.14***	***±3894.26***	***±6.13***

BOD

Raw
mg/L
3600.00
2900.00
4830.00
3060.00
8740.00
1720.00
3200.00
1690.00
1410.00
7630.00
1938.00
2472.00
3912.00
4374.00
2538.00
3936.00
894.00
1044.00
3327.11
±2108.53

A1-250P		A2-250UP	
mg/L	RE %	mg/L	RE %
620.00	82.78	612.00	83.00
550.00	81.03	512.00	82.34
410.00	91.51	452.00	90.64
216.00	92.94	237.00	92.25
540.00	93.82	660.00	92.45
336.00	80.47	384.00	77.67
420.00	86.88	480.00	85.00
50.70	97.00	66.60	96.06
172.80	87.74	170.40	87.91
684.00	91.04	912.00	88.05
46.50	97.60	88.50	95.43
64.20	97.40	109.05	95.59
98.55	97.48	100.35	97.43
112.20	97.43	111.75	97.45
106.80	95.79	108.75	95.72
102.15	97.40	105.60	97.32
99.45	88.88	106.80	88.05
116.10	88.88	118.50	88.65
263.64	***91.45***	***296.41***	***90.61***
±217.68	***±5.89***	***±252.65***	***±5.93***

	A1-250P			A1-250UP		
Raw	kg TS/m2.yr		RE %	kg TS/m2.yr		RE %
kg TS/m2.yr	Eff. Mass	MRR		Eff. Mass	MRR	
547.37	43.36	504.00	92.08	54.90	492.46	89.97
667.10	46.81	620.28	92.98	55.36	611.74	91.70
604.70	20.53	584.17	96.60	30.56	574.14	94.95
391.26	12.98	378.28	96.68	20.00	371.26	94.89
1117.53	33.83	1083.70	96.97	45.57	1071.96	95.92
358.72	44.85	313.87	87.50	56.86	301.86	84.15
1101.89	70.87	1031.03	93.57	72.72	1029.17	93.40
322.40	4.06	318.33	98.74	3.81	318.58	98.82
254.86	10.62	244.24	95.83	24.33	230.53	90.45
485.22	17.83	467.39	96.32	42.92	442.30	91.15
251.47	3.20	248.27	98.73	9.65	241.82	96.16
516.72	7.52	509.21	98.55	19.83	496.89	96.16
505.58	4.84	500.74	99.04	8.56	497.02	98.31
489.04	4.14	484.90	99.15	7.25	481.80	98.52
1525.24	23.11	1502.13	98.49	26.14	1499.10	98.29
1391.40	11.56	1379.85	99.17	10.83	1380.58	99.22
66.12	2.13	63.99	96.77	1.90	64.23	97.13
64.35	3.79	60.56	94.11	3.07	61.28	95.23
592.28	***20.34***	***571.94***	***96.18***	***27.46***	***564.82***	***94.69***
±422.95	***±19.76***	***±414.82***	***±3.12***	***±22.11***	***±415.67***	***±3.95***

NH$_3$-N

Raw
mg/L
406.35
677.25
234.78
695.31
504.18
386.79
216.72
336.96
178.20
153.90
408.00
326.40
186.00

A1-250P		A2-250UP	
mg/L	RE %	mg/L	RE %
94.35	76.78	97.41	76.03
132.09	80.50	140.76	79.22
68.85	70.67	78.54	66.55
116.54	83.24	98.98	85.76
74.97	85.13	84.41	83.26
107.36	72.24	126.48	67.30
64.90	70.05	78.10	63.96
88.20	73.82	79.20	76.50
101.00	43.32	102.80	42.31
30.60	80.12	81.60	46.98
78.00	80.88	61.20	85.00
91.80	71.88	96.60	70.40
15.00	91.94	79.80	57.10

198.40
167.40
254.20
295.80
260.10
327.04
±163.00

124.20	37.40	118.80	40.12
99.60	40.50	112.80	32.62
109.80	56.81	110.40	56.57
139.20	52.94	126.60	57.20
114.06	56.15	123.36	52.57
91.70	***68.02***	***99.88***	***63.30***
±32.65	***±16.30***	***±21.88***	***±16.20***

	A1-250P			A1-250UP		
Raw	kg TS/m2.yr		RE %	kg TS/m2.yr		RE %
kg TS/m2.yr	Eff. Mass	MRR		Eff. Mass	MRR	
61.78	6.60	55.18	89.32	8.74	53.05	85.86
155.79	11.24	144.55	92.78	15.22	140.57	90.23
29.39	3.45	25.95	88.27	5.31	24.08	81.94
88.91	7.00	81.90	92.12	8.35	80.55	90.60
64.47	4.70	59.77	92.71	5.83	58.64	90.96
80.67	14.33	66.34	82.24	18.73	61.94	76.78
74.63	10.95	63.68	85.33	11.83	62.79	84.14
64.28	7.07	57.21	89.01	4.53	59.75	92.95
32.21	6.21	26.00	80.73	14.68	17.53	54.43
9.79	0.80	8.99	91.85	3.84	5.95	60.76
52.94	5.36	47.58	89.87	6.67	46.27	87.40
68.23	10.75	57.48	84.25	17.57	50.66	74.25
24.04	0.74	23.30	96.94	6.81	17.23	71.68
22.18	4.58	17.60	79.34	7.70	14.48	65.27
100.60	21.55	79.05	78.58	27.12	73.49	73.05
89.86	12.42	77.44	86.18	11.32	78.54	87.41
21.88	2.99	18.89	86.35	2.25	19.63	89.73
16.03	3.73	12.31	76.76	3.19	12.84	80.08
58.76	***7.47***	***51.29***	***86.81***	***9.98***	***48.78***	***79.86***
±37.31	***±5.26***	***±33.61***	***±5.64***	***±6.53***	***±33.68***	***±11.29***

TN

Raw
mg/L
969.00
1,479.00
714.00
1,190.00
1,616.00
1,660.50
1,053.00
526.50
372.00
1,271.00
638.00
539.00
1,302.00
1,085.00
1,479.00
765.00
1,085.00
1,116.00
1047.78
±388.44

A1-250P		A2-250UP	
mg/L	RE %	mg/L	RE %
267.30	72.41	284.90	70.60
287.10	80.59	294.80	80.07
264.00	63.03	275.00	61.48
288.00	75.80	513.00	56.89
220.00	86.39	275.00	82.98
231.00	86.09	247.50	85.09
198.00	81.20	275.00	73.88
197.00	62.58	241.00	54.23
156.00	58.06	194.00	47.85
126.00	90.09	651.00	48.78
150.00	76.49	168.00	73.67
282.00	47.68	258.00	52.13
108.00	91.71	186.00	85.71
510.00	53.00	576.00	46.91
318.00	78.50	276.00	81.34
168.00	78.04	210.00	72.55
342.00	68.48	360.00	66.82
432.00	61.29	486.00	56.45
252.47	***72.86***	***320.62***	***66.52***
±104.58	***±12.89***	***±140.53***	***±13.66***

	A1-250P			A1-250UP		
Raw	kg TS/m2.yr		RE %	kg TS/m2.yr		RE %
kg TS/m2.yr	Eff. Mass	MRR		Eff. Mass	MRR	
147.33	18.70	128.64	87.31	25.56	121.77	82.65
340.22	24.44	315.78	92.82	31.87	308.35	90.63
89.39	13.22	76.17	85.21	18.59	70.80	79.20
152.16	17.31	134.85	88.63	43.29	108.87	71.55
206.63	13.78	192.84	93.33	18.99	187.64	90.81
346.31	30.83	315.48	91.10	36.65	309.66	89.42
362.59	33.41	329.18	90.79	41.67	320.93	88.51
100.44	15.78	84.65	84.28	13.79	86.65	86.27
67.24	9.59	57.65	85.74	27.70	39.54	58.80
80.83	3.29	77.54	95.94	30.64	50.19	62.10
82.78	10.32	72.47	87.54	18.31	64.47	77.88

112.67	33.01	79.66	70.70	46.92	65.75	58.36
168.27	5.30	162.97	96.85	15.87	152.40	90.57
121.31	18.82	102.49	84.49	37.35	83.96	69.21
888.82	68.80	820.02	92.26	66.35	822.48	92.54
270.43	19.00	251.43	92.97	21.53	248.90	92.04
80.25	7.34	72.92	90.86	6.39	73.86	92.04
68.79	14.11	54.67	79.48	12.58	56.21	81.71
204.80	***19.84***	***184.97***	***88.35***	***28.56***	***176.25***	***80.79***
±197.89	***±15.09***	***±184.49***	***±6.28***	***±14.94***	***±187.73***	***±11.93***

TS

Raw
mg/L
31620.00
20900.00
38401.00
37600.00
37600.00
23052.00
13962.00
25202.00
26598.00
75600.00
37052.00
23000.00
37200.00
43000.00
8000.00
13600.00
65000.00
78000.00
35299.28
±19980.91

A1-250P		A2-250UP	
mg/L	RE %	mg/L	RE %
4734.00	85.03	4902.00	84.50
3941.00	81.14	4387.00	79.01
4952.00	87.10	5922.00	84.58
2400.00	93.62	2000.00	94.68
2668.00	92.90	2480.00	93.40
2044.00	91.13	4036.00	82.49
1436.00	89.71	1896.00	86.42
2552.00	89.87	3156.00	87.48
2124.00	92.01	2328.00	91.25
16400.00	78.31	20800.00	72.49
1512.00	95.92	3152.00	91.49
1540.00	93.30	3712.00	83.86
4552.00	87.76	7432.00	80.02
4248.00	90.12	6036.00	85.96
1552.00	80.60	2388.00	70.15
2080.00	84.71	2696.00	80.18
2152.00	96.69	2676.00	95.88
2176.00	97.21	3956.00	94.93
3503.50	***89.29***	***4664.17***	***85.49***
±3431.26	***±5.58***	***±4311.30***	***±7.42***

	A1-250P			A1-250UP		
Raw	kg TS/m2.yr		RE %	kg TS/m2.yr		RE %
kg TS/m2.yr	Eff. Mass	MRR		Eff. Mass	MRR	
4,807.69	331.10	4,476.59	93.11	439.74	4,367.95	90.85
4,807.69	335.43	4,472.26	93.02	474.30	4,333.39	90.13
4,807.69	247.99	4,559.70	94.84	400.37	4,407.33	91.67
4,807.69	144.23	4,663.46	97.00	168.78	4,638.91	96.49
4,807.69	167.16	4,640.53	96.52	171.24	4,636.46	96.44
4,807.69	272.83	4,534.86	94.33	597.64	4,210.06	87.57
4,807.69	242.29	4,565.40	94.96	287.26	4,520.43	94.02
4,807.69	204.47	4,603.22	95.75	180.62	4,627.07	96.24
4,807.69	130.53	4,677.16	97.28	332.43	4,475.26	93.09
4,807.69	427.60	4,380.09	91.11	978.84	3,828.86	79.64
4,807.69	103.98	4,703.71	97.84	343.55	4,464.14	92.85
4,807.69	180.27	4,627.42	96.25	675.05	4,132.64	85.96
4,807.69	223.55	4,584.14	95.35	633.93	4,173.76	86.81
4,807.69	156.74	4,650.96	96.74	391.42	4,416.27	91.86
4,807.69	335.77	4,471.92	93.02	574.04	4,233.65	88.06
4,807.69	235.29	4,572.40	95.11	276.39	4,531.31	94.25
4,807.69	46.16	4,761.53	99.04	47.50	4,760.19	99.01
4,807.69	71.08	4,736.61	98.52	102.41	4,705.28	97.87
4807.69	***214.25***	***4593.44***	***95.54***	***393.08***	***4414.61***	***91.82***
±0.00	***±101.20***	***±101.20***	***±2.10***	***±235.59***	***±235.59***	***±4.90***

TSS

	A1-250P		A2-250UP	
Raw	mg/L	RE %	mg/L	RE %
mg/L				
22,560.00	580.00	97.43	840.00	96.28
19,662.00	250.00	98.73	1,650.00	91.61
31,710.00	1,228.00	96.13	1,640.00	94.83
26,890.00	1,680.00	93.75	1,416.00	94.73
30,000.00	875.00	97.08	2,000.00	93.33
5,200.00	80.00	98.46	550.00	89.42
12,500.00	850.00	93.20	1,516.00	87.87
25,333.33	1,730.00	92.28	2,432.00	89.15
24,400.00	1,400.00	94.26	1,590.00	93.48
50,500.00	4,940.00	90.22	6,400.00	87.33
11,300.00	1,600.00	85.84	3,000.00	73.45

9,100.00	360.00	96.04	1,700.00	81.32
26,800.00	2,000.00	92.54	6,100.00	77.24
38,300.00	2,800.00	92.69	4,100.00	89.30
6,700.00	1,233.33	81.59	1,400.00	79.10
12,500.00	825.00	93.40	1,350.00	89.20
60,900.00	1,550.00	97.45	1,475.00	97.58
31,300.00	1,975.00	93.69	2,825.00	90.97
24758.63	***1442.02***	***93.60***	***2332.44***	***88.68***
±14844.84	***±1116.33***	***±4.37***	***±1645.84***	***±6.78***

	A1-250P			A1-250UP		
Raw	kg TS/m2.yr		RE %	kg TS/m2.yr		RE %
kg TS/m2.yr	Eff. Mass	MRR		Eff. Mass	MRR	
3,430.16	40.57	3,389.59	98.82	75.35	3,354.80	97.80
4,522.91	21.28	4,501.63	99.53	178.39	4,344.52	96.06
3,970.00	61.50	3,908.50	98.45	110.87	3,859.12	97.21
3,438.27	100.96	3,337.31	97.06	119.50	3,318.77	96.52
3,835.92	54.82	3,781.10	98.57	138.09	3,697.83	96.40
1,084.50	10.68	1,073.83	99.02	81.44	1,003.06	92.49
4,304.27	143.42	4,160.85	96.67	229.69	4,074.58	94.66
4,832.75	138.61	4,694.14	97.13	139.18	4,693.56	97.12
4,410.40	86.04	4,324.36	98.05	227.04	4,183.35	94.85
3,211.49	128.80	3,082.68	95.99	301.18	2,910.31	90.62
1,466.23	110.03	1,356.20	92.50	326.98	1,139.25	77.70
1,902.17	42.14	1,860.03	97.78	309.16	1,593.02	83.75
3,463.61	98.22	3,365.38	97.16	520.32	2,943.29	84.98
4,282.20	103.31	4,178.89	97.59	265.88	4,016.32	93.79
4,026.44	266.83	3,759.62	93.37	336.54	3,689.90	91.64
4,418.83	93.33	4,325.51	97.89	138.40	4,280.44	96.87
4,504.44	33.25	4,471.19	99.26	26.18	4,478.25	99.42
1,929.24	64.52	1,864.72	96.66	73.13	1,856.11	96.21
3501.88	***88.80***	***3413.09***	***97.31***	***199.85***	***3302.03***	***93.23***
±1149.39	***±59.62***	***±1134.62***	***±1.87***	***±125.46***	***±1166.31***	***±5.71***

VSS

Raw
mg/L
13,400.00
12,800.00
22,800.00
16,800.00
20,000.00
4,100.00
7,800.00
11,900.00
11,900.00
21,600.00
8,800.00
4,600.00
19,200.00
20,200.00
5,300.00
9,200.00
29,000.00
20,850.00
14458.33
±7169.63

A1-250P		A2-250UP	
mg/L	RE %	mg/L	RE %
165.00	98.77	170.00	98.73
50.00	99.61	400.00	96.87
305.00	98.66	515.00	97.74
720.00	95.71	700.00	95.83
635.00	96.82	1,489.50	92.55
35.00	99.15	310.00	92.44
350.00	95.51	852.00	89.08
1,340.00	88.74	1,956.00	83.56
640.00	94.62	1,100.00	90.76
1,900.00	91.20	3,260.00	84.91
600.00	93.18	2,000.00	77.27
160.00	96.52	500.00	89.13
750.00	96.09	4,800.00	75.00
1,650.00	91.83	3,000.00	85.15
566.67	89.31	1,250.00	76.42
375.00	95.92	1,075.00	88.32
675.00	97.67	700.00	97.59
925.00	95.56	2,000.00	90.41
657.87	***95.27***	***1448.75***	***88.99***
±522.25	***±3.26***	***±1221.54***	***±7.42***

	A1-250P			A1-250UP		
Raw	kg TS/m2.yr		RE %	kg TS/m2.yr		RE %
kg TS/m2.yr	Eff. Mass	MRR		Eff. Mass	MRR	
2,037.42	11.54	2,025.88	99.43	15.25	2,022.17	99.25
2,944.42	4.26	2,940.17	99.86	43.25	2,901.18	98.53
2,854.49	15.27	2,839.22	99.46	34.82	2,819.68	98.78
2,148.12	43.27	2,104.85	97.99	59.07	2,089.04	97.25
2,557.28	39.78	2,517.50	98.44	102.84	2,454.44	95.98
855.09	4.67	850.42	99.45	45.90	809.19	94.63
2,685.86	59.05	2,626.81	97.80	129.09	2,556.77	95.19
2,270.12	107.36	2,162.76	95.27	111.94	2,158.18	95.07
2,150.97	39.33	2,111.64	98.17	157.08	1,993.90	92.70
1,373.63	49.54	1,324.09	96.39	153.41	1,220.21	88.83
1,141.85	41.26	1,100.58	96.39	217.99	923.86	80.91
961.54	18.73	942.81	98.05	90.93	870.61	90.54

2,481.39	36.83	2,444.56	98.52	409.43	2,071.96	83.50
2,258.50	60.88	2,197.62	97.30	194.54	2,063.95	91.39
3,185.10	122.60	3,062.50	96.15	300.48	2,884.62	90.57
3,252.26	42.42	3,209.84	98.70	110.21	3,142.06	96.61
2,144.97	14.48	2,130.49	99.33	12.43	2,132.54	99.42
1,285.13	30.22	1,254.92	97.65	51.78	1,233.36	95.97
2143.79	***41.19***	***2102.59***	***98.02***	***124.47***	***2019.32***	***93.62***
±746.41	***±31.99***	***±736.31***	***±1.31***	***±104.20***	***±735.18***	***±5.24***

SLR 350 kg TS/m^2.yr

COD

Raw
mg/L
8,030.00
55,180.00
33,790.00
20,770.00
8,990.00
58,280.00
39,370.00
109,120.00
50,840.00
35,650.00
42002.00
±29497.59

A2-350P		A2-350UP	
mg/L	RE %	mg/L	RE %
2,100.00	73.85	2,520.00	68.62
3,300.00	94.02	6,120.00	88.91
1,440.00	95.74	2,340.00	93.07
1,740.00	91.62	2,100.00	89.89
1,380.00	84.65	2,340.00	73.97
600.00	98.97	3,480.00	94.03
1,080.00	97.26	2,040.00	94.82
810.00	99.26	2,100.00	98.08
1,020.00	97.99	3,060.00	93.98
1,080.00	96.97	2,160.00	93.94
1455.00	***93.03***	***2826.00***	***88.93***
±783.49	***±8.03***	***±1247.86***	***±9.71***

	A2-350P			A2-350UP		
Raw	kg TS/m2.yr		RE %	kg TS/m2.yr		RE %
kg TS/m2.yr	Eff. Mass	MRR		Eff. Mass	MRR	
2,056.94	206.56	1,850.37	89.96	370.53	1,686.41	81.99
5,204.07	106.75	5,097.32	97.95	272.43	4,931.64	94.77
4,358.95	44.40	4,314.56	98.98	131.31	4,227.64	96.99
4,922.12	110.51	4,811.61	97.75	119.94	4,802.18	97.56
3,901.83	107.21	3,794.62	97.25	353.43	3,548.40	90.94
4,062.69	10.96	4,051.73	99.73	79.08	3,983.61	98.05
4,631.40	22.11	4,609.30	99.52	48.96	4,582.45	98.94
4,887.81	4.06	4,883.74	99.92	36.59	4,851.22	99.25
12,776.00	40.24	12,735.75	99.69	234.54	12,541.46	98.16
6,767.60	33.62	6,733.97	99.50	116.45	6,651.15	98.28
5356.94	***68.64***	***5288.30***	***98.03***	***176.33***	***5180.62***	***95.49***
±2861.04	***±63.24***	***±2886.19***	***±2.99***	***±122.79***	***±2871.91***	***±5.35***

BOD

Raw
mg/L
455.40
2,466.00
3,644.00
4,264.00
4,326.00
2,790.00
2,886.00
4,182.00
3,951.00
4,693.00
3365.74
±1265.70

A2-350P		A2-350UP	
mg/L	RE %	mg/L	RE %
26.66	94.15	28.95	93.64
101.10	95.90	142.20	94.23
43.65	98.80	168.30	95.38
88.20	97.93	231.00	94.58
175.80	95.94	353.40	91.83
113.70	95.92	180.60	93.53
99.60	96.55	202.20	92.99
72.75	98.26	217.20	94.81
262.20	93.36	268.80	93.20
147.60	96.85	459.60	90.21
113.13	***96.37***	***225.23***	***93.44***
±68.49	***±1.72***	***±117.63***	***±1.52***

	A2-350P			A2-350UP		
Raw	kg TS/m2.yr		RE %	kg TS/m2.yr		RE %
kg TS/m2.yr	Eff. Mass	MRR		Eff. Mass	MRR	
116.65	2.62	114.03	97.75	4.26	112.40	96.35
232.57	3.27	229.30	98.59	6.33	226.24	97.28
470.08	1.35	468.73	99.71	9.44	460.64	97.99
1,010.49	5.60	1,004.89	99.45	13.19	997.30	98.69
1,877.57	13.66	1,863.91	99.27	53.38	1,824.19	97.16
194.49	2.08	192.41	98.93	4.10	190.39	97.89
339.50	2.04	337.46	99.40	4.85	334.65	98.57
187.32	0.36	186.96	99.81	3.78	183.54	97.98
992.88	10.34	982.53	98.96	20.60	972.28	97.92
890.89	4.60	886.30	99.48	24.78	866.11	97.22
631.24	***4.59***	***626.65***	***99.14***	***14.47***	***616.77***	***97.71***
±559.56	***±4.26***	***±555.69***	***±0.61***	***±15.53***	***±544.83***	***±0.71***

NH_3-N

Raw
mg/L
129.80
223.20
158.10
105.40
62.00
204.60
232.50
406.10
365.80
260.40
214.79
±109.40

A2-350P		A2-350UP	
mg/L	RE %	mg/L	RE %
49.20	62.10	58.20	55.16
76.20	65.86	80.40	63.98
31.20	80.27	44.40	71.92
40.80	61.29	66.60	36.81
41.40	33.23	50.40	18.71
63.60	68.91	132.00	35.48
50.40	78.32	75.60	67.48
40.80	89.95	87.00	78.58
66.60	81.79	107.40	70.64
94.20	63.82	109.80	57.83
55.44	***68.55***	***81.18***	***55.66***
±19.44	***±15.77***	***±28.28***	***±19.31***

	A2-350P			A2-350UP		
Raw	kg TS/m2.yr		RE %	kg TS/m2.yr		RE %
kg TS/m2.yr	Eff. Mass	MRR		Eff. Mass	MRR	
33.25	4.84	28.41	85.44	8.56	24.69	74.26
21.05	2.46	18.59	88.29	3.58	17.47	83.00
20.40	0.96	19.43	95.28	2.49	17.90	87.78
24.98	2.59	22.39	89.63	3.80	21.17	84.77
26.91	3.22	23.69	88.05	7.61	19.30	71.71
14.26	1.16	13.10	91.86	3.00	11.26	78.97
27.35	1.03	26.32	96.23	1.81	25.54	93.37
18.19	0.20	17.99	98.87	1.52	16.67	91.67
91.92	2.63	89.30	97.14	8.23	83.69	91.05
49.43	2.93	46.50	94.07	5.92	43.51	88.02
32.77	***2.20***	***30.57***	***92.49***	***4.65***	***28.12***	***84.46***
±22.96	***±1.37***	***±22.54***	***±4.50***	***±2.70***	***±21.35***	***±7.43***

TN

Raw
mg/L
275.00
1,209.00
806.00
651.00
341.00
775.00
1,054.00
1,240.00
1,426.00
1,023.00
880.00
±381.83

A2-350P		A2-350UP	
mg/L	RE %	mg/L	RE %
126.00	54.18	150.00	45.45
162.00	86.60	336.00	72.21
186.00	76.92	210.00	73.95
120.00	81.57	168.00	74.19
138.00	59.53	162.00	52.49
108.00	86.06	234.00	69.81
198.00	81.21	246.00	76.66
120.00	90.32	210.00	83.06
162.00	88.64	276.00	80.65
216.00	78.89	282.00	72.43
153.60	***78.39***	***227.40***	***70.09***
±37.12	***±12.18***	***±59.56***	***±11.93***

	A2-350P			A2-350UP		
Raw	kg TS/m2.yr		RE %	kg TS/m2.yr		RE %
kg TS/m2.yr	Eff. Mass	MRR		Eff. Mass	MRR	
70.44	12.39	58.05	82.41	22.06	48.39	68.69
114.02	5.24	108.78	95.40	14.96	99.06	86.88
103.98	5.73	98.24	94.48	11.78	92.19	88.67
154.28	7.62	146.65	95.06	9.59	144.68	93.78
148.00	10.72	137.28	92.76	24.47	123.53	83.47
54.03	1.97	52.05	96.35	5.32	48.71	90.16
123.99	4.05	119.94	96.73	5.90	118.09	95.24
55.54	0.60	54.94	98.92	3.66	51.88	93.41
358.35	6.39	351.96	98.22	21.15	337.20	94.10
194.20	6.72	187.48	96.54	15.20	179.00	92.17
137.68	***6.14***	***131.54***	***94.69***	***13.41***	***124.27***	***88.66***
±89.70	***±3.59***	***±89.02***	***±4.67***	***±7.43***	***±86.39***	***±7.92***

TS

Raw
mg/L
26,276.00
71,368.00
52,176.00
28,402.00
15,508.00
96,554.00
57,216.00
150,264.00
26,784.00
35,456.00
56000.40
±41288.96

A2-350P		A2-350UP	
mg/L	RE %	mg/L	RE %
2,308.00	91.22	2,884.00	89.02
5,132.00	92.81	3,844.00	94.61
3,824.00	92.67	4,572.00	91.24
2,664.00	90.62	3,800.00	86.62
3,384.00	78.18	3,116.00	79.91
1,500.00	98.45	3,260.00	96.62
2,344.00	95.90	2,996.00	94.76
1,204.00	99.20	1,376.00	99.08
3,512.00	86.89	3,460.00	87.08
3,784.00	89.33	3,988.00	88.75
2965.60	***91.53***	***3329.60***	***90.77***
±1189.52	***±6.09***	***±860.03***	***±5.68***

	A2-350P			A2-350UP		
Raw	kg TS/m2.yr		RE %	kg TS/m2.yr		RE %
kg TS/m2.yr	Eff. Mass	MRR		Eff. Mass	MRR	
6,730.77	227.02	6,503.74	96.63	424.05	6,306.72	93.70
6,730.77	166.01	6,564.76	97.53	171.11	6,559.65	97.46
6,730.77	117.90	6,612.87	98.25	256.56	6,474.21	96.19
6,730.77	169.19	6,561.58	97.49	217.03	6,513.74	96.78
6,730.77	262.90	6,467.87	96.09	470.64	6,260.13	93.01
6,730.77	27.40	6,703.37	99.59	74.08	6,656.68	98.90
6,730.77	47.98	6,682.79	99.29	71.90	6,658.87	98.93
6,730.77	6.04	6,724.73	99.91	23.98	6,706.79	99.64
6,730.77	138.56	6,592.21	97.94	265.19	6,465.57	96.06
6,730.77	117.81	6,612.96	98.25	215.00	6,515.76	96.81
6730.77	***128.08***	***6602.69***	***98.10***	***218.95***	***6511.81***	***96.75***
±0.00	***±83.57***	***±83.57***	***±1.24***	***±146.02***	***±146.02***	***±2.17***

TSS

Raw
mg/L
24,766.67
69,160.00
51,400.00
23,850.00
12,600.00
92,250.00
56,600.00
119,900.00
23,700.00
34,400.00
50862.67
±34529.55

A2-350P		A2-350UP	
mg/L	RE %	mg/L	RE %
1,683.33	93.20	1,766.67	92.87
2,333.33	96.63	2,425.00	96.49
340.00	99.34	2,920.00	94.32
420.00	98.24	1,360.00	94.30
1,330.00	89.44	1,557.14	87.64
265.00	99.71	2,530.00	97.26
1,640.00	97.10	1,755.00	96.90
370.00	99.69	7,860.00	93.44
1,025.00	95.68	1,320.00	94.43
1,305.00	96.21	2,120.00	93.84
1071.17	***96.52***	***2561.38***	***94.15***
±708.31	***±3.22***	***±1934.86***	***±2.74***

	A2-350P			A2-350UP		
Raw	kg TS/m2.yr		RE %	kg TS/m2.yr		RE %
kg TS/m2.yr	Eff. Mass	MRR		Eff. Mass	MRR	
6,344.14	165.58	6,178.56	97.39	259.76	6,084.38	95.91
6,522.53	75.48	6,447.05	98.84	107.95	6,414.58	98.34
6,630.66	10.48	6,620.18	99.84	163.86	6,466.81	97.53
5,652.03	26.67	5,625.35	99.53	77.67	5,574.35	98.63
5,468.64	103.33	5,365.31	98.11	235.19	5,233.45	95.70
6,430.74	4.84	6,425.90	99.92	57.50	6,373.24	99.11
6,658.30	33.57	6,624.74	99.50	42.12	6,616.19	99.37
5,370.68	1.86	5,368.82	99.97	136.96	5,233.72	97.45
5,955.77	40.44	5,915.33	99.32	101.17	5,854.59	98.30
6,530.30	40.63	6,489.68	99.38	114.30	6,416.01	98.25
6156.38	***50.29***	***6106.09***	***99.18***	***129.65***	***6026.73***	***97.86***
±499.58	***±51.38***	***±501.56***	***±0.84***	***±71.78***	***±522.70***	***±1.24***

VSS

Raw
mg/L
16,966.67
53,640.00
31,150.00
16,550.00
8,300.00
47,550.00
44,450.00
81,200.00
16,600.00
27,300.00
34370.67
±22400.15

A2-350P		A2-350UP	
mg/L	RE %	mg/L	RE %
833.33	95.09	1,333.33	92.14
1,716.67	96.80	1,450.00	97.30
320.00	98.97	2,320.00	92.55
320.00	98.07	900.00	94.56
1,020.00	87.71	1,228.57	85.20
180.00	99.62	1,570.00	96.70
1,520.00	96.58	1,610.00	96.38
300.00	99.63	3,200.00	96.06
750.00	95.48	960.00	94.22
1,195.00	95.62	1,820.00	93.33
815.50	***96.36***	***1639.19***	***93.84***
±543.60	***±3.48***	***±686.67***	***±3.52***

	A2-350P			A2-350UP		
Raw	kg TS/m2.yr		RE %	kg TS/m2.yr		RE %
kg TS/m2.yr	Eff. Mass	MRR		Eff. Mass	MRR	
4,346.12	81.97	4,264.15	98.11	196.05	4,150.08	95.49
5,058.83	55.53	5,003.30	98.90	64.55	4,994.28	98.72
4,018.39	9.87	4,008.52	99.75	130.19	3,888.20	96.76
3,922.06	20.32	3,901.73	99.48	51.40	3,870.65	98.69
3,602.36	79.24	3,523.12	97.80	185.56	3,416.80	94.85
3,314.71	3.29	3,311.42	99.90	35.68	3,279.03	98.92
5,229.00	31.11	5,197.89	99.40	38.64	5,190.37	99.26
3,637.19	1.51	3,635.68	99.96	55.76	3,581.43	98.47
4,171.55	29.59	4,141.96	99.29	73.58	4,097.97	98.24
5,182.48	37.20	5,145.28	99.28	98.12	5,084.36	98.11
4248.27	***34.96***	***4213.31***	***99.19***	***92.95***	***4155.32***	***97.75***
±693.50	***±29.07***	***±685.74***	***±0.73***	***±58.82***	***±702.11***	***±1.52***

Appendix C : Second Stage wetlands (Application related)

(C1) Effect of Hydraulic Loading Rate (HLR)

COD

Eff
mg/L
3000.00
3120.00
1500.00
2580.00
1680.00
2610.00
3360.00
1180.00
1050.00
2160.00
2224.00
±834.24

B-MM		B-HH	
mg/L	RE %	mg/L	RE %
160.00	94.67	200.00	93.33
130.00	95.83	150.00	95.19
100.00	93.33	120.00	92.00
60.00	97.67	120.00	95.35
170.00	89.88	250.00	85.12
45.00	98.28	130.00	95.02
20.00	99.40	183.33	94.54
110.00	90.68	200.00	83.05
105.00	90.00	210.00	80.00
150.00	93.06	270.00	87.50
105.00	***94.28***	***183.33***	***90.11***
±50.33	***±3.48***	***±52.92***	***±5.72***

		B-MM			B-HH		
Eff (g/m2.d)		g/m2.d		RE %	g/m2.d		RE %
HLR 8.75	HKR 17.5	Eff. Mass	MRR		Eff. Mass	MRR	
262.50	525.00	10.91	251.59	95.85	32.41	492.59	93.83
273.00	546.00	10.07	262.93	96.31	23.02	522.98	95.78
131.25	262.50	7.18	124.08	94.53	19.05	243.45	92.74
225.75	451.50	3.98	221.77	98.24	16.65	434.85	96.31
147.00	294.00	12.11	134.89	91.76	36.05	257.95	87.74
228.38	456.75	2.70	225.68	98.82	18.29	438.46	96.00
294.00	588.00	1.53	292.47	99.48	29.87	558.13	94.92
103.25	206.50	7.58	95.67	92.65	31.64	174.86	84.68
91.88	183.75	7.43	84.44	91.91	30.36	153.39	83.48
189.00	378.00	9.78	179.22	94.83	36.71	341.29	90.29
194.60	***389.20***	***7.33***	***187.27***	***95.44***	***27.40***	***361.80***	***91.58***
±73.00	***±145.99***	***±3.58***	***±74.06***	***±2.82***	***±7.50***	***±147.74***	***±4.79***

BOD

Eff
mg/L
182.70
296.10
351.60
246.60
221.10
184.80
183.00
215.10
223.50
315.80
242.03
±59.79

B-MM		B-HH	
mg/L	RE %	mg/L	RE %
5.55	96.96	10.35	94.33
6.45	97.82	11.85	96.00
3.90	98.89	20.40	94.20
2.70	98.91	21.30	91.36
0.24	99.89	14.94	93.24
0.72	99.61	31.74	82.82
0.36	99.80	27.66	84.89
4.59	97.87	21.54	89.99
5.55	97.52	39.30	82.42
2.94	99.07	39.12	87.61
3.30	***98.63***	***23.82***	***89.69***
±2.29	***±1.03***	***±10.42***	***±5.00***

		B-MM			B-HH		
Eff (g/m2.d)		g/m2.d		RE %	g/m2.d		RE %
HLR 8.75	HKR 17.5	Eff. Mass	MRR		Eff. Mass	MRR	
15.99	31.97	0.38	15.61	97.63	1.68	30.30	94.75
25.91	51.82	0.50	25.41	98.07	1.82	50.00	96.49
30.77	61.53	0.28	30.49	99.09	3.24	58.29	94.74
21.58	43.16	0.18	21.40	99.17	2.96	40.20	93.15
19.35	38.69	0.02	19.33	99.91	2.15	36.54	94.43
16.17	32.34	0.04	16.13	99.73	4.47	27.87	86.19
16.01	32.03	0.03	15.98	99.83	4.51	27.52	85.93
18.82	37.64	0.32	18.50	98.32	3.41	34.23	90.95
19.56	39.11	0.39	19.16	97.99	5.68	33.43	85.48
27.63	55.27	0.19	27.44	99.31	5.32	49.95	90.37
21.18	***42.36***	***0.23***	***20.95***	***98.91***	***3.52***	***38.83***	***91.25***
±5.23	***±10.47***	***±0.17***	***±5.18***	***±0.84***	***±1.43***	***±10.57***	***±4.13***

NH_3-N

Eff
mg/L
39.60
23.40
76.80
42.60

B-MM		B-HH	
mg/L	RE %	mg/L	RE %
0.60	98.48	10.10	74.49
0.70	97.01	5.60	76.07
1.30	98.31	15.30	80.08
1.20	97.18	13.90	67.37

108.50
43.20
40.20
62.40
47.40
68.40
55.25
±24.44

0.50	99.54	25.60	76.41
2.10	95.14	15.10	65.05
1.20	97.01	13.90	65.42
0.20	99.68	16.10	74.20
0.30	99.37	16.10	66.03
0.20	99.71	18.90	72.37
0.83	***98.14***	***15.06***	***71.75***
±0.61	***±1.52***	***±5.22***	***±5.38***

		B-MM			B-HH		
Eff (g/m2.d)		g/m2.d		RE %	g/m2.d		RE %
HLR 8.75	HLR 17.5	Eff. Mass	MRR		Eff. Mass	MRR	
3.47	6.93	0.04	3.42	98.82	1.64	5.29	76.38
2.05	4.10	0.05	1.99	97.35	0.86	3.24	79.01
6.72	13.44	0.09	6.63	98.61	2.43	11.01	81.93
3.73	7.46	0.08	3.65	97.86	1.93	5.53	74.13
9.49	18.99	0.04	9.46	99.62	3.69	15.30	80.56
3.78	7.56	0.13	3.65	96.67	2.12	5.44	71.90
3.52	7.04	0.09	3.43	97.39	2.26	4.77	67.81
5.46	10.92	0.01	5.45	99.75	2.55	8.37	76.68
4.15	8.30	0.02	4.13	99.49	2.33	5.97	71.94
5.99	11.97	0.01	5.97	99.78	2.57	9.40	78.53
4.84	***9.67***	***0.06***	***4.78***	***98.53***	***2.24***	***7.43***	***75.89***
±2.14	***±4.28***	***±0.04***	***±2.15***	***±1.15***	***±0.72***	***±3.63***	***±4.42***

TN

Eff
mg/L
300.00
270.00
366.00
324.00
234.00
216.00
264.00
132.00
120.00
216.00
244.20
±78.23

B-MM		B-HH	
mg/L	RE %	mg/L	RE %
63.00	79.00	65.00	78.33
89.00	67.04	117.00	56.67
88.00	75.96	126.00	65.57
79.00	75.62	124.00	61.73
21.00	91.03	52.00	77.78
76.00	64.81	96.00	55.56
61.00	76.89	89.00	66.29
42.00	68.18	51.00	61.36
37.00	69.17	46.00	61.67
32.00	85.19	59.00	72.69
58.80	***75.29***	***82.50***	***65.77***
±24.48	***±8.36***	***±31.87***	***±8.10***

		B-MM			B-HH		
Eff (g/m2.d)		g/m2.d		RE %	g/m2.d		RE %
HLR 8.75	HKR 17.5	Eff. Mass	MRR		Eff. Mass	MRR	
26.25	52.50	4.29	21.96	83.64	10.53	41.97	79.94
23.63	47.25	6.89	16.73	70.83	17.96	29.29	62.00
32.03	64.05	6.31	25.71	80.28	20.00	44.05	68.78
28.35	56.70	5.24	23.11	81.52	17.21	39.49	69.65
20.48	40.95	1.50	18.98	92.69	7.50	33.45	81.69
18.90	37.80	4.56	14.34	75.90	13.51	24.29	64.27
23.10	46.20	4.66	18.44	79.81	14.50	31.70	68.61
11.55	23.10	2.90	8.65	74.93	8.07	15.03	65.07
10.50	21.00	2.62	7.88	75.06	6.65	14.35	68.34
18.90	37.80	2.09	16.81	88.96	8.02	29.78	78.78
21.37	***42.74***	***4.11***	***17.26***	***80.36***	***12.40***	***30.34***	***70.71***
±6.85	***±13.69***	***±1.79***	***±5.80***	***±6.72***	***±4.90***	***±10.26***	***±6.95***

TS

Eff
mg/L
3824.00
7476.00
3276.00
4152.00

B-MM		B-HH	
mg/L	RE %	mg/L	RE %
2272.00	40.59	1984.00	48.12
2904.00	61.16	2468.00	66.99
1052.00	67.89	980.00	70.09
1216.00	70.71	1088.00	73.80

4980.00
3596.00
3380.00
3980.00
2716.00
3216.00
4059.60
±1349.78

1848.00	62.89	1608.00	67.71
1320.00	63.29	1044.00	70.97
1368.00	59.53	1028.00	69.59
1548.00	61.11	1144.00	71.26
1128.00	58.47	904.00	66.72
1332.00	58.58	964.00	70.02
1598.80	***60.42***	***1321.20***	***67.53***
±586.02	***±8.02***	***±527.40***	***±7.15***

		B-MM			B-HH		
Eff (g/m2.d)		g/m2.d		RE %	g/m2.d		RE %
HLR 8.75	HKR 17.5	Eff. Mass	MRR		Eff. Mass	MRR	
334.60	669.20	154.87	179.73	53.72	321.51	347.69	51.96
654.15	1308.30	224.88	429.27	65.62	378.78	929.52	71.05
286.65	573.30	75.48	211.17	73.67	155.55	417.75	72.87
363.30	726.60	80.65	282.65	77.80	150.99	575.61	79.22
435.75	871.50	131.62	304.13	69.79	231.87	639.63	73.39
314.65	629.30	79.12	235.53	74.86	146.89	482.41	76.66
295.75	591.50	104.62	191.13	64.63	167.49	424.01	71.68
348.25	696.50	106.73	241.52	69.35	180.98	515.52	74.02
237.65	475.30	79.85	157.80	66.40	130.67	344.63	72.51
281.40	562.80	86.83	194.57	69.14	131.08	431.72	76.71
355.22	***710.43***	***112.47***	***242.75***	***68.50***	***199.58***	***510.85***	***72.01***
±118.11	***±236.21***	***±47.27***	***±79.84***	***±6.69***	***±85.58***	***±174.36***	***±7.50***

TSS

Eff
mg/L
1550.00
2270.00
1080.00
3710.00
2066.67
2400.00
2300.00
3350.00
1640.00
3300.00
2366.67
±856.22

B-MM		B-HH	
mg/L	RE %	mg/L	RE %
84.00	94.58	68.00	95.61
100.00	95.59	128.00	94.36
35.00	96.76	50.00	95.37
65.00	98.25	95.00	97.44
90.00	95.65	150.00	92.74
10.00	99.58	85.00	96.46
5.00	99.78	110.00	95.22
8.00	99.76	92.00	97.25
44.00	97.32	96.00	94.15
16.00	99.52	156.00	95.27
45.70	***97.68***	***103.00***	***95.39***
±36.67	***±1.98***	***±33.80***	***±1.43***

		B-MM			B-HH		
Eff (g/m2.d)		kg TS/m2.yr		RE %	kg TS/m2.yr		RE %
HLR 8.75	HKR 17.5	Eff. Mass	MRR		Eff. Mass	MRR	
135.63	271.25	5.73	129.90	95.78	11.02	260.23	95.94
198.62	397.25	7.74	190.88	96.10	19.64	377.61	95.05
94.50	189.00	2.51	91.99	97.34	7.94	181.06	95.80
324.63	649.25	4.31	320.31	98.67	13.18	636.07	97.97
180.83	361.67	6.41	174.42	96.46	21.63	340.04	94.02
210.00	420.00	0.60	209.40	99.71	11.96	408.04	97.15
201.25	402.50	0.38	200.87	99.81	17.92	384.58	95.55
293.13	586.25	0.55	292.57	99.81	14.55	571.70	97.52
143.50	287.00	3.11	140.39	97.83	13.88	273.12	95.16
288.75	577.50	1.04	287.71	99.64	21.21	556.29	96.33
207.08	***414.17***	***3.24***	***203.84***	***98.12***	***15.29***	***398.87***	***96.05***
±74.92	***±149.84***	***±2.70***	***±75.68***	***±1.63***	***±4.61***	***±148.17***	***±1.22***

VSS

Eff
mg/L
950.00
830.00
970.00
3300.00

B-MM		B-HH	
mg/L	RE %	mg/L	RE %
48.00	94.95	44.00	95.37
24.00	97.11	112.00	86.51
30.00	96.91	40.00	95.88
50.00	98.48	80.00	97.58

1866.67
1620.00
1440.00
3020.00
1200.00
2950.00
1814.67
±939.12

65.00	96.52	55.00	97.05
5.00	99.69	70.00	95.68
0.00	100.00	70.00	95.14
4.00	99.87	80.00	97.35
36.00	97.00	76.00	93.67
12.00	99.59	136.00	95.39
27.40	***98.01***	***76.30***	***94.96***
±22.31	***±1.75***	***±29.36***	***±3.19***

		B-MM			B-HH		
Eff (g/m2.d)		g/m2.d		RE %	g/m2.d		RE %
HLR 8.75	HKR 17.5	Eff. Mass	MRR		Eff. Mass	MRR	
83.13	166.25	3.27	79.85	96.06	7.13	159.12	95.71
72.62	145.25	1.86	70.77	97.44	17.19	128.06	88.17
84.88	169.75	2.15	82.72	97.46	6.35	163.40	96.26
288.75	577.50	3.32	285.43	98.85	11.10	566.40	98.08
163.33	326.67	4.63	158.70	97.17	7.93	318.74	97.57
141.75	283.50	0.30	141.45	99.79	9.85	273.65	96.53
126.00	252.00	0.00	126.00	100.00	11.40	240.60	95.47
264.25	528.50	0.28	263.97	99.90	12.66	515.84	97.61
105.00	210.00	2.55	102.45	97.57	10.99	199.01	94.77
258.12	516.25	0.78	257.34	99.70	18.49	497.76	96.42
158.78	***317.57***	***1.91***	***156.87***	***98.39***	***11.31***	***306.26***	***95.66***
±82.17	***±164.35***	***±1.56***	***±82.39***	***±1.42***	***±4.00***	***±163.00***	***±2.83***

(C2) Effects of Dosing Frequency

<u>Medium HLR</u>

COD

Eff
mg/L
1890.00
7326.00
8734.00
7744.00
2050.00
1692.00
7050.00
3344.00
5270.00
3500.00
4860.00
±2693.03

B-MM (4x)		B-MM (8x)	
mg/L	RE %	mg/L	RE %
210.00	88.89	230.00	87.83
160.00	97.82	150.00	97.95
180.00	97.94	200.00	97.71
180.00	97.68	180.00	97.68
370.00	81.95	390.00	80.98
220.00	87.00	250.00	85.22
220.00	96.88	220.00	96.88
120.00	96.41	110.00	96.71
200.00	96.20	190.00	96.39
130.00	96.29	140.00	96.00
199.00	***93.71***	***206.00***	***93.34***
±69.51	***±5.65***	***±77.63***	***±6.22***

Eff
g/m2.d
165.38
641.03
764.23
677.60
179.38
148.05
616.88
292.60
461.13
306.25
425.25
±235.64

B-MM (4x)			B-MM 8x)		
g/m2.d		RE %	g/m2.d		RE %
Eff. Mass	MRR		Eff. Mass	MRR	
16.00	149.37	90.32	17.39	147.99	89.49
10.96	630.06	98.29	9.99	631.04	98.44
11.72	752.51	98.47	12.74	751.49	98.33
13.43	664.17	98.02	13.26	664.34	98.04
26.90	152.47	85.00	27.68	151.70	84.57
17.25	130.80	88.35	19.36	128.69	86.92
16.23	600.65	97.37	15.98	600.90	97.41
7.78	284.82	97.34	6.99	285.61	97.61
14.39	446.74	96.88	13.45	447.68	97.08
11.16	295.09	96.36	9.82	296.43	96.79
14.58	***410.67***	***94.64***	***14.67***	***410.59***	***94.47***
±5.21	***±237.84***	***±4.87***	***±5.89***	***±238.26***	***±5.31***

BOD

Eff
mg/L
258.00
473.40
209.20
163.80
216.40
222.00
210.60
211.20
238.50
270.00
247.31
±84.65

B-MM (4x)		B-MM (8x)	
mg/L	RE %	mg/L	RE %
14.25	94.48	18.15	92.97
17.40	96.32	13.65	97.12
12.20	94.17	12.40	94.07
1.95	98.81	4.47	97.27
4.62	97.87	22.14	89.77
4.92	97.78	4.50	97.97
4.14	98.03	3.72	98.23
12.06	94.29	12.48	94.09
6.42	97.31	8.04	96.63
0.96	99.64	1.92	99.29
7.89	***96.87***	***10.15***	***95.74***
±5.64	***±1.97***	***±6.73***	***±2.94***

Eff
g/m2.d
22.58
41.42
18.31
14.33
18.94
19.43
18.43
18.48
20.87
23.63
21.64
±7.41

B-MM (4x)			B-MM 8x)		
g/m2.d		RE %	g/m2.d		RE %
Eff. Mass	MRR		Eff. Mass	MRR	
1.09	21.49	95.19	1.37	21.20	93.92
1.19	40.23	97.12	0.91	40.51	97.81
0.79	17.51	95.66	0.79	17.52	95.68
0.15	14.19	98.98	0.33	14.00	97.70
0.34	18.60	98.23	1.57	17.36	91.70
0.39	19.04	98.01	0.35	19.08	98.21
0.31	18.12	98.34	0.27	18.16	98.53
0.78	17.70	95.77	0.79	17.69	95.71
0.46	20.41	97.79	0.57	20.30	97.27
0.08	23.54	99.65	0.13	23.49	99.43
0.56	***21.08***	***97.47***	***0.71***	***20.93***	***96.60***
±0.38	***±7.18***	***±1.50***	***±0.48***	***±7.34***	***±2.36***

NH_3-N

Eff
mg/L
69.90
105.06
132.60
197.96

B-MM (4x)		B-MM (8x)	
mg/L	RE %	mg/L	RE %
9.70	86.12	10.90	84.41
8.30	92.10	9.80	90.67
1.30	99.02	3.60	97.29
0.20	99.90	2.10	98.94

68.34
156.91
150.52
140.58
151.23
106.50
127.96
±40.66

0.96	98.60	2.43	96.44
6.90	95.60	17.10	89.10
0.00	100.00	2.90	98.07
3.50	97.51	7.30	94.81
0.00	100.00	2.60	98.28
3.10	97.09	6.70	93.71
3.40	***96.59***	***6.54***	***94.17***
±3.65	***±4.42***	***±4.90***	***±4.76***

Eff
g/m2.d
6.12
9.19
11.60
17.32
5.98
13.73
13.17
12.30
13.23
9.32
11.196
±3.56

B-MM (4x)			B-MM 8x)		
g/m2.d		RE %	g/m2.d		RE %
Eff. Load	MRR		Eff. Load	MRR	
0.74	5.38	87.91	0.02	6.09	99.63
0.57	8.62	93.81	0.03	9.17	99.71
0.08	11.52	99.27	0.17	11.44	98.57
0.01	17.31	99.91	0.02	17.30	99.87
0.07	5.91	98.83	0.00	5.98	100.00
0.54	13.19	96.06	0.12	13.61	99.14
0.00	13.17	100.00	0.00	13.17	100.00
0.23	12.07	98.16	0.08	12.22	99.37
0.00	13.23	100.00	0.00	13.23	100.00
0.27	9.05	97.14	0.20	9.12	97.84
0.251	***10.945***	***97.109***	***0.064***	***11.133***	***99.413***
±0.27	***±3.69***	***±3.80***	***±0.07***	***±3.56***	***±0.72***

TN

Eff
mg/L
165.00
294.50
285.20
266.60
260.40
384.00
628.00
320.00
298.00
190.00
309.17
±128.00

B-MM (4x)		B-MM (8x)	
mg/L	RE %	mg/L	RE %
43.00	73.94	48.00	70.91
31.00	89.47	33.00	88.79
26.00	90.88	26.00	90.88
13.00	95.12	15.00	94.37
37.00	85.79	42.00	83.87
48.00	87.50	49.00	87.24
28.00	95.54	31.00	95.06
79.00	75.31	85.00	73.44
64.00	78.52	66.00	77.85
78.00	58.95	79.00	58.42
44.70	***83.10***	***47.40***	***82.08***
±22.49	***±11.43***	***±23.03***	***±11.78***

Eff
g/m2.d
14.44
25.77
24.96
23.33
22.79
33.60
54.95
28.00
26.08
16.63
27.06
±11.20

B-MM (4x)			B-MM 8x)		
g/m2.d		RE %	g/m2.d		RE %
Eff. Mass	MRR		Eff. Mass	MRR	
3.28	11.16	77.30	3.63	10.81	74.87
2.12	23.64	91.76	2.20	23.57	91.47
1.69	23.26	93.22	1.66	23.30	93.36
0.97	22.36	95.84	1.11	22.22	95.26
2.69	20.09	88.19	2.98	19.80	86.92
3.76	29.84	88.80	3.79	29.81	88.71
2.07	52.88	96.24	2.25	52.70	95.90
5.12	22.88	81.71	5.40	22.60	80.72
4.60	21.47	82.35	4.67	21.40	82.08
6.70	9.93	59.73	5.54	11.08	66.65
3.30	***23.75***	***85.51***	***3.32***	***23.73***	***85.59***
±1.77	***±11.82***	***±11.03***	***±1.55***	***±11.68***	***±9.52***

TS

Eff
mg/L
6,216.00
10,586.00
7,400.00
6,543.00
14,000.00
18,800.00
6,800.00
4,800.00
5,960.00
4,308.00
8541.30
±4613.21

B-MM (4x)		B-MM (8x)	
mg/L	RE %	mg/L	RE %
2,688.00	56.76	2,736.00	55.98
2,556.00	75.85	2,656.00	74.91
1,888.00	74.49	1,612.00	78.22
2,704.00	58.67	2,860.00	56.29
2,996.00	78.60	2,690.00	80.79
1,852.00	90.15	1,840.00	90.21
2,348.00	65.47	2,268.18	66.64
2,304.00	52.00	2,237.50	53.39
2,772.00	53.49	2,465.00	58.64
1,612.00	62.58	1,525.71	64.58
2372.00	***66.81***	***2289.04***	***67.97***
±457.14	***±12.51***	***±482.81***	***±12.50***

Eff
g/m2.d
543.90
926.28
647.50
572.51

B-MM (4x)			B-MM 8x)		
g/m2.d		RE %	g/m2.d		RE %
Eff. Load	MRR		Eff. Load	MRR	
204.86	339.04	62.34	298.07	245.83	45.20
175.12	751.16	81.09	199.75	726.53	78.44
122.91	524.59	81.02	160.49	487.01	75.21
201.82	370.69	64.75	223.34	349.17	60.99

1,225
1,645
595.00
420.00
521.50
376.95
747.364
±403.66

217.85	1,007.15	82.22	200.24	1,024.76	83.65
145.20	1,499.80	91.17	211.34	1,433.66	87.15
173.19	421.81	70.89	239.88	355.12	59.68
149.39	270.61	64.43	192.18	227.82	54.24
199.38	322.12	61.77	279.77	241.73	46.35
138.38	238.57	63.29	207.75	169.20	44.89
172.81	***574.554***	***72.297***	***221.281***	***526.083***	***63.58***
±32.65	***±403.63***	***±10.65***	***±41.36***	***±415.04***	***±16.36***

TSS

Eff
mg/L
1,560.00
5,560.00
2,720.00
2,165.00
3,225.00
1,872.00
2,732.00
1,884.00
2,152.00
2,788.00
2665.80
±1139.70

B-MM (4x)		B-MM (8x)	
mg/L	RE %	mg/L	RE %
112.00	92.82	108.00	93.08
156.00	97.19	152.00	97.27
10.00	99.63	22.00	99.19
115.00	94.69	130.00	94.00
150.00	95.35	215.00	93.33
44.00	97.65	68.00	96.37
148.00	94.58	156.00	94.29
56.00	97.03	64.00	96.60
84.00	96.10	128.00	94.05
44.00	98.42	40.00	98.57
91.90	***96.35***	***108.30***	***95.68***
±51.87	***±2.04***	***±59.75***	***±2.22***

Eff
g/m2.d
136.50
486.50
238.00
189.44
282.19
163.80
239.05
164.85
188.30
243.95
233.26
±99.72

B-MM (4x)			B-MM 8x)		
g/m2.d		RE %	g/m2.d		RE %
Eff. Mass	MRR		Eff. Mass	MRR	
8.54	127.96	93.75	8.16	128.34	94.02
10.69	475.81	97.80	10.12	476.38	97.92
0.65	237.35	99.73	1.40	236.60	99.41
8.58	180.85	95.47	9.58	179.86	94.94
10.91	271.28	96.13	15.26	266.93	94.59
3.45	160.35	97.89	5.27	158.53	96.79
10.92	228.13	95.43	11.33	227.72	95.26
3.63	161.22	97.80	4.07	160.78	97.53
6.04	182.26	96.79	9.06	179.24	95.19
3.78	240.17	98.45	2.81	241.14	98.85
6.72	***226.54***	***96.92***	***7.71***	***225.55***	***96.45***
±3.71	***±98.24***	***±1.76***	***±4.27***	***±98.53***	***±1.90***

VSS

Eff
mg/L
1,350.00
5,372.00
2,275.00
955.00
2,885.00
1,144.00
2,096.00
1,516.00
1,284.00
2,184.00
2106.10
±1297.60

B-MM (4x)		B-MM (8x)	
mg/L	RE %	mg/L	RE %
60.00	95.56	80.00	94.07
84.00	98.44	68.00	98.73
6.00	99.74	20.00	99.12
75.00	92.15	65.00	93.19
75.00	97.40	100.00	96.53
28.00	97.55	16.00	98.60
36.00	98.28	28.00	98.66
32.00	97.89	0.00	100.00
44.00	96.57	72.00	94.39
8.00	99.63	4.00	99.82
44.80	***97.32***	***45.30***	***97.31***
±27.84	***±2.21***	***±35.54***	***±2.56***

Eff
g/m2.d
118.13
470.05
199.06
83.56
252.44
100.10
183.40
132.65
112.35
191.10
184.28
±113.54

B-MM (4x)			B-MM 8x)		
g/m2.d		RE %	g/m2.d		RE %
Eff. Mass	MRR		Eff. Mass	MRR	
4.57	113.55	96.13	6.05	112.08	94.88
5.76	464.29	98.78	4.53	465.52	99.04
0.39	198.67	99.80	1.27	197.79	99.36
5.60	77.96	93.30	4.79	78.77	94.27
5.45	246.98	97.84	7.10	245.34	97.19
2.20	97.90	97.81	1.24	98.86	98.76
2.66	180.74	98.55	2.03	181.37	98.89
2.07	130.58	98.44	0.00	132.65	100.00
3.16	109.19	97.18	5.10	107.25	95.46
0.69	190.41	99.64	0.28	190.82	99.85
3.26	***181.03***	***97.75***	***3.24***	***181.05***	***97.77***
±2.00	***±112.93***	***±1.91***	***±2.56***	***±113.13***	***±2.16***

High HLR

COD

Eff
mg/L
3000.00
3120.00
1500.00
2580.00
1680.00
2610.00
3360.00
1180.00
1050.00
2160.00
2224.00
±834.24

B-HH (4x)		B-HH (8x)	
mg/L	RE %	mg/L	RE %
180.00	94.00	200.00	93.33
110.00	96.47	150.00	95.19
90.00	94.00	120.00	92.00
110.00	95.74	120.00	95.35
210.00	87.50	250.00	85.12
110.00	95.79	130.00	95.02
170.00	94.94	183.33	94.54
190.00	83.90	200.00	83.05
180.00	82.86	210.00	80.00
230.00	89.35	270.00	87.50
158.00	***91.46***	***183.33***	***90.11***
±48.94	***±5.15***	***±52.92***	***±5.72***

Eff
g/m2.d
525.00
546.00
262.50
451.50
294.00
456.75
588.00
206.50
183.75
378.00
389.20
±145.99

B-HH (4x)			B-HH (8x)		
g/m2.d		RE %	g/m2.d		RE %
Eff. Mass	MRR		Eff. Mass	MRR	
29.33	495.67	94.41	32.41	492.59	93.83
16.96	529.04	96.89	23.02	522.98	95.78
14.36	248.14	94.53	19.05	243.45	92.74
15.38	436.12	96.59	16.65	434.85	96.31
30.43	263.57	89.65	36.05	257.95	87.74
15.52	441.23	96.60	18.29	438.46	96.00
27.61	560.39	95.30	29.87	558.13	94.92
30.16	176.34	85.40	31.64	174.86	84.68
26.24	157.51	85.72	30.36	153.39	83.48
31.52	346.48	91.66	36.71	341.29	90.29
23.75	***365.45***	***92.68***	***27.40***	***361.80***	***91.58***
±7.23	***±147.56***	***±4.39***	***±7.50***	***±147.74***	***±4.79***

BOD

Eff
mg/L
182.70
296.10
351.60
246.60
221.10
184.80
183.00
215.10
223.50
315.80
242.03
±59.79

B-HH (4x)		B-HH (8x)	
mg/L	RE %	mg/L	RE %
5.45	97.02	10.35	94.33
8.11	97.26	11.85	96.00
6.47	98.16	20.40	94.20
8.65	96.49	21.30	91.36
10.11	95.43	14.94	93.24
22.76	87.68	31.74	82.82
18.59	89.84	27.66	84.89
14.93	93.06	21.54	89.99
19.53	91.26	39.30	82.42
26.87	91.49	39.12	87.61
14.15	***93.77***	***23.82***	***89.69***
±7.48	***±3.60***	***±10.42***	***±5.00***

Eff
g/m2.d
31.97
51.82
61.53
43.16
38.69
32.34
32.03
37.64
39.11
55.27
42.36
±10.47

B-HH (4x)			B-HH (8x)		
g/m2.d		RE %	g/m2.d		RE %
Eff. Mass	MRR		Eff. Mass	MRR	
0.89	31.08	97.22	1.68	30.30	94.75
1.25	50.57	97.59	1.82	50.00	96.49
1.03	60.50	98.32	3.24	58.29	94.74
1.21	41.95	97.20	2.96	40.20	93.15
1.46	37.23	96.21	2.15	36.54	94.43
3.21	29.13	90.07	4.47	27.87	86.19
3.02	29.01	90.57	4.51	27.52	85.93
2.37	35.27	93.70	3.41	34.23	90.95
2.85	36.27	92.72	5.68	33.43	85.48
3.68	51.58	93.34	5.32	49.95	90.37
2.10	***40.26***	***94.69***	***3.52***	***38.83***	***91.25***
±1.04	***±10.71***	***±3.01***	***±1.43***	***±10.57***	***±4.13***

NH_3-N

Eff
mg/L
39.60
23.40
76.80
42.60
108.50
43.20
40.20
62.40
47.40
68.40
55.25
±24.44

B-HH (4x)		B-HH (8x)	
mg/L	RE %	mg/L	RE %
6.40	83.84	10.10	74.49
3.10	86.75	5.60	76.07
8.70	88.67	15.30	80.08
7.10	83.33	13.90	67.37
11.80	89.12	25.60	76.41
9.50	78.01	15.10	65.05
8.80	78.11	13.90	65.42
10.80	82.69	16.10	74.20
10.30	78.27	16.10	66.03
11.40	83.33	18.90	72.37
8.79	***83.21***	***15.06***	***71.75***
±2.66	***±4.16***	***±5.22***	***±5.38***

Eff
g/m2.d
6.93
4.10
13.44
7.46
18.99
7.56
7.04
10.92
8.30
11.97
9.67
±4.28

B-HH (4x)			B-HH (8x)		
g/m2.d		RE %	g/m2.d		RE %
Eff. Mass	MRR		Eff. Mass	MRR	
1.04	5.89	84.95	1.64	5.29	76.38
0.48	3.62	88.33	0.86	3.24	79.01
1.39	12.05	89.67	2.43	11.01	81.93
0.99	6.46	86.68	1.93	5.53	74.13
1.71	17.28	91.00	3.69	15.30	80.56
1.34	6.22	82.28	2.12	5.44	71.90
1.43	5.61	79.69	2.26	4.77	67.81
1.71	9.21	84.30	2.55	8.37	76.68
1.50	6.79	81.90	2.33	5.97	71.94
1.56	10.41	86.95	2.57	9.40	78.53
1.32	***8.35***	***85.58***	***2.24***	***7.43***	***75.89***
±0.38	***±4.01***	***±3.62***	***±0.72***	***±3.63***	***±4.42***

TN

Eff
mg/L
300.00
270.00
366.00
324.00
234.00
216.00
264.00
132.00
120.00
216.00
244.20
±78.23

B-HH (4x)		B-HH (8x)	
mg/L	RE %	mg/L	RE %
59.00	80.33	65.00	78.33
99.00	63.33	117.00	56.67
92.00	74.86	126.00	65.57
108.00	66.67	124.00	61.73
27.00	88.46	52.00	77.78
90.00	58.33	96.00	55.56
81.00	69.32	89.00	66.29
40.00	69.70	51.00	61.36
37.00	69.17	46.00	61.67
42.00	80.56	59.00	72.69
67.50	***72.07***	***82.50***	***65.77***
±29.76	***±9.02***	***±31.87***	***±8.10***

Eff
g/m2.d
52.50
47.25
64.05
56.70
40.95
37.80
46.20
23.10
21.00
37.80
42.74
±13.69

B-HH (4x)			B-HH (8x)		
g/m2.d		RE %	g/m2.d		RE %
Eff. Mass	MRR		Eff. Mass	MRR	
9.61	42.89	81.69	10.53	41.97	79.94
15.26	31.99	67.70	17.96	29.29	62.00
14.68	49.37	77.08	20.00	44.05	68.78
15.10	41.60	73.37	17.21	39.49	69.65
3.91	37.04	90.45	7.50	33.45	81.69
12.69	25.11	66.42	13.51	24.29	64.27
13.15	33.05	71.53	14.50	31.70	68.61
6.35	16.75	72.52	8.07	15.03	65.07
5.39	15.61	74.32	6.65	14.35	68.34
5.76	32.04	84.78	8.02	29.78	78.78
10.19	***32.55***	***75.99***	***12.40***	***30.34***	***70.71***
±4.50	***±10.98***	***±7.62***	***±4.90***	***±10.26***	***±6.95***

TS

Eff
mg/L
3824.00
7476.00
3276.00
4152.00
4980.00
3596.00
3380.00
3980.00
2716.00
3216.00
4059.60
±1349.78

B-HH (4x)		B-HH (8x)	
mg/L	RE %	mg/L	RE %
2098.00	45.14	1984.00	48.12
2562.00	65.73	2468.00	66.99
1003.00	69.38	980.00	70.09
1224.00	70.52	1088.00	73.80
1772.00	64.42	1608.00	67.71
1201.00	66.60	1044.00	70.97
1123.00	66.78	1028.00	69.59
1346.00	66.18	1144.00	71.26
1011.00	62.78	904.00	66.72
998.00	68.97	964.00	70.02
1433.80	***64.65***	***1321.20***	***67.53***
±535.95	***±7.24***	***±527.40***	***±7.15***

Eff
g/m2.d
669.20
1308.30
573.30
726.60
871.50
629.30
591.50
696.50
475.30
562.80
710.43
±236.21

B-HH (4x)			B-HH (8x)		
g/m2.d		RE %	g/m2.d		RE %
Eff. Mass	MRR		Eff. Mass	MRR	
341.82	327.38	48.92	321.51	347.69	51.96
395.00	913.30	69.81	378.78	929.52	71.05
160.08	413.22	72.08	155.55	417.75	72.87
171.15	555.45	76.45	150.99	575.61	79.22
256.76	614.74	70.54	231.87	639.63	73.39
169.40	459.90	73.08	146.89	482.41	76.66
182.38	409.12	69.17	167.49	424.01	71.68
213.64	482.86	69.33	180.98	515.52	74.02
147.38	327.92	68.99	130.67	344.63	72.51
136.75	426.05	75.70	131.08	431.72	76.71
217.44	***492.99***	***69.41***	***199.58***	***510.85***	***72.01***
±87.53	***±172.93***	***±7.68***	***±85.58***	***±174.36***	***±7.50***

TSS

Eff
mg/L
1550.00
2270.00
1080.00
3710.00
2066.67
2400.00
2300.00
3350.00
1640.00
3300.00
2366.67
±856.22

B-HH (4x)		B-HH (8x)	
mg/L	RE %	mg/L	RE %
71.00	95.42	68.00	95.61
117.00	94.85	128.00	94.36
46.00	95.74	50.00	95.37
99.00	97.33	95.00	97.44
152.00	92.65	150.00	92.74
79.00	96.71	85.00	96.46
116.00	94.96	110.00	95.22
90.00	97.31	92.00	97.25
88.00	94.63	96.00	94.15
150.00	95.45	156.00	95.27
100.80	***95.51***	***103.00***	***95.39***
±33.64	***±1.40***	***±33.80***	***±1.43***

Eff
g/m2.d
271.25
397.25
189.00
649.25
361.67
420.00
402.50
586.25
287.00
577.50
414.17
±149.84

B-HH (4x)			B-HH (8x)		
g/m2.d		RE %	g/m2.d		RE %
Eff. Mass	MRR		Eff. Mass	MRR	
11.57	259.68	95.74	11.02	260.23	95.94
18.04	379.21	95.46	19.64	377.61	95.05
7.34	181.66	96.12	7.94	181.06	95.80
13.84	635.41	97.87	13.18	636.07	97.97
22.02	339.64	93.91	21.63	340.04	94.02
11.14	408.86	97.35	11.96	408.04	97.15
18.84	383.66	95.32	17.92	384.58	95.55
14.29	571.96	97.56	14.55	571.70	97.52
12.83	274.17	95.53	13.88	273.12	95.16
20.55	556.95	96.44	21.21	556.29	96.33
15.05	***399.12***	***96.13***	***15.29***	***398.87***	***96.05***
±4.67	***±148.04***	***±1.21***	***±4.61***	***±148.17***	***±1.22***

VSS

Eff
mg/L
950.00
830.00
970.00
3300.00
1866.67
1620.00
1440.00
3020.00
1200.00
2950.00
1814.67
±939.12

B-HH (4x)		B-HH (8x)	
mg/L	RE %	mg/L	RE %
41.00	95.68	44.00	95.37
97.00	88.31	112.00	86.51
36.00	96.29	40.00	95.88
78.00	97.64	80.00	97.58
52.00	97.21	55.00	97.05
62.00	96.17	70.00	95.68
56.00	96.11	70.00	95.14
74.00	97.55	80.00	97.35
71.00	94.08	76.00	93.67
119.00	95.97	136.00	95.39
68.60	***95.50***	***76.30***	***94.96***
±25.33	***±2.73***	***±29.36***	***±3.19***

Eff
g/m2.d
166.25
145.25
169.75
577.50
326.67
283.50
252.00
528.50
210.00
516.25
317.57
±164.35

B-HH (4x)			B-HH (8x)		
g/m2.d		RE %	g/m2.d		RE %
Eff. Mass	MRR		Eff. Mass	MRR	
6.68	159.57	95.98	7.13	159.12	95.71
14.95	130.30	89.70	17.19	128.06	88.17
5.75	164.00	96.62	6.35	163.40	96.26
10.91	566.59	98.11	11.10	566.40	98.08
7.53	319.13	97.69	7.93	318.74	97.57
8.75	274.75	96.92	9.85	273.65	96.53
9.09	242.91	96.39	11.40	240.60	95.47
11.75	516.75	97.78	12.66	515.84	97.61
10.35	199.65	95.07	10.99	199.01	94.77
16.31	499.94	96.84	18.49	497.76	96.42
10.21	***307.36***	***96.11***	***11.31***	***306.26***	***95.66***
±3.42	***±162.90***	***±2.43***	***±4.00***	***±163.00***	***±2.83***

(C3) Effects of Operational Mode (P:R)

COD

Raw
mg/L
3850.00
3850.00
5720.00
5720.00
1760.00
1430.00
1430.00
8800.00
8800.00
7695.00
7695.00
5159.09
±2877.44

B-PR1		B-PR2		B-PR3	
mg/L	RE %	mg/L	RE %	mg/L	RE %
720.00	81.30	780.00	79.74	238.00	93.82
870.00	77.40	660.00	82.86	60.00	96.79
630.00	88.99	510.00	91.08	258.00	95.49
1200.00	79.02	660.00	88.46	220.00	96.15
360.00	79.55	180.00	89.77	150.00	91.48
270.00	81.12	180.00	87.41	300.00	79.02
60.00	95.80	120.00	91.61	60.00	95.80
270.00	96.93	210.00	97.61	110.00	98.75
270.00	96.93	170.00	98.07	90.00	98.98
245.00	96.82	240.00	96.88	210.00	97.27
315.00	95.91	225.00	97.08	210.00	97.60
473.64	***88.16***	***357.73***	***90.96***	***173.27***	***94.65***
±339.96	***±8.47***	***±243.41***	***±6.16***	***±83.34***	***±5.61***

BOD

Eff
mg/L
291.00
291.00
196.00
196.00
354.00
241.00
241.00
396.00
396.00
210.30
210.30
274.78
±76.94

B-PR1		B-PR2		B-PR3	
mg/L	RE %	mg/L	RE %	mg/L	RE %
36.42	87.48	16.78	94.23	22.60	92.23
23.91	91.78	16.15	94.45	19.14	93.42
36.00	81.63	34.20	82.55	24.00	87.76
32.40	83.47	28.80	85.31	18.90	90.36
29.85	91.57	24.06	93.20	20.63	94.17
24.97	89.64	21.37	91.13	24.07	90.01
19.97	91.71	18.54	92.31	14.09	94.15
18.90	95.23	23.70	94.02	24.60	93.79
19.80	95.00	19.50	95.08	16.20	95.91
20.25	90.37	18.90	91.01	22.20	89.44
36.00	82.88	21.90	89.59	19.20	90.87
27.13	***89.16***	***22.17***	***91.17***	***20.51***	***92.01***
±7.17	***±4.72***	***±5.40***	***±4.00***	***±3.39***	***±2.50***

NH_3-N

Eff
mg/L
117.16
117.16
159.08
159.08
84.66
35.70
35.70
62.70
62.70
53.40
53.40
85.52
±45.71

B-PR1		B-PR2		B-PR3	
mg/L	RE %	mg/L	RE %	mg/L	RE %
32.00	72.69	27.90	76.19	15.20	87.03
27.76	76.31	24.20	79.34	21.50	81.65
55.08	65.37	27.14	82.94	34.17	78.52
33.66	78.84	20.10	87.36	19.89	87.50
35.24	58.37	26.52	68.67	13.26	84.34
21.42	40.00	15.30	57.14	15.81	55.71
22.20	37.82	18.60	47.90	2.70	92.44
16.80	73.21	17.50	72.09	14.50	76.87
11.45	81.74	16.30	74.00	3.90	93.78
12.90	75.84	9.80	81.65	3.70	93.07
19.40	63.67	18.10	66.10	5.80	89.14
26.17	***65.81***	***20.13***	***72.13***	***13.68***	***83.64***
±12.55	***±14.99***	***±5.70***	***±11.71***	***±9.51***	***±10.87***

TN

Eff
mg/L
209.00
209.00
242.00
242.00
143.00
165.00
165.00
385.00
385.00
213.00
213.00
233.73
±81.03

B-PR1		B-PR2		B-PR3	
mg/L	RE %	mg/L	RE %	mg/L	RE %
69.86	63.00	73.21	56.00	87.08	27.00
58.37	87.00	66.99	69.00	81.34	39.00
66.53	81.00	76.45	57.00	81.40	45.00
75.21	60.00	80.17	48.00	80.17	48.00
62.24	54.00	68.53	45.00	79.02	30.00
78.18	36.00	89.09	18.00	85.45	24.00
65.45	57.00	85.45	24.00	89.09	18.00
86.88	50.50	87.14	49.50	93.51	25.00
91.04	34.50	87.53	48.00	95.58	17.00
88.03	25.50	81.69	39.00	88.97	23.50
82.86	36.50	85.45	31.00	87.79	26.00
74.97	***53.18***	***80.15***	***44.05***	***86.31***	***29.32***
±11.26	***±19.42***	***±7.82***	***±15.07***	***±5.44***	***±10.33***

TS

Eff
mg/L
6280.00
6280.00
6800.00
6800.00
3836.00
6700.00
6700.00
7684.00
7684.00
5900.00
5900.00
6414.91
±1043.92

B-PR1		B-PR2		B-PR3	
mg/L	RE %	mg/L	RE %	mg/L	RE %
2510.00	60.03	2440.00	61.15	2466.00	60.73
2200.00	64.97	2350.00	62.58	2201.00	64.95
2400.00	64.71	2800.00	58.82	2400.00	64.71
2492.00	63.35	2800.00	58.82	2488.00	63.41
2048.00	46.61	1724.00	55.06	2196.00	42.75
1996.00	70.21	2192.00	67.28	1868.00	72.12
1684.00	74.87	2004.00	70.09	2000.00	70.15
1504.00	80.43	2032.00	73.56	2260.00	70.59
1360.00	82.30	1800.00	76.57	1600.00	79.18
1376.00	76.68	1648.00	72.07	1232.00	79.12
1448.00	75.46	1356.00	77.02	1244.00	78.92
1910.73	***69.06***	***2104.18***	***66.64***	***1995.91***	***67.88***
±454.57	***±10.45***	***±465.77***	***±7.74***	***±458.29***	***±10.62***

TSS

Eff
mg/L
1380.00
1380.00
2160.00
2160.00
1850.00
2400.00
2400.00
950.00
950.00
5083.33
5083.33
2345.15
±1451.58

B-PR1		B-PR2		B-PR3	
mg/L	RE %	mg/L	RE %	mg/L	RE %
84.00	93.91	80.00	94.20	89.00	93.55
72.00	94.78	83.00	93.99	81.00	94.13
175.00	91.90	205.00	90.51	145.00	93.29
210.00	90.28	280.00	87.04	200.00	90.74
35.00	98.11	75.00	95.95	45.00	97.57
196.00	91.83	200.00	91.67	96.00	96.00
368.00	84.67	344.00	85.67	328.00	86.33
28.00	97.05	88.00	90.74	44.00	95.37
44.00	95.37	52.00	94.53	8.00	99.16
48.00	99.06	72.00	98.58	40.00	99.21
244.00	95.20	280.00	94.49	152.00	97.01
136.73	***93.83***	***159.91***	***92.49***	***111.64***	***94.76***
±109.98	***±4.07***	***±105.08***	***±3.82***	***±91.62***	***±3.81***

VSS

Eff
mg/L
640.00
640.00
1680.00
1680.00
1190.00
1256.00
1256.00
450.00
450.00
2833.33
2833.33
1355.33
±853.79

B-PR1		B-PR2		B-PR3	
mg/L	RE %	mg/L	RE %	mg/L	RE %
44.00	93.12	44.00	93.12	32.00	95.00
48.00	92.50	40.00	93.75	36.00	94.37
125.00	92.56	140.00	91.67	90.00	94.64
65.00	96.13	60.00	96.43	135.00	91.96
25.00	97.90	40.00	96.64	15.00	98.74
192.00	84.71	144.00	88.54	32.00	97.45
356.00	71.66	304.00	75.80	252.00	79.94
24.00	94.67	76.00	83.11	20.00	95.56
32.00	92.89	36.00	92.00	4.00	99.11
36.00	98.73	44.00	98.45	28.00	99.01
156.00	94.49	144.00	94.92	56.00	98.02
100.27	***91.76***	***97.45***	***91.31***	***63.64***	***94.89***
±102.44	***±7.61***	***±81.71***	***±6.66***	***±72.93***	***±5.47***

COD

Raw
g/m2.batch
336.88
336.88
500.50
500.50
154.00
125.13
125.13
770.00
770.00
673.31
673.31
451.42
±251.77

B-PR1			B-PR2			B-PR3		
g/m2.d		RE %	g/m2.d		RE %	g/m2.d		RE %
Eff. Mass	MRR		Eff. Mass	MRR		Eff. Mass	MRR	
50.72	286.16	84.95	48.66	288.21	85.55	12.54	324.34	96.28
53.74	283.13	84.05	39.67	297.20	88.22	3.44	333.44	98.98
36.88	463.62	92.63	32.53	467.97	93.50	13.73	486.77	97.26
64.47	436.03	87.12	34.59	465.91	93.09	7.78	492.72	98.45
22.40	131.60	85.46	11.25	142.75	92.70	7.42	146.58	95.18
15.07	110.05	87.95	12.84	112.29	89.74	13.57	111.55	89.15
4.22	120.91	96.63	7.31	117.82	94.16	2.11	123.01	98.31
14.06	755.94	98.17	7.41	762.59	99.04	6.21	763.79	99.19
18.10	751.90	97.65	7.36	762.64	99.04	4.74	765.26	99.38
14.88	658.43	97.79	13.92	659.39	97.93	5.92	667.40	99.12
23.21	650.10	96.55	13.41	659.91	98.01	6.73	666.59	99.00
28.89	***422.53***	***91.72***	***20.81***	***430.61***	***93.73***	***7.65***	***443.77***	***97.30***
±19.57	***±253.03***	***±5.84***	***±15.03***	***±254.58***	***±4.55***	***±3.98***	***±252.52***	***±3.02***

BOD

Raw
g/m2.batch
25.46
25.46
17.15
17.15
30.98
21.09
21.09
34.65
34.65
18.40
18.40
24.04
±6.73

B-PR1			B-PR2			B-PR3		
g/m2.d		RE %	g/m2.d		RE %	g/m2.d		RE %
Eff. Mass	MRR		Eff. Mass	MRR		Eff. Mass	MRR	
2.57	22.90	89.93	1.05	24.42	95.89	1.19	24.27	95.32
1.48	23.99	94.20	0.97	24.49	96.19	1.10	24.37	95.69
2.11	15.04	87.71	2.18	14.97	87.28	1.28	15.87	92.56
1.74	15.41	89.85	1.51	15.64	91.20	0.67	16.48	96.10
1.86	29.12	94.00	1.50	29.47	95.15	1.02	29.96	96.71
1.39	19.69	93.39	1.52	19.56	92.77	1.09	20.00	94.84
1.40	19.68	93.35	1.13	19.96	94.65	0.50	20.59	97.65
0.98	33.67	97.16	0.84	33.81	97.59	1.39	33.26	95.99
1.33	33.32	96.17	0.84	33.81	97.56	0.85	33.80	97.54
1.23	17.17	93.32	1.10	17.30	94.04	0.63	17.78	96.60
2.65	15.75	85.59	1.30	17.10	92.91	0.61	17.79	96.66
1.70	***22.34***	***92.24***	***1.27***	***22.78***	***94.11***	***0.94***	***23.11***	***95.97***
±0.54	***±6.95***	***±3.55***	***±0.39***	***±6.97***	***±3.02***	***±0.30***	***±6.61***	***±1.42***

NH_3-N

Raw
g/m2.batch
10.25
10.25
13.92
13.92
7.41
3.12
3.12
5.49
5.49
4.67
4.67
7.48
±4.00

B-PR1			B-PR2			B-PR3		
g/m2.d		RE %	g/m2.d		RE %	g/m2.d		RE %
Eff. Mass	MRR		Eff. Mass	MRR		Eff. Mass	MRR	
2.25	8.00	78.01	1.74	8.51	83.02	0.80	9.45	92.19
1.71	8.54	83.27	1.45	8.80	85.81	1.23	9.02	87.98
3.22	10.69	76.84	1.73	12.19	87.56	1.82	12.10	86.94
1.81	12.11	87.01	1.05	12.87	92.43	0.70	13.22	94.95
2.19	5.22	70.40	1.66	5.75	77.63	0.66	6.75	91.15
1.20	1.93	61.72	1.09	2.03	65.07	0.72	2.41	77.10
1.56	1.56	50.07	1.13	1.99	63.74	0.09	3.03	96.96
0.87	4.61	84.06	0.62	4.87	88.75	0.82	4.67	85.08
0.77	4.72	86.01	0.71	4.78	87.13	0.21	5.28	96.26
0.78	3.89	83.23	0.57	4.10	87.83	0.10	4.57	97.77
1.43	3.24	69.41	1.08	3.59	76.92	0.19	4.49	96.02
1.62	***5.86***	***75.46***	***1.17***	***6.32***	***81.44***	***0.67***	***6.82***	***91.13***
±0.74	***±3.49***	***±11.59***	***±0.43***	***±3.78***	***±9.61***	***±0.53***	***±3.63***	***±6.36***

TN

	B-PR1			B-PR2			B-PR3		
Raw	g/m2.d		RE %	g/m2.d		RE %	g/m2.d		RE %
g/m2.batch	Eff. Mass	MRR		Eff. Mass	MRR		Eff. Mass	MRR	
18.29	4.44	13.85	75.73	3.49	14.79	80.90	1.42	16.87	92.22
18.29	5.37	12.91	70.61	4.15	14.14	77.32	2.24	16.05	87.78
21.18	4.74	16.43	77.61	3.64	17.54	82.83	2.39	18.78	88.69
21.18	3.22	17.95	84.78	2.52	18.66	88.12	1.70	19.48	91.99
12.51	3.36	9.15	73.15	2.81	9.70	77.53	1.48	11.03	88.15
14.44	2.01	12.43	86.08	1.28	13.15	91.11	1.09	13.35	92.48
14.44	4.00	10.43	72.26	1.46	12.98	89.88	0.63	13.80	95.61
33.69	2.63	31.06	92.20	1.75	31.94	94.82	1.41	32.28	95.81
33.69	2.31	31.38	93.14	2.08	31.61	93.83	0.90	32.79	97.34
18.64	1.55	17.09	91.69	2.26	16.38	87.86	0.66	17.98	96.45
18.64	2.69	15.95	85.57	1.85	16.79	90.09	0.83	17.80	95.53
20.45	***3.30***	***17.15***	***82.07***	***2.48***	***17.97***	***86.75***	***1.34***	***19.11***	***92.91***
±7.09	***±1.21***	***±7.48***	***±8.49***	***±0.94***	***±7.26***	***±6.18***	***±0.60***	***±7.11***	***±3.51***

TS

	B-PR1			B-PR2			B-PR3		
Raw	g/m2.d		RE %	g/m2.d		RE %	g/m2.d		RE %
g/m2.batch	Eff. Mass	MRR		Eff. Mass	MRR		Eff. Mass	MRR	
549.50	176.80	372.70	67.83	152.23	397.27	72.30	129.90	419.60	76.36
549.50	135.91	413.60	75.27	141.26	408.24	74.29	126.14	423.36	77.04
595.00	140.49	454.51	76.39	178.61	416.40	69.98	127.68	467.32	78.54
595.00	133.88	461.12	77.50	146.76	448.25	75.34	87.95	507.05	85.22
335.65	127.41	208.24	62.04	107.71	227.94	67.91	108.56	227.09	67.66
586.25	111.43	474.82	80.99	156.32	429.93	73.34	84.50	501.75	85.59
586.25	118.32	467.93	79.82	122.04	464.21	79.18	70.35	515.90	88.00
672.35	78.30	594.05	88.35	71.65	600.70	89.34	127.55	544.80	81.03
672.35	91.15	581.20	86.44	77.96	594.39	88.40	84.28	588.07	87.46
516.25	83.56	432.69	83.81	95.60	420.65	81.48	34.71	481.54	93.28
516.25	106.68	409.57	79.34	80.80	435.45	84.35	39.84	476.41	92.28
561.30	***118.54***	***442.77***	***77.98***	***120.99***	***440.31***	***77.81***	***92.86***	***468.44***	***82.95***
±91.34	***±28.77***	***±103.03***	***±7.71***	***±36.53***	***±99.58***	***±7.29***	***±34.65***	***±93.75***	***±7.66***

TSS

Raw
g/m2.batch
120.75
120.75
189.00
189.00
161.88
210.00
210.00
83.12
83.12
444.79
444.79
205.20
±127.01

B-PR1			B-PR2			B-PR3		
g/m2.d		RE %	g/m2.d		RE %	g/m2.d		RE %
Eff. Mass	MRR		Eff. Mass	MRR		Eff. Mass	MRR	
5.92	114.83	95.10	4.99	115.76	95.87	4.69	116.06	96.12
4.45	116.30	96.32	4.99	115.76	95.87	4.64	116.11	96.16
10.24	178.76	94.58	13.08	175.92	93.08	7.71	181.29	95.92
11.28	177.72	94.03	14.68	174.32	92.24	7.07	181.93	96.26
2.18	159.70	98.65	4.69	157.19	97.11	2.22	159.65	98.63
10.94	199.06	94.79	14.26	195.74	93.21	4.34	205.66	97.93
25.86	184.14	87.69	20.95	189.05	90.02	11.54	198.46	94.51
1.46	81.67	98.25	3.10	80.02	96.27	2.48	80.64	97.01
2.95	80.18	96.45	2.25	80.87	97.29	0.42	82.70	99.49
2.91	441.88	99.34	4.18	440.61	99.06	1.13	443.66	99.75
17.98	426.81	95.96	16.68	428.11	96.25	4.87	439.92	98.91
8.74	***196.46***	***95.56***	***9.44***	***195.76***	***95.12***	***4.65***	***200.55***	***97.34***
±7.63	***±124.60***	***±3.14***	***±6.56***	***±124.79***	***±2.65***	***±3.22***	***±127.03***	***±1.71***

VSS

Raw
g/m2.batch
56.00
56.00
147.00
147.00
104.13
109.90
109.90
39.38
39.38
247.92
247.92
118.59
±74.71

B-PR1			B-PR2			B-PR3		
g/m2.d		RE %	g/m2.d		RE %	g/m2.d		RE %
Eff. Mass	MRR		Eff. Mass	MRR		Eff. Mass	MRR	
3.10	52.90	94.47	2.75	53.25	95.10	1.69	54.31	96.99
2.97	53.03	94.70	2.40	53.60	95.71	2.06	53.94	96.32
7.32	139.68	95.02	8.93	138.07	93.93	4.79	142.21	96.74
3.49	143.51	97.62	3.14	143.86	97.86	4.77	142.23	96.75
1.56	102.57	98.51	2.50	101.63	97.60	0.74	103.38	99.29
10.72	99.18	90.25	10.27	99.63	90.66	1.45	108.45	98.68
25.01	84.89	77.24	18.51	91.39	83.15	8.86	101.04	91.93
1.25	38.13	96.83	2.68	36.70	93.19	1.13	38.25	97.13
2.14	37.23	94.55	1.56	37.82	96.04	0.21	39.16	99.46
2.19	245.73	99.12	2.55	245.36	98.97	0.79	247.13	99.68
11.49	236.42	95.36	8.58	239.34	96.54	1.79	246.12	99.28
6.48	***112.12***	***93.97***	***5.81***	***112.79***	***94.43***	***2.57***	***116.02***	***97.48***
±7.13	***±73.57***	***±6.05***	***±5.26***	***±73.76***	***±4.41***	***±2.58***	***±74.53***	***±2.24***

Appendix D : Second Stage wetlands (System related)

(D1) Effect of Plant Presence

COD

Eff
mg/L
1890.00
7326.00
8734.00
7744.00
2050.00
1692.00
7050.00
3344.00
5270.00
3500.00
4860.00
±2693.03

B-P		B-UP	
mg/L	RE %	mg/L	RE %
210.00	88.89	140.00	92.59
160.00	97.82	70.00	99.04
180.00	97.94	140.00	98.40
180.00	97.68	170.00	97.80
370.00	81.95	445.00	78.29
220.00	87.00	380.00	77.54
220.00	96.88	120.00	98.30
120.00	96.41	270.00	91.93
200.00	96.20	350.00	93.36
130.00	96.29	190.00	94.57
199.00	***93.71***	***227.50***	***92.18***
±69.51	***±5.65***	***±126.39***	***±7.95***

Eff
g/m2.d
165.38
641.03
764.23
677.60
179.38
148.05
616.88
292.60
461.13
306.25
425.25
±235.64

B-P			B-UP		
g/m2.d		RE %	g/m2.d		RE %
Eff. Mass	MRR		Eff. Mass	MRR	
16.00	149.37	90.32	11.22	154.15	93.21
10.96	630.06	98.29	4.92	636.10	99.23
11.72	752.51	98.47	10.03	754.19	98.69
13.43	664.17	98.02	12.97	664.63	98.09
26.90	152.47	85.00	35.28	144.10	80.33
17.25	130.80	88.35	30.69	117.36	79.27
16.23	600.65	97.37	9.57	607.31	98.45
7.78	284.82	97.34	18.45	274.15	93.69
14.39	446.74	96.88	27.44	433.69	94.05
11.16	295.09	96.36	14.33	291.92	95.32
14.58	***410.67***	***94.64***	***17.49***	***407.76***	***93.03***
±5.21	***±237.84***	***±4.87***	***±10.20***	***±242.23***	***±7.32***

BOD

Eff
mg/L
258.00
473.40
209.20
163.80
216.40
222.00
210.60
211.20
238.50
270.00
247.31
±84.65

B-P		B-UP	
mg/L	RE %	mg/L	RE %
14.25	94.48	17.55	93.20
17.40	96.32	0.30	99.94
12.20	94.17	9.40	95.51
1.95	98.81	5.07	96.90
4.62	97.87	5.40	97.50
4.92	97.78	8.88	96.00
4.14	98.03	7.50	96.44
12.06	94.29	13.62	93.55
6.42	97.31	17.58	92.63
0.96	99.64	1.50	99.44
7.89	***96.87***	***8.68***	***96.11***
±5.64	***±1.97***	***±6.05***	***±2.49***

Eff
g/m2.d
22.58
41.42
18.31
14.33
18.94
19.43
18.43
18.48
20.87
23.63
21.64
±7.41

B-P			B-UP		
g/m2.d		RE %	g/m2.d		RE %
Eff. Mass	MRR		Eff. Mass	MRR	
1.09	21.49	95.19	1.41	21.17	93.77
1.19	40.23	97.12	0.02	41.40	99.95
0.79	17.51	95.66	0.67	17.63	96.32
0.15	14.19	98.98	0.39	13.95	97.30
0.34	18.60	98.23	0.43	18.51	97.74
0.39	19.04	98.01	0.72	18.71	96.31
0.31	18.12	98.34	0.60	17.83	96.76
0.78	17.70	95.77	0.93	17.55	94.96
0.46	20.41	97.79	1.38	19.49	93.40
0.08	23.54	99.65	0.11	23.51	99.52
0.56	***21.08***	***97.47***	***0.67***	***20.98***	***96.60***
±0.38	***±7.18***	***±1.50***	***±0.47***	***±7.60***	***±2.18***

NH_3-N

Eff
mg/L
69.90
105.06
132.60
197.96

B-P		B-UP	
mg/L	RE %	mg/L	RE %
9.70	86.12	24.30	65.24
8.30	92.10	10.60	89.91
1.30	99.02	8.20	93.82
0.20	99.90	3.60	98.18

68.34
156.91
150.52
140.58
151.23
106.50
127.96
±40.66

0.96	98.60	12.80	81.27
6.90	95.60	32.70	79.16
0.00	100.00	40.40	73.16
3.50	97.51	55.10	60.81
0.00	100.00	55.80	63.10
3.10	97.09	57.30	46.20
3.40	***96.59***	***30.08***	***75.09***
±3.65	***±4.42***	***±21.17***	***±16.47***

Eff
g/m2.d
6.12
9.19
11.60
17.32
5.98
13.73
13.17
12.30
13.23
9.32
11.20
±3.56

B-P			B-UP		
g/m2.d		RE %	g/m2.d		RE %
Eff. Mass	MRR		Eff. Mass	MRR	
0.74	5.38	87.91	1.95	4.17	68.16
0.57	8.62	93.81	0.75	8.45	91.89
0.08	11.52	99.27	0.59	11.01	94.94
0.01	17.31	99.91	0.27	17.05	98.41
0.07	5.91	98.83	1.01	4.97	83.03
0.54	13.19	96.06	2.64	11.09	80.76
0.00	13.17	100.00	3.22	9.95	75.55
0.23	12.07	98.16	3.77	8.54	69.39
0.00	13.23	100.00	4.37	8.86	66.94
0.27	9.05	97.14	4.32	5.00	53.62
0.25	***10.95***	***97.11***	***2.29***	***8.91***	***78.27***
±0.27	***±3.69***	***±3.80***	***±1.59***	***±3.80***	***±14.23***

TN

Eff
mg/L
165.00
294.50
285.20
266.60
260.40
384.00
628.00
320.00
298.00
190.00
309.17
±128.00

B-P		B-UP	
mg/L	RE %	mg/L	RE %
43.00	73.94	59.00	64.24
31.00	89.47	40.00	86.42
26.00	90.88	38.00	86.68
13.00	95.12	22.00	91.75
37.00	85.79	35.00	86.56
48.00	87.50	59.00	84.64
28.00	95.54	41.00	93.47
79.00	75.31	91.00	71.56
64.00	78.52	76.00	74.50
78.00	58.95	95.00	50.00
44.70	***83.10***	***55.60***	***78.98***
±22.49	***±11.43***	***±24.86***	***±13.78***

Eff
g/m2.d
14.44
25.77
24.96
23.33
22.79
33.60
54.95
28.00
26.08
16.63
27.06
±11.20

B-P			B-UP		
g/m2.d		RE %	g/m2.d		RE %
Eff. Mass	MRR		Eff. Mass	MRR	
3.28	11.16	77.30	4.73	9.71	67.25
2.12	23.64	91.76	2.81	22.95	89.08
1.69	23.26	93.22	2.72	22.23	89.09
0.97	22.36	95.84	1.68	21.65	92.80
2.69	20.09	88.19	2.77	20.01	87.82
3.76	29.84	88.80	4.76	28.84	85.82
2.07	52.88	96.24	3.27	51.68	94.05
5.12	22.88	81.71	6.22	21.78	77.79
4.60	21.47	82.35	5.96	20.12	77.15
6.70	9.93	59.73	7.17	9.46	56.90
3.30	***23.75***	***85.51***	***4.21***	***22.84***	***81.78***
±1.77	***±11.82***	***±11.03***	***±1.82***	***±11.73***	***±12.01***

NO$_3$-N

Eff
mg/L
1.50
58.30
65.40
4.10

B-P	B-UP
mg/L	
4.60	0.40
4.20	0.80
15.10	3.60
6.50	1.00

63.00
69.30
39.40
29.70
6.00
1.10
33.78
±28.92

33.10	2.24
6.10	4.20
10.10	0.50
31.40	0.00
36.40	1.80
71.20	3.90
21.87	***1.84***
±21.45	***±1.57***

Raw
kg TS/m2.yr
0.13
5.10
5.72
0.36
5.51
6.06
3.45
2.60
0.53
0.10
2.96
±2.53

B-P	B-UP
kg TS/m2.yr	
0.35	0.03
0.29	0.06
0.98	0.26
0.49	0.08
2.41	0.18
0.48	0.34
0.75	0.04
2.04	0.00
2.62	0.14
6.11	0.29
1.65	***0.14***
±1.80	***±0.12***

TS

Eff
mg/L
6,216.00
10,586.00
7,400.00
6,543.00
14,000.00
18,800.00
6,800.00
4,800.00
5,960.00
4,308.00
8541.30
±4613.21

B-P		B-UP	
mg/L	RE %	mg/L	RE %
2,688.00	56.76	2,896.00	53.41
2,556.00	75.85	3,348.00	68.37
1,888.00	74.49	2,476.00	66.54
2,704.00	58.67	3,112.00	52.44
2,996.00	78.60	2,244.00	83.97
1,852.00	90.15	1,640.00	91.28
2,348.00	65.47	2,032.00	70.12
2,304.00	52.00	2,032.00	57.67
2,772.00	53.49	2,144.00	64.03
1,612.00	62.58	1,660.00	61.47
2372.00	***66.81***	***2358.40***	***66.93***
±457.14	***±12.51***	***±589.36***	***±12.53***

	B-P			B-UP		
Eff	g/m2.d		RE %	g/m2.d		RE %
g/m2.d	Eff. Mass	MRR		Eff. Mass	MRR	
543.90	204.86	339.04	62.34	232.11	311.79	57.32
926.28	175.12	751.16	81.09	235.53	690.74	74.57
647.50	122.91	524.59	81.02	177.44	470.06	72.60
572.51	201.82	370.69	64.75	237.45	335.07	58.53
1,225.00	217.85	1,007.15	82.22	177.89	1,047.11	85.48
1,645.00	145.20	1,499.80	91.17	132.45	1,512.55	91.95
595.00	173.19	421.81	70.89	161.98	433.02	72.78
420.00	149.39	270.61	64.43	138.86	281.14	66.94
521.50	199.38	322.12	61.77	168.09	353.41	67.77
376.95	138.38	238.57	63.29	125.21	251.74	66.78
747.36	***172.81***	***574.55***	***72.30***	***178.70***	***568.66***	***71.47***
±403.66	***±32.65***	***±403.63***	***±10.65***	***±42.84***	***±409.99***	***±10.81***

TSS

Eff	B-P		B-UP	
mg/L	mg/L	RE %	mg/L	RE %
1,560.00	112.00	92.82	192.00	87.69
5,560.00	156.00	97.19	148.00	97.34
2,720.00	10.00	99.63	12.00	99.56
2,165.00	115.00	94.69	170.00	92.15
3,225.00	150.00	95.35	220.00	93.18
1,872.00	44.00	97.65	136.00	92.74
2,732.00	148.00	94.58	164.00	94.00
1,884.00	56.00	97.03	235.00	87.53
2,152.00	84.00	96.10	208.00	90.33
2,788.00	44.00	98.42	60.00	97.85
2665.80	***91.90***	***96.35***	***154.50***	***93.24***
±1139.70	***±51.87***	***±2.04***	***±70.70***	***±4.11***

Eff
g/m2.d
136.50
486.50
238.00
189.44
282.19
163.80
239.05
164.85
188.30
243.95
233.26
±99.72

B-P			B-UP		
g/m2.d		RE %	g/m2.d		RE %
Eff. Mass	MRR		Eff. Mass	MRR	
8.54	127.96	93.75	15.39	121.11	88.73
10.69	475.81	97.80	10.41	476.09	97.86
0.65	237.35	99.73	0.86	237.14	99.64
8.58	180.85	95.47	12.97	176.47	93.15
10.91	271.28	96.13	17.44	264.75	93.82
3.45	160.35	97.89	10.98	152.82	93.29
10.92	228.13	95.43	13.07	225.98	94.53
3.63	161.22	97.80	16.06	148.79	90.26
6.04	182.26	96.79	16.31	171.99	91.34
3.78	240.17	98.45	4.53	239.42	98.14
6.72	***226.54***	***96.92***	***11.80***	***221.46***	***94.08***
±3.71	***±98.24***	***±1.76***	***±5.39***	***±101.01***	***±3.56***

VSS

Eff
mg/L
1,350.00
5,372.00
2,275.00
955.00
2,885.00
1,144.00
2,096.00
1,516.00
1,284.00
2,184.00
2106.10
±1297.60

B-P		B-UP	
mg/L	RE %	mg/L	RE %
60.00	95.56	72.00	94.67
84.00	98.44	80.00	98.51
6.00	99.74	4.00	99.82
75.00	92.15	80.00	91.62
75.00	97.40	90.00	96.88
28.00	97.55	40.00	96.50
36.00	98.28	-92.00	104.39
32.00	97.89	20.00	98.68
44.00	96.57	88.00	93.15
8.00	99.63	24.00	98.90
44.80	***97.32***	***40.60***	***97.31***
±27.84	***±2.21***	***±56.17***	***±3.65***

Eff
g/m2.d
118.13
470.05
199.06
83.56
252.44
100.10
183.40
132.65
112.35
191.10
184.28
±113.54

B-P			B-UP		
g/m2.d		RE %	g/m2.d		RE %
Eff. Mass	MRR		Eff. Mass	MRR	
4.57	113.55	96.13	5.77	112.35	95.11
5.76	464.29	98.78	5.63	464.42	98.80
0.39	198.67	99.80	0.29	198.78	99.86
5.60	77.96	93.30	6.10	77.46	92.70
5.45	246.98	97.84	7.13	245.30	97.17
2.20	97.90	97.81	3.23	96.87	96.77
2.66	180.74	98.55	-7.33	190.73	104.00
2.07	130.58	98.44	1.37	131.28	98.97
3.16	109.19	97.18	6.90	105.45	93.86
0.69	190.41	99.64	1.81	189.29	99.05
3.26	***181.03***	***97.75***	***3.09***	***181.19***	***97.63***
±2.00	***±112.93***	***±1.91***	***±4.40***	***±113.35***	***±3.28***

(D2) Effect of Plant Type

COD

Eff
mg/L
3000.00
3120.00
1500.00
2580.00
1680.00
2610.00
3360.00
1180.00
1050.00
2160.00
2224.00
±834.24

B-Phrag		B-Costus	
mg/L	RE %	mg/L	RE %
160.00	94.67	170.00	94.33
130.00	95.83	150.00	95.19
100.00	93.33	110.00	92.67
60.00	97.67	90.00	96.51
170.00	89.88	220.00	86.90
45.00	98.28	120.00	95.40
20.00	99.40	90.00	97.32
110.00	90.68	140.00	88.14
105.00	90.00	125.00	88.10
150.00	93.06	170.00	92.13
105.00	***94.28***	***138.50***	***92.67***
±50.33	***±3.48***	***±40.56***	***±3.77***

Eff
g/m2.d
262.50
273.00
131.25
225.75
147.00
228.38
294.00
103.25
91.88
189.00
194.60
±73.00

B-Phrag			B-Costus		
g/m2.d		RE %	g/m2.d		RE %
Eff. Mass	MRR		Eff. Mass	MRR	
10.91	251.59	95.85	12.14	250.36	95.38
10.07	262.93	96.31	11.14	261.86	95.92
7.18	124.08	94.53	8.32	122.93	93.66
3.98	221.77	98.24	7.02	218.73	96.89
12.11	134.89	91.76	17.88	129.12	87.83
2.70	225.68	98.82	8.84	219.53	96.13
1.53	292.47	99.48	7.23	286.77	97.54
7.58	95.67	92.65	9.63	93.62	90.67
7.43	84.44	91.91	9.64	82.24	89.51
9.78	179.22	94.83	12.33	176.67	93.48
7.33	***187.27***	***95.44***	***10.42***	***184.18***	***93.70***
±3.58	***±74.06***	***±2.82***	***±3.21***	***±73.65***	***±3.33***

BOD

Eff
mg/L
182.70
296.10
351.60
246.60
221.10
184.80
183.00
215.10
223.50
315.80
242.03
±59.79

B-Phrag		B-Costus	
mg/L	RE %	mg/L	RE %
5.55	96.96	6.15	96.63
6.45	97.82	5.40	98.18
3.90	98.89	9.15	97.40
2.70	98.91	4.05	98.36
0.24	99.89	0.30	99.86
0.72	99.61	12.72	93.12
0.36	99.80	4.26	97.67
4.59	97.87	2.73	98.73
5.55	97.52	6.12	97.26
2.94	99.07	3.42	98.92
3.30	***98.63***	***5.43***	***97.61***
±2.29	***±1.03***	***±3.48***	***±1.83***

Eff
g/m2.d
15.99
25.91
30.77
21.58
19.35
16.17
16.01
18.82
19.56
27.63
21.18
±5.23

B-Phrag			B-Costus		
g/m2.d		RE %	g/m2.d		RE %
Eff. Mass	MRR		Eff. Mass	MRR	
0.38	15.61	97.63	0.44	15.55	97.25
0.50	25.41	98.07	0.40	25.51	98.45
0.28	30.49	99.09	0.69	30.07	97.75
0.18	21.40	99.17	0.32	21.26	98.54
0.02	19.33	99.91	0.02	19.32	99.87
0.04	16.13	99.73	0.94	15.23	94.20
0.03	15.98	99.83	0.34	15.67	97.86
0.32	18.50	98.32	0.19	18.63	99.00
0.39	19.16	97.99	0.47	19.08	97.59
0.19	27.44	99.31	0.25	27.38	99.10
0.23	***20.95***	***98.91***	***0.41***	***20.77***	***97.96***
±0.17	***±5.18***	***±0.84***	***±0.26***	***±5.23***	***±1.54***

NH$_3$-N

Eff
mg/L
39.60
23.40
76.80
42.60

B-Phrag		B-Costus	
mg/L	RE %	mg/L	RE %
0.60	98.48	4.10	89.65
0.70	97.01	0.90	96.15
1.30	98.31	2.00	97.40
1.20	97.18	2.10	95.07

108.50
43.20
40.20
62.40
47.40
68.40
55.25
±24.44

0.50	99.54	5.10	95.30
2.10	95.14	2.70	93.75
1.20	97.01	1.00	97.51
0.20	99.68	0.50	99.20
0.30	99.37	2.00	95.78
0.20	99.71	0.70	98.98
0.83	***98.14***	***2.11***	***95.88***
±0.61	***±1.52***	***±1.51***	***±2.79***

Eff
g/m2.d
3.47
2.05
6.72
3.73
9.49
3.78
3.52
5.46
4.15
5.99
4.84
±2.14

B-Phrag			B-Costus		
g/m2.d		RE %	g/m2.d		RE %
Eff. Mass	MRR		Eff. Mass	MRR	
0.04	3.42	98.82	0.29	3.17	91.55
0.05	1.99	97.35	0.07	1.98	96.73
0.09	6.63	98.61	0.15	6.57	97.75
0.08	3.65	97.86	0.16	3.56	95.60
0.04	9.46	99.62	0.41	9.08	95.63
0.13	3.65	96.67	0.20	3.58	94.74
0.09	3.43	97.39	0.08	3.44	97.72
0.01	5.45	99.75	0.03	5.43	99.37
0.02	4.13	99.49	0.15	3.99	96.28
0.01	5.97	99.78	0.05	5.93	99.15
0.06	***4.78***	***98.53***	***0.16***	***4.67***	***96.45***
±0.04	***±2.15***	***±1.15***	***±0.12***	***±2.08***	***±2.30***

TN

Eff
mg/L
300.00
270.00
366.00
324.00
234.00
216.00
264.00
132.00
120.00
216.00
244.20
±78.23

B-Phrag		B-Costus	
mg/L	RE %	mg/L	RE %
63.00	79.00	57.00	81.00
89.00	67.04	113.00	58.15
88.00	75.96	127.00	65.30
79.00	75.62	118.00	63.58
21.00	91.03	32.00	86.32
76.00	64.81	89.00	58.80
61.00	76.89	72.00	72.73
42.00	68.18	40.00	69.70
37.00	69.17	41.00	65.83
32.00	85.19	36.00	83.33
58.80	***75.29***	***72.50***	***70.47***
±24.48	***±8.36***	***±36.84***	***±10.09***

Eff
g/m2.d
26.25
23.63
32.03
28.35
20.48
18.90
23.10
11.55
10.50
18.90
21.37
±6.85

B-Phrag			B-Costus		
g/m2.d		RE %	g/m2.d		RE %
Eff. Mass	MRR		Eff. Mass	MRR	
4.29	21.96	83.64	4.07	22.18	84.50
6.89	16.73	70.83	8.39	15.23	64.47
6.31	25.71	80.28	9.60	22.42	70.02
5.24	23.11	81.52	9.21	19.14	67.51
1.50	18.98	92.69	2.60	17.87	87.30
4.56	14.34	75.90	6.56	12.34	65.31
4.66	18.44	79.81	5.78	17.32	74.96
2.90	8.65	74.93	2.75	8.80	76.18
2.62	7.88	75.06	3.16	7.34	69.90
2.09	16.81	88.96	2.61	16.29	86.18
4.11	***17.26***	***80.36***	***5.47***	***15.89***	***74.63***
±1.79	***±5.80***	***±6.72***	***±2.83***	***±5.11***	***±8.68***

TS

Eff
mg/L
3824.00
7476.00
3276.00
4152.00

B-Phrag		B-Costus	
mg/L	RE %	mg/L	RE %
2272.00	40.59	2280.00	40.38
2904.00	61.16	2604.00	65.17
1052.00	67.89	1068.00	67.40
1216.00	70.71	1224.00	70.52

4980.00
3596.00
3380.00
3980.00
2716.00
3216.00
4059.60
±1349.78

1848.00	62.89	1460.00	70.68
1320.00	63.29	1096.00	69.52
1368.00	59.53	1164.00	65.56
1548.00	61.11	1296.00	67.44
1128.00	58.47	1024.00	62.30
1332.00	58.58	1124.00	65.05
1598.80	***60.42***	***1434.00***	***64.40***
±586.02	***±8.02***	***±551.13***	***±8.85***

Eff
g/m2.d
334.60
654.15
286.65
363.30
435.75
314.65
295.75
348.25
237.65
281.40
355.22
±118.11

B-Phrag			B-Costus		
g/m2.d		RE %	g/m2.d		RE %
Eff. Mass	MRR		Eff. Mass	MRR	
154.87	179.73	53.72	162.79	171.81	51.35
224.88	429.27	65.62	193.44	460.71	70.43
75.48	211.17	73.67	80.74	205.91	71.83
80.65	282.65	77.80	95.53	267.77	73.70
131.62	304.13	69.79	118.68	317.07	72.76
79.12	235.53	74.86	80.75	233.90	74.34
104.62	191.13	64.63	93.50	202.25	68.39
106.73	241.52	69.35	89.13	259.12	74.41
79.85	157.80	66.40	78.94	158.71	66.78
86.83	194.57	69.14	81.53	199.87	71.03
112.47	***242.75***	***68.50***	***107.50***	***247.71***	***69.50***
±47.27	***±79.84***	***±6.69***	***±39.67***	***±88.62***	***±6.85***

TSS

Eff
mg/L
1550.00
2270.00
1080.00
3710.00
2066.67
2400.00
2300.00
3350.00
1640.00
3300.00
2366.67
±856.22

B-Phrag		B-Costus	
mg/L	RE %	mg/L	RE %
84.00	94.58	72.00	95.35
100.00	95.59	84.00	96.30
35.00	96.76	45.00	95.83
65.00	98.25	90.00	97.57
90.00	95.65	145.00	92.98
10.00	99.58	70.00	97.08
5.00	99.78	40.00	98.26
8.00	99.76	68.00	97.97
44.00	97.32	64.00	96.10
16.00	99.52	68.00	97.94
45.70	***97.68***	***74.60***	***96.54***
±36.67	***±1.98***	***±29.03***	***±1.60***

Eff
g/m2.d
135.63
198.62
94.50
324.63
180.83
210.00
201.25
293.13
143.50
288.75
207.08
±74.92

B-Phrag			B-Costus		
g/m2.d		RE %	g/m2.d		RE %
Eff. Mass	MRR		Eff. Mass	MRR	
5.73	129.90	95.78	5.14	130.48	96.21
7.74	190.88	96.10	6.24	192.38	96.86
2.51	91.99	97.34	3.40	91.10	96.40
4.31	320.31	98.67	7.02	317.60	97.84
6.41	174.42	96.46	11.79	169.05	93.48
0.60	209.40	99.71	5.16	204.84	97.54
0.38	200.87	99.81	3.21	198.04	98.40
0.55	292.57	99.81	4.68	288.45	98.40
3.11	140.39	97.83	4.93	138.57	96.56
1.04	287.71	99.64	4.93	283.82	98.29
3.24	***203.84***	***98.12***	***5.65***	***201.43***	***97.00***
±2.70	***±75.68***	***±1.63***	***±2.44***	***±74.66***	***±1.50***

VSS

Eff
mg/L
950.00
830.00
970.00
3300.00
1866.67
1620.00
1440.00
3020.00
1200.00
2950.00
1814.67
±939.12

B-Phrag		B-Costus	
mg/L	RE %	mg/L	RE %
48.00	94.95	32.00	96.63
24.00	97.11	16.00	98.07
30.00	96.91	25.00	97.42
50.00	98.48	35.00	98.94
65.00	96.52	70.00	96.25
5.00	99.69	35.00	97.84
0.00	100.00	35.00	97.57
4.00	99.87	40.00	98.68
36.00	97.00	48.00	96.00
12.00	99.59	40.00	98.64
27.40	***98.01***	***37.60***	***97.60***
±22.31	***±1.75***	***±14.32***	***±1.04***

Eff
g/m2.d
83.13
72.62
84.88
288.75
163.33
141.75
126.00
264.25
105.00
258.12
158.78
±82.17

B-Phrag			B-Costus		
g/m2.d		RE %	g/m2.d		RE %
Eff. Mass	MRR		Eff. Mass	MRR	
3.27	79.85	96.06	2.28	80.84	97.25
1.86	70.77	97.44	1.19	71.44	98.36
2.15	82.72	97.46	1.89	82.99	97.77
3.32	285.43	98.85	2.73	286.02	99.05
4.63	158.70	97.17	5.69	157.64	96.52
0.30	141.45	99.79	2.58	139.17	98.18
0.00	126.00	100.00	2.81	123.19	97.77
0.28	263.97	99.90	2.75	261.50	98.96
2.55	102.45	97.57	3.70	101.30	96.48
0.78	257.34	99.70	2.90	255.22	98.88
1.91	***156.87***	***98.39***	***2.85***	***155.93***	***97.92***
±1.56	***±82.39***	***±1.42***	***±1.20***	***±81.90***	***±0.95***

(D3) Effects of Substrate Type

Batch Feeding

COD

Eff
mg/L
3850.00
3850.00
5720.00
5720.00
1760.00
1430.00
1430.00
8800.00
8800.00
7695.00
7695.00
5159.09
±2877.44

B-PKS (I)		B-SD (I)	
mg/L	RE %	mg/L	RE %
238.00	93.82	70.00	98.18
60.00	96.79	180.00	95.32
258.00	95.49	174.00	96.96
220.00	96.15	60.00	98.95
150.00	91.48	100.00	94.32
300.00	79.02	240.00	83.22
60.00	95.80	42.00	97.06
110.00	98.75	60.00	99.32
90.00	98.98	125.00	98.58
210.00	97.27	200.00	97.40
210.00	97.60	150.00	98.05
173.27	***94.65***	***127.36***	***96.12***
±83.34	***±5.61***	***±66.20***	***±4.54***

Eff
g/m2.batch
336.88
336.88
500.50
500.50
154.00
125.13
125.13
770.00
770.00
673.31
673.31
451.42
±251.77

B-PKS (I)			B-SD (I)		
g/m2.batch		RE %	g/m2.batch		RE %
Eff. Mass	MRR		Eff. Mass	MRR	
12.54	324.34	96.28	3.83	333.05	98.86
3.44	333.44	98.98	10.80	326.07	96.79
13.73	486.77	97.26	8.98	491.52	98.21
7.78	492.72	98.45	2.38	498.12	99.52
7.42	146.58	95.18	4.45	149.56	97.11
13.57	111.55	89.15	11.42	113.70	90.87
2.11	123.01	98.31	1.69	123.43	98.65
6.21	763.79	99.19	3.46	766.54	99.55
4.74	765.26	99.38	6.98	763.02	99.09
5.92	667.40	99.12	6.46	666.86	99.04
6.73	666.59	99.00	5.01	668.30	99.26
7.65	***443.77***	***97.30***	***5.95***	***445.47***	***97.90***
±3.98	***±252.52***	***±3.02***	***±3.30***	***±252.14***	***±2.51***

BOD

Eff
mg/L
291.00
291.00
196.00
196.00
354.00
241.00
241.00
396.00
396.00
210.30
210.30
274.78
±76.94

B-PKS (I)		B-SD (I)	
mg/L	RE %	mg/L	RE %
22.60	92.23	7.52	97.42
19.14	93.42	9.73	96.66
24.00	87.76	16.80	91.43
18.90	90.36	8.10	95.87
20.63	94.17	10.56	97.02
24.07	90.01	12.31	94.89
14.09	94.15	8.72	96.38
24.60	93.79	6.60	98.33
16.20	95.91	12.60	96.82
22.20	89.44	15.90	92.44
19.20	90.87	12.60	94.01
20.51	***92.01***	***11.04***	***95.57***
±3.39	***±2.50***	***±3.34***	***±2.16***

Eff
g/m2.batch
25.46
25.46
17.15
17.15
30.98
21.09
21.09
34.65
34.65
18.40
18.40
24.04
±6.73

B-PKS (I)			B-SD (I)		
g/m2.batch		RE %	g/m2.batch		RE %
Eff. Mass	MRR		Eff. Mass	MRR	
1.19	24.27	95.32	0.41	25.05	98.38
1.10	24.37	95.69	0.58	24.88	97.71
1.28	15.87	92.56	0.87	16.28	94.94
0.67	16.48	96.10	0.32	16.83	98.13
1.02	29.96	96.71	0.47	30.51	98.48
1.09	20.00	94.84	0.59	20.50	97.22
0.50	20.59	97.65	0.35	20.74	98.34
1.39	33.26	95.99	0.38	34.27	98.90
0.85	33.80	97.54	0.70	33.95	97.97
0.63	17.78	96.60	0.51	17.89	97.21
0.61	17.79	96.66	0.42	17.98	97.71
0.94	***23.11***	***95.97***	***0.51***	***23.53***	***97.73***
±0.30	***±6.61***	***±1.42***	***±0.17***	***±6.74***	***±1.06***

NH_3-N

Eff
mg/L
117.16
117.16

B-PKS (I)		B-SD (I)	
mg/L	RE %	mg/L	RE %
15.20	87.03	13.30	88.65
21.50	81.65	20.00	82.93

159.08
159.08
84.66
35.70
35.70
62.70
62.70
53.40
53.40
85.52
±45.71

34.17	78.52	33.15	79.16
19.89	87.50	20.91	86.86
13.26	84.34	7.14	91.57
15.81	55.71	1.02	97.14
2.70	92.44	1.20	96.64
14.50	76.87	1.20	98.09
3.90	93.78	1.50	97.61
3.70	93.07	0.90	98.31
5.80	89.14	2.30	95.69
13.68	***83.64***	***9.33***	***92.06***
±9.51	***±10.87***	***±11.04***	***±6.74***

Eff
g/m2.batch
10.25
10.25
13.92
13.92
7.41
3.12
3.12
5.49
5.49
4.67
4.67
7.48
±4.00

B-PKS (I)			B-SD (I)		
g/m2.batch		RE %	g/m2.batch		RE %
Eff. Mass	MRR		Eff. Mass	MRR	
0.80	9.45	92.19	0.73	9.52	92.91
1.23	9.02	87.98	1.20	9.05	88.29
1.82	12.10	86.94	1.71	12.21	87.70
0.70	13.22	94.95	0.83	13.09	94.05
0.66	6.75	91.15	0.32	7.09	95.72
0.72	2.41	77.10	0.05	3.08	98.45
0.09	3.03	96.96	0.05	3.08	98.45
0.82	4.67	85.08	0.07	5.42	98.74
0.21	5.28	96.26	0.08	5.40	98.47
0.10	4.57	97.77	0.03	4.64	99.38
0.19	4.49	96.02	0.08	4.60	98.35
0.67	***6.82***	***91.13***	***0.47***	***7.02***	***95.50***
±0.53	***±3.63***	***±6.36***	***±0.57***	***±3.49***	***±4.26***

TN

Eff
mg/L
209.00
209.00
242.00
242.00
143.00
165.00
165.00
385.00

B-PKS (I)		B-SD (I)	
mg/L	RE %	mg/L	RE %
87.08	27.00	79.90	42.00
81.34	39.00	77.03	48.00
81.40	45.00	73.97	63.00
80.17	48.00	77.69	54.00
79.02	30.00	74.83	36.00
85.45	24.00	76.36	39.00
89.09	18.00	63.64	60.00
93.51	25.00	92.21	30.00

385.00	
213.00	
213.00	
233.73	
±81.03	

95.58	17.00	83.12	65.00
88.97	23.50	63.15	78.50
87.79	26.00	69.25	65.50
86.31	***29.32***	***75.56***	***52.82***
±5.44	***±10.33***	***±8.36***	***±15.03***

Eff
g/m2.batch
18.29
18.29
21.18
21.18
12.51
14.44
14.44
33.69
33.69
18.64
18.64
20.45
±7.09

B-PKS (I)			B-SD (I)		
g/m2.batch		RE %	g/m2.batch		RE %
Eff. Mass	MRR		Eff. Mass	MRR	
1.42	16.87	92.22	2.30	15.99	87.44
2.24	16.05	87.78	2.88	15.41	84.24
2.39	18.78	88.69	3.25	17.92	84.64
1.70	19.48	91.99	2.14	19.03	89.89
1.48	11.03	88.15	1.60	10.91	87.21
1.09	13.35	92.48	1.86	12.58	87.14
0.63	13.80	95.61	2.42	12.02	83.27
1.41	32.28	95.81	1.73	31.96	94.86
0.90	32.79	97.34	3.63	30.06	89.23
0.66	17.98	96.45	2.53	16.10	86.40
0.83	17.80	95.53	2.19	16.45	88.25
1.34	***19.11***	***92.91***	***2.41***	***18.04***	***87.51***
±0.60	***±7.11***	***±3.51***	***±0.63***	***±6.88***	***±3.19***

TS

Eff
mg/L
6280.00
6280.00
6800.00
6800.00
3836.00
6700.00
6700.00
7684.00
7684.00
5900.00
5900.00
6414.91
±1043.92

B-PKS (I)		B-SD (I)	
mg/L	RE %	mg/L	RE %
2466.00	60.73	2299.00	63.39
2201.00	64.95	2359.00	62.44
2400.00	64.71	2000.00	70.59
2488.00	63.41	2628.00	61.35
2196.00	42.75	2000.00	47.86
1868.00	72.12	1760.00	73.73
2000.00	70.15	1600.00	76.12
2260.00	70.59	1600.00	79.18
1600.00	79.18	1520.00	80.22
1232.00	79.12	1200.00	79.66
1244.00	78.92	1048.00	82.24
1995.91	***67.88***	***1819.45***	***70.62***
±458.29	***±10.62***	***±490.76***	***±10.70***

Eff
g/m2.batch
549.50
549.50
595.00
595.00
335.65
586.25
586.25
672.35
672.35
516.25
516.25
561.30
±91.34

B-PKS (I)			B-SD (I)		
g/m2.batch		RE %	g/m2.batch		RE %
Eff. Mass	MRR		Eff. Mass	MRR	
129.90	419.60	76.36	125.73	423.77	77.12
126.14	423.36	77.04	141.60	407.90	74.23
127.68	467.32	78.54	103.25	491.75	82.65
87.95	507.05	85.22	104.17	490.83	82.49
108.56	227.09	67.66	88.90	246.75	73.51
84.50	501.75	85.59	83.78	502.47	85.71
70.35	515.90	88.00	64.40	521.85	89.01
127.55	544.80	81.03	92.26	580.09	86.28
84.28	588.07	87.46	84.85	587.50	87.38
34.71	481.54	93.28	38.75	477.51	92.49
39.84	476.41	92.28	35.03	481.22	93.21
92.86	***468.44***	***82.95***	***87.52***	***473.79***	***84.01***
±34.65	***±93.75***	***±7.66***	***±32.59***	***±92.97***	***±6.77***

TSS

Eff
mg/L
1380.00
1380.00
2160.00
2160.00
1850.00
2400.00
2400.00
950.00
950.00
5083.33
5083.33
2345.15
±1451.58

B-PKS (I)		B-SD (I)	
mg/L	RE %	mg/L	RE %
89.00	93.55	77.00	94.42
81.00	94.13	62.00	95.51
145.00	93.29	120.00	94.44
200.00	90.74	30.00	98.61
45.00	97.57	30.00	98.38
96.00	96.00	12.00	99.50
328.00	86.33	272.00	88.67
44.00	95.37	32.00	96.63
8.00	99.16	3.20	99.66
40.00	99.21	48.00	99.06
152.00	97.01	56.00	98.90
111.64	***94.76***	***67.47***	***96.71***
±91.62	***±3.81***	***±75.16***	***±3.31***

	B-PKS (I)			B-SD (I)		
Eff	g/m2.batch		RE %	g/m2.batch		RE %
g/m2.batch	Eff. Mass	MRR		Eff. Mass	MRR	
120.75	4.69	116.06	96.12	4.21	116.54	96.51
120.75	4.64	116.11	96.16	3.72	117.03	96.92
189.00	7.71	181.29	95.92	6.20	182.81	96.72
189.00	7.07	181.93	96.26	1.19	187.81	99.37
161.88	2.22	159.65	98.63	1.33	160.54	99.18
210.00	4.34	205.66	97.93	0.57	209.43	99.73
210.00	11.54	198.46	94.51	10.95	199.05	94.79
83.12	2.48	80.64	97.01	1.85	81.28	97.78
83.12	0.42	82.70	99.49	0.18	82.95	99.79
444.79	1.13	443.66	99.75	1.55	443.24	99.65
444.79	4.87	439.92	98.91	1.87	442.92	99.58
205.20	***4.65***	***200.55***	***97.34***	***3.06***	***202.15***	***98.18***
±127.01	***±3.22***	***±127.03***	***±1.71***	***±3.16***	***±127.22***	***±1.72***

VSS

Eff
mg/L
640.00
640.00
1680.00
1680.00
1190.00
1256.00
1256.00
450.00
450.00
2833.33
2833.33
1355.33
±853.79

B-PKS (I)		B-SD (I)	
mg/L	RE %	mg/L	RE %
32.00	95.00	20.00	96.88
36.00	94.37	12.00	98.12
90.00	94.64	45.00	97.32
135.00	91.96	10.00	99.40
15.00	98.74	5.00	99.58
32.00	97.45	4.00	99.68
252.00	79.94	216.00	82.80
20.00	95.56	16.00	96.44
4.00	99.11	0.00	100.00
28.00	99.01	12.00	99.58
56.00	98.02	16.00	99.44
63.64	***94.89***	***32.36***	***97.20***
±72.93	***±5.47***	***±62.05***	***±4.94***

	B-PKS (I)			B-SD (I)		
Eff	g/m2.batch		RE %	g/m2.batch		RE %
g/m2.batch	Eff. Mass	MRR		Eff. Mass	MRR	
56.00	1.69	54.31	96.99	1.09	54.91	98.05
56.00	2.06	53.94	96.32	0.72	55.28	98.71
147.00	4.79	142.21	96.74	2.32	144.68	98.42
147.00	4.77	142.23	96.75	0.40	146.60	99.73
104.13	0.74	103.38	99.29	0.22	103.90	99.79
109.90	1.45	108.45	98.68	0.19	109.71	99.83
109.90	8.86	101.04	91.93	8.69	101.21	92.09
39.38	1.13	38.25	97.13	0.92	38.45	97.66
39.38	0.21	39.16	99.46	0.00	39.38	100.00
247.92	0.79	247.13	99.68	0.39	247.53	99.84
247.92	1.79	246.12	99.28	0.53	247.38	99.78
118.59	***2.57***	***116.02***	***97.48***	***1.41***	***117.18***	***98.54***
±74.71	***±2.58***	***±74.53***	***±2.24***	***±2.50***	***±74.84***	***±2.29***

Intermittent Feeding

COD

Eff
mg/L
1890.00
7326.00
8734.00
7744.00
2050.00
1692.00
7050.00
3344.00
5270.00
3500.00
4860.00
±2693.03

B-PKS (II)		B-SD (II)	
mg/L	RE %	mg/L	RE %
210.00	88.89	180.00	90.48
160.00	97.82	110.00	98.50
180.00	97.94	150.00	98.28
180.00	97.68	140.00	98.19
370.00	81.95	260.00	87.32
220.00	87.00	200.00	88.18
220.00	96.88	80.00	98.87
120.00	96.41	80.00	97.61
200.00	96.20	140.00	97.34
130.00	96.29	110.00	96.86
199.00	***93.71***	***145.00***	***95.16***
±69.51	***±5.65***	***±56.22***	***±4.59***

Eff
g/m2.d
165.38
641.03
764.23
677.60
179.38
148.05
616.88
292.60
461.13
306.25
425.25
±235.64

B-PKS (II)			B-SD (II)		
g/m2.d		RE %	g/m2.d		RE %
Eff. Mass	MRR		Eff. Mass	MRR	
16.00	149.37	90.32	13.69	151.69	91.72
10.96	630.06	98.29	7.35	633.67	98.85
11.72	752.51	98.47	9.57	754.66	98.75
13.43	664.17	98.02	10.54	667.07	98.45
26.90	152.47	85.00	18.97	160.40	89.42
17.25	130.80	88.35	14.72	133.33	90.06
16.23	600.65	97.37	5.90	610.97	99.04
7.78	284.82	97.34	5.17	287.43	98.23
14.39	446.74	96.88	10.46	450.66	97.73
11.16	295.09	96.36	7.90	298.35	97.42
14.58	***410.67***	***94.64***	***10.43***	***414.82***	***95.97***
±5.21	***±237.84***	***±4.87***	***±4.30***	***±237.99***	***±3.91***

BOD

Eff
mg/L
258.00
473.40
209.20
163.80
216.40
222.00
210.60
211.20
238.50
270.00
247.31

B-PKS (II)		B-SD (II)	
mg/L	RE %	mg/L	RE %
14.25	94.48	5.55	97.85
17.40	96.32	6.00	98.73
12.20	94.17	5.20	97.51
1.95	98.81	0.78	99.52
4.62	97.87	3.96	98.17
4.92	97.78	2.28	98.97
4.14	98.03	4.20	98.01
12.06	94.29	4.50	97.87
6.42	97.31	5.40	97.74
0.96	99.64	0.66	99.76
7.89	***96.87***	***3.85***	***98.41***

Eff
g/m2.d
22.58
41.42
18.31
14.33
18.94

B-PKS (II)			B-SD (II)		
g/m2.d		RE %	g/m2.d		RE %
Eff. Mass	MRR		Eff. Mass	MRR	
1.09	21.49	95.19	0.42	22.15	98.13
1.19	40.23	97.12	0.40	41.02	99.03
0.79	17.51	95.66	0.33	17.97	98.19
0.15	14.19	98.98	0.06	14.27	99.59

19.43
18.43
18.48
20.87
23.63
21.64
±7.41

0.34	18.60	98.23	0.29	18.65	98.47
0.39	19.04	98.01	0.17	19.26	99.14
0.31	18.12	98.34	0.31	18.12	98.32
0.78	17.70	95.77	0.29	18.19	98.43
0.46	20.41	97.79	0.40	20.47	98.07
0.08	23.54	99.65	0.05	23.58	99.80
0.56	***21.08***	***97.47***	***0.27***	***21.37***	***98.72***
±0.38	***±7.18***	***±1.50***	***±0.14***	***±7.36***	***±0.63***

NH$_3$-N

Eff
mg/L
69.90
105.06
132.60
197.96
68.34
156.91
150.52
140.58
151.23
106.50
±40.66

B-PKS (II)		B-SD (II)	
mg/L	RE %	mg/L	RE %
9.70	86.12	0.30	99.57
8.30	92.10	0.40	99.62
1.30	99.02	2.60	98.04
0.20	99.90	0.30	99.85
0.96	98.60	0.00	100.00
6.90	95.60	1.60	98.98
0.00	100.00	0.00	100.00
3.50	97.51	1.20	99.15
0.00	100.00	0.00	100.00
3.10	97.09	2.80	97.37
±3.65	***±4.42***	***±1.08***	***±0.90***

Eff
g/m2.d
6.12
9.19
11.60
17.32
5.98
13.73
13.17
12.30
13.23
9.32
11.20
±3.56

B-PKS (II)			B-SD (II)		
g/m2.d		RE %	g/m2.d		RE %
Eff. Mass	MRR		Eff. Mass	MRR	
0.74	5.38	87.91	0.02	6.09	99.63
0.57	8.62	93.81	0.03	9.17	99.71
0.08	11.52	99.27	0.17	11.44	98.57
0.01	17.31	99.91	0.02	17.30	99.87
0.07	5.91	98.83	0.00	5.98	100.00
0.54	13.19	96.06	0.12	13.61	99.14
0.00	13.17	100.00	0.00	13.17	100.00
0.23	12.07	98.16	0.08	12.22	99.37
0.00	13.23	100.00	0.00	13.23	100.00
0.27	9.05	97.14	0.20	9.12	97.84
0.25	***10.95***	***97.11***	***0.06***	***11.13***	***99.41***
±0.27	***±3.69***	***±3.80***	***±0.07***	***±3.56***	***±0.72***

TN

Eff
mg/L
165.00
294.50
285.20
266.60
260.40
384.00
628.00
320.00
298.00
190.00
309.17
±128.00

B-PKS (II)		B-SD (II)	
mg/L	RE %	mg/L	RE %
43.00	73.94	122.00	26.06
31.00	89.47	62.00	78.95
26.00	90.88	73.00	74.40
13.00	95.12	53.00	80.12
37.00	85.79	73.00	71.97
48.00	87.50	96.00	75.00
28.00	95.54	101.00	83.92
79.00	75.31	126.00	60.63
64.00	78.52	101.00	66.11
78.00	58.95	142.00	25.26
44.70	***83.10***	***94.90***	***64.24***
±22.49	***±11.43***	***±29.43***	***±21.42***

Eff
g/m2.d
14.44
25.77
24.96
23.33

B-PKS (II)			B-SD (II)		
g/m2.d		RE %	g/m2.d		RE %
Eff. Mass	MRR		Eff. Mass	MRR	
3.28	11.16	77.30	9.28	5.16	35.75
2.12	23.64	91.76	4.14	21.62	83.92
1.69	23.26	93.22	4.66	20.30	81.34

22.79
33.60
54.95
28.00
26.08
16.63
27.06
±11.20

0.97	22.36	95.84	3.99	19.34	82.90
2.69	20.09	88.19	5.33	17.46	76.62
3.76	29.84	88.80	7.06	26.54	78.98
2.07	52.88	96.24	7.45	47.50	86.44
5.12	22.88	81.71	8.15	19.85	70.90
4.60	21.47	82.35	7.55	18.53	71.06
6.70	9.93	59.73	10.20	6.42	38.64
3.30	***23.75***	***85.51***	***6.78***	***20.27***	***70.66***
±1.77	***±11.82***	***±11.03***	***±2.17***	***±11.62***	***±18.37***

TS

Eff
mg/L
6,216.00
10,586.00
7,400.00
6,543.00
14,000.00
18,800.00
6,800.00
4,800.00
5,960.00
4,308.00
8541.30
±4613.21

B-PKS (II)		B-SD (II)	
mg/L	RE %	mg/L	RE %
2,688.00	56.76	3,920.00	36.94
2,556.00	75.85	2,988.00	71.77
1,888.00	74.49	2,516.00	66.00
2,704.00	58.67	2,968.00	54.64
2,996.00	78.60	2,744.00	80.40
1,852.00	90.15	2,872.00	84.72
2,348.00	65.47	3,252.00	52.18
2,304.00	52.00	2,972.00	38.08
2,772.00	53.49	3,744.00	37.18
1,612.00	62.58	2,892.00	32.87
2372.00	***66.81***	***3086.80***	***55.48***
±457.14	***±12.51***	***±436.89***	***±19.31***

Eff
g/m2.d
543.90
926.28
647.50
572.51
1,225.00
1,645.00
595.00
420.00
521.50
376.95
747.36
±403.66

B-PKS (II)			B-SD (II)		
g/m2.d		RE %	g/m2.d		RE %
Eff. Mass	MRR		Eff. Mass	MRR	
204.86	339.04	62.34	298.07	245.83	45.20
175.12	751.16	81.09	199.75	726.53	78.44
122.91	524.59	81.02	160.49	487.01	75.21
201.82	370.69	64.75	223.34	349.17	60.99
217.85	1,007.15	82.22	200.24	1,024.76	83.65
145.20	1,499.80	91.17	211.34	1,433.66	87.15
173.19	421.81	70.89	239.88	355.12	59.68
149.39	270.61	64.43	192.18	227.82	54.24
199.38	322.12	61.77	279.77	241.73	46.35
138.38	238.57	63.29	207.75	169.20	44.89
172.81	***574.55***	***72.30***	***221.28***	***526.08***	***63.58***
±32.65	***±403.63***	***±10.65***	***±41.36***	***±415.04***	***±16.36***

TSS

Eff
mg/L
1,560.00
5,560.00
2,720.00
2,165.00
3,225.00
1,872.00
2,732.00
1,884.00
2,152.00
2,788.00
2665.80
±1139.70

B-PKS (II)		B-SD (II)	
mg/L	RE %	mg/L	RE %
112.00	92.82	68.00	95.64
156.00	97.19	84.00	98.49
10.00	99.63	8.00	99.71
115.00	94.69	145.00	93.30
150.00	95.35	80.00	97.52
44.00	97.65	48.00	97.44
148.00	94.58	136.00	95.02
56.00	97.03	84.00	95.54
84.00	96.10	76.00	96.47
44.00	98.42	36.00	98.71
91.90	***96.35***	***76.50***	***96.78***
±51.87	***±2.04***	***±41.60***	***±1.95***

Eff
g/m2.d
136.50
486.50
238.00

B-PKS (II)			B-SD (II)		
g/m2.d		RE %	g/m2.d		RE %
Eff. Mass	MRR		Eff. Mass	MRR	
8.54	127.96	93.75	5.17	131.33	96.21
10.69	475.81	97.80	5.62	480.88	98.85
0.65	237.35	99.73	0.51	237.49	99.79

189.44	8.58	180.85	95.47	10.91	178.53	94.24
282.19	10.91	271.28	96.13	5.84	276.35	97.93
163.80	3.45	160.35	97.89	3.53	160.27	97.84
239.05	10.92	228.13	95.43	10.03	229.02	95.80
164.85	3.63	161.22	97.80	5.43	159.42	96.71
188.30	6.04	182.26	96.79	5.68	182.62	96.98
243.95	3.78	240.17	98.45	2.59	241.36	98.94
233.26	***6.72***	***226.54***	***96.92***	***5.53***	***227.73***	***97.33***
±99.72	***±3.71***	***±98.24***	***±1.76***	***±3.11***	***±99.83***	***±1.67***

VSS

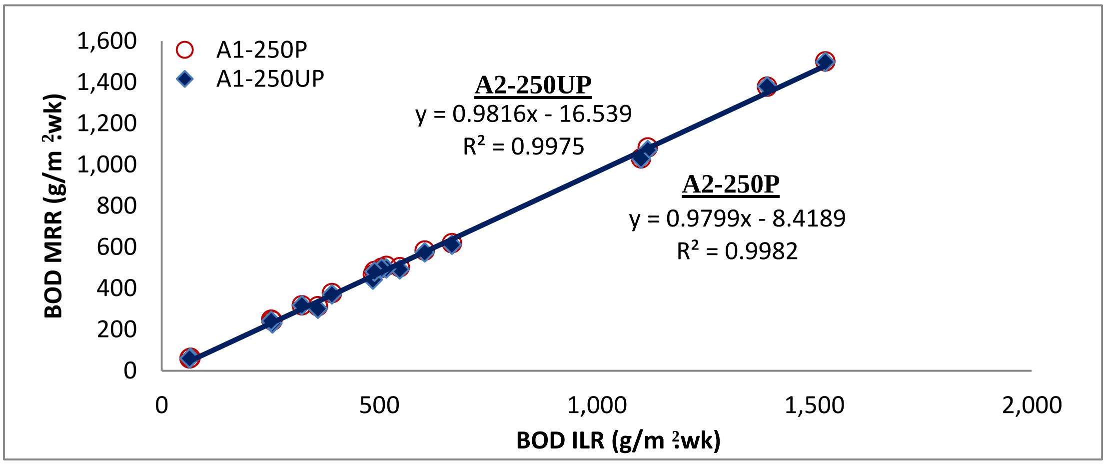
Eff	B-PKS (II)		B-SD (II)	
mg/L	mg/L	RE %	mg/L	RE %
1,350.00	60.00	95.56	48.00	96.44
5,372.00	84.00	98.44	56.00	98.96
2,275.00	6.00	99.74	4.00	99.82
955.00	75.00	92.15	65.00	93.19
2,885.00	75.00	97.40	60.00	97.92
1,144.00	28.00	97.55	32.00	97.20
2,096.00	36.00	98.28	20.00	99.05
1,516.00	32.00	97.89	28.00	98.15
1,284.00	44.00	96.57	32.00	97.51
2,184.00	8.00	99.63	16.00	99.27
2106.10	***44.80***	***97.32***	***36.10***	***97.75***
±1297.60	***±27.84***	***±2.21***	***±20.38***	***±1.91***

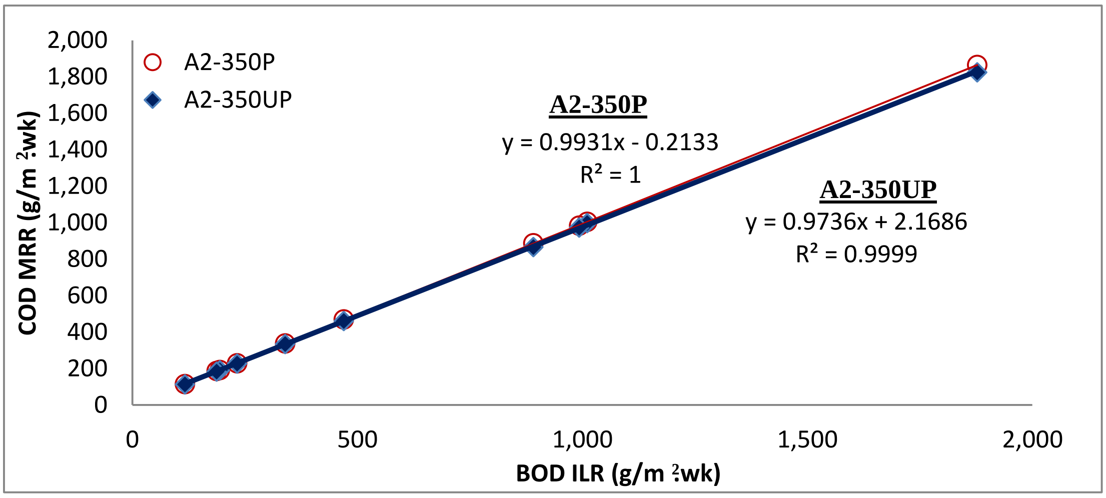
Eff
g/m2.d
118.13
470.05
199.06
83.56
252.44
100.10
183.40
132.65
112.35
191.10
184.28
±113.54

B-PKS (II)			B-SD (II)		
g/m2.d		RE %	g/m2.d		RE %
Eff. Mass	MRR		Eff. Mass	MRR	
4.57	113.55	96.13	3.65	114.48	96.91
5.76	464.29	98.78	3.74	466.31	99.20
0.39	198.67	99.80	0.26	198.81	99.87
5.60	77.96	93.30	4.89	78.67	94.15
5.45	246.98	97.84	4.38	248.06	98.27
2.20	97.90	97.81	2.35	97.75	97.65
2.66	180.74	98.55	1.48	181.92	99.20
2.07	130.58	98.44	1.81	130.84	98.64
3.16	109.19	97.18	2.39	109.96	97.87
0.69	190.41	99.64	1.15	189.95	99.40
3.26	***181.03***	***97.75***	***2.61***	***181.68***	***98.12***
±2.00	***±112.93***	***±1.91***	***±1.50***	***±113.37***	***±1.66***

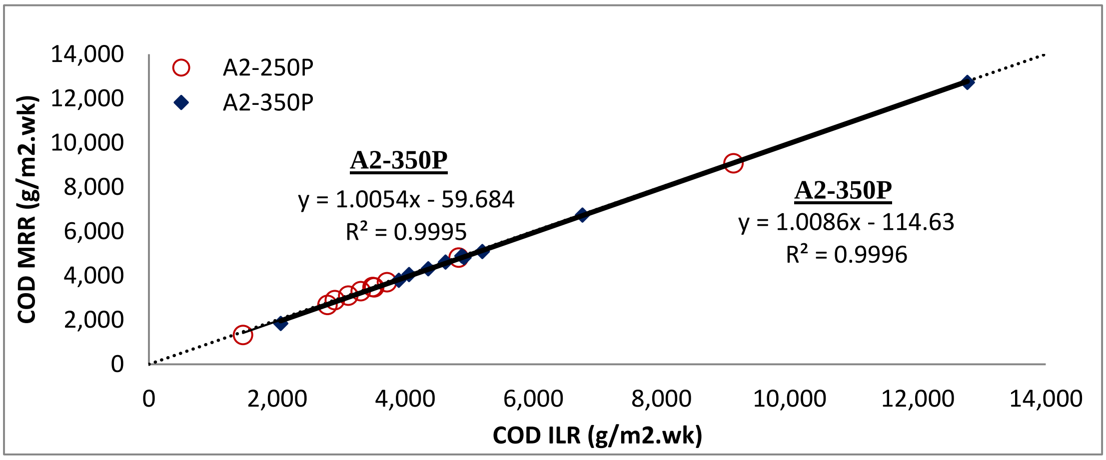
Appendix E: Regression Graphs

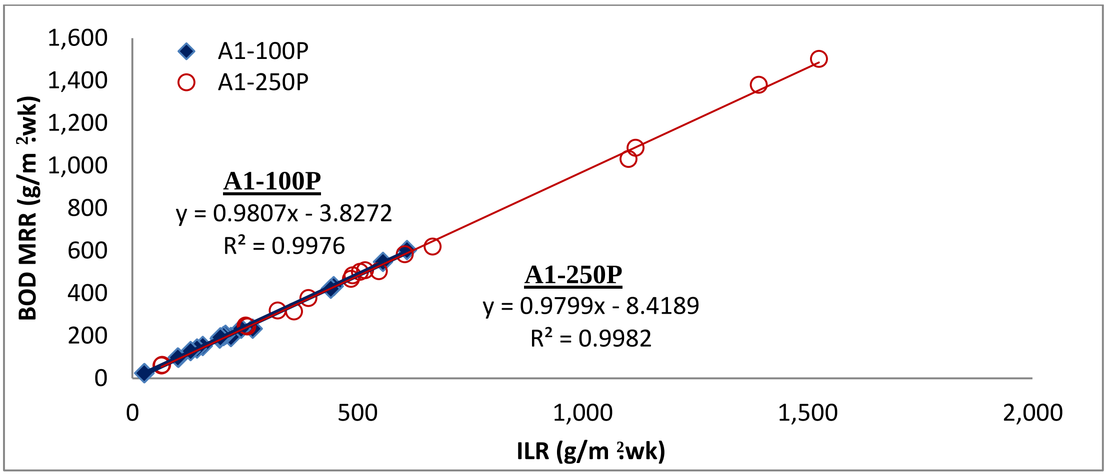
Effects of Plant Presence (First Stage)

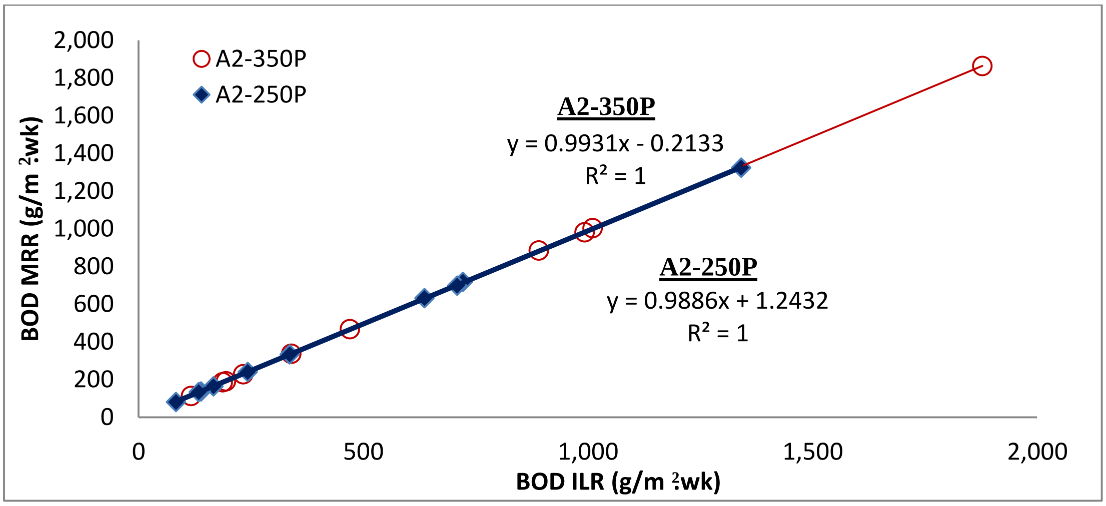




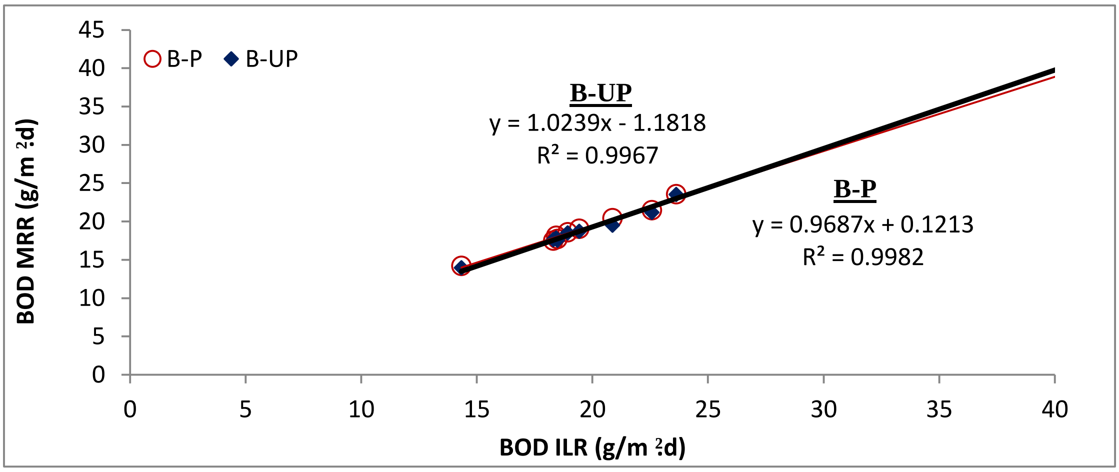
Effects of SLR (First Stage)

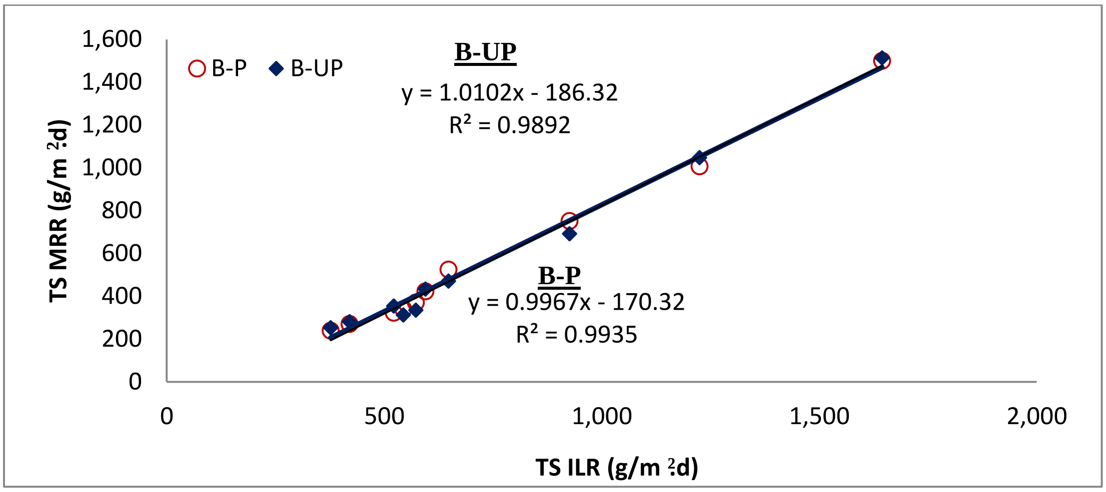


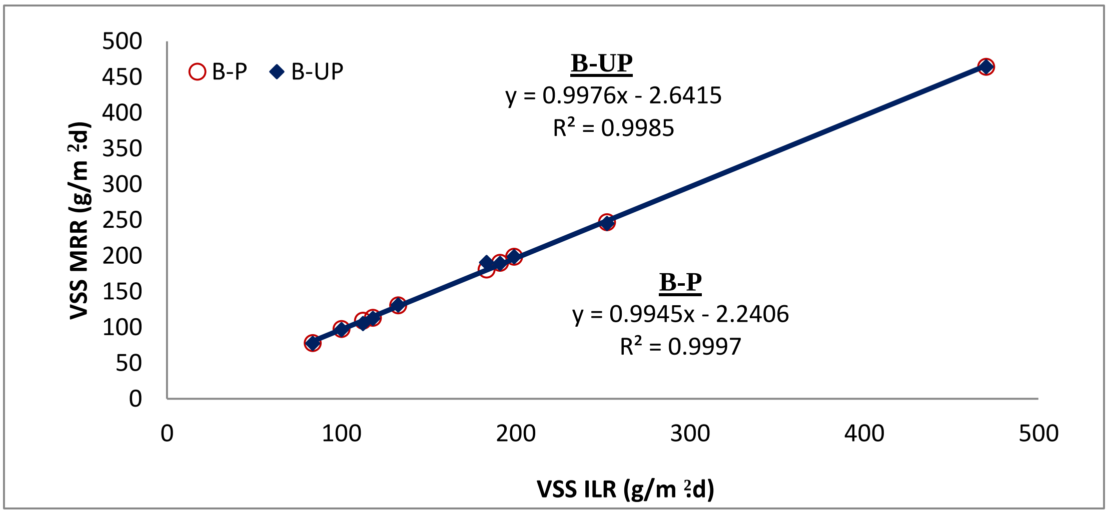




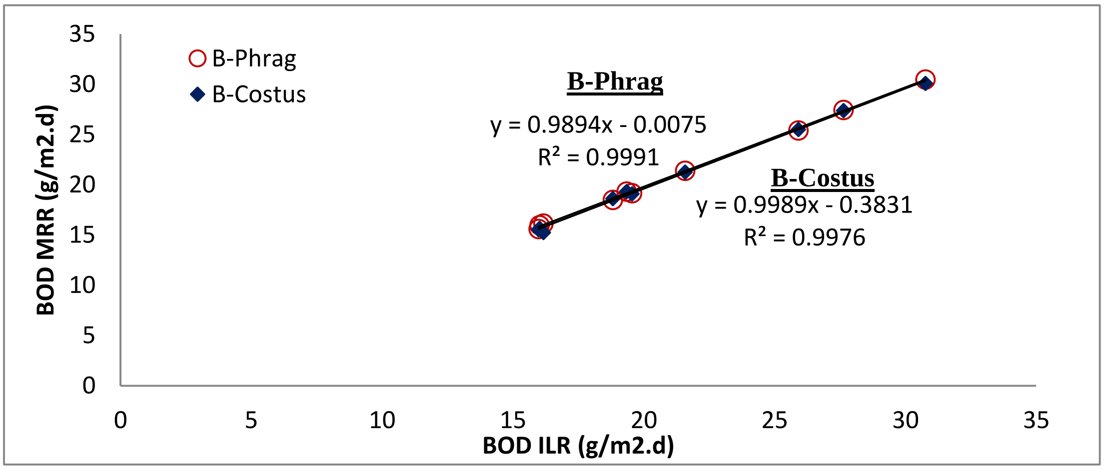
Effect of Plant Presence (2nd stage)



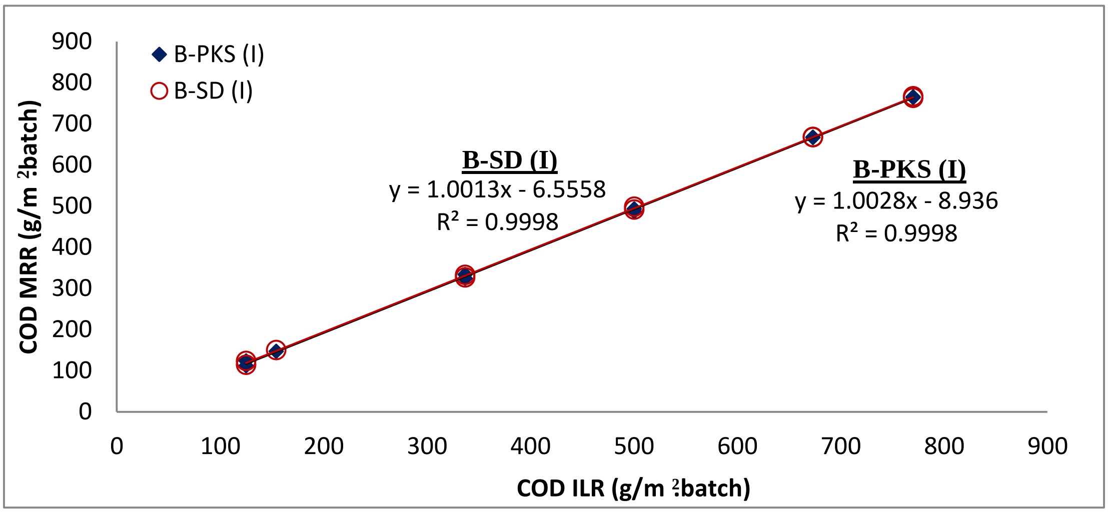


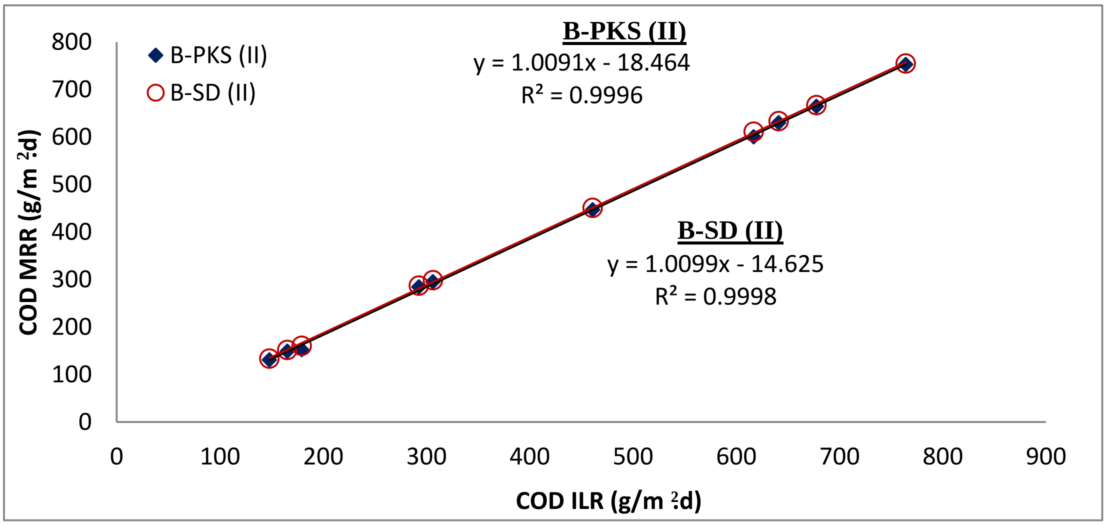


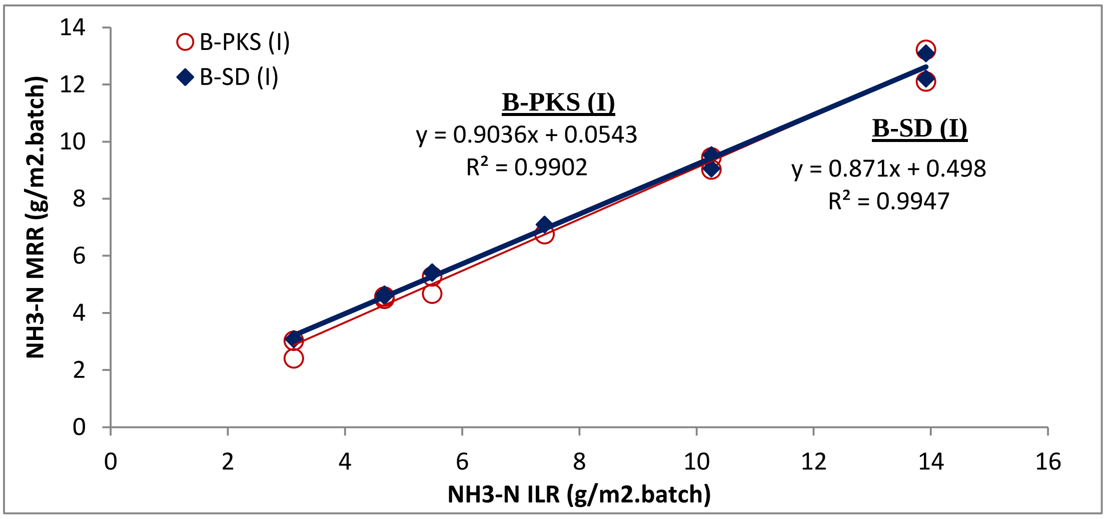
Effect of Plant Type

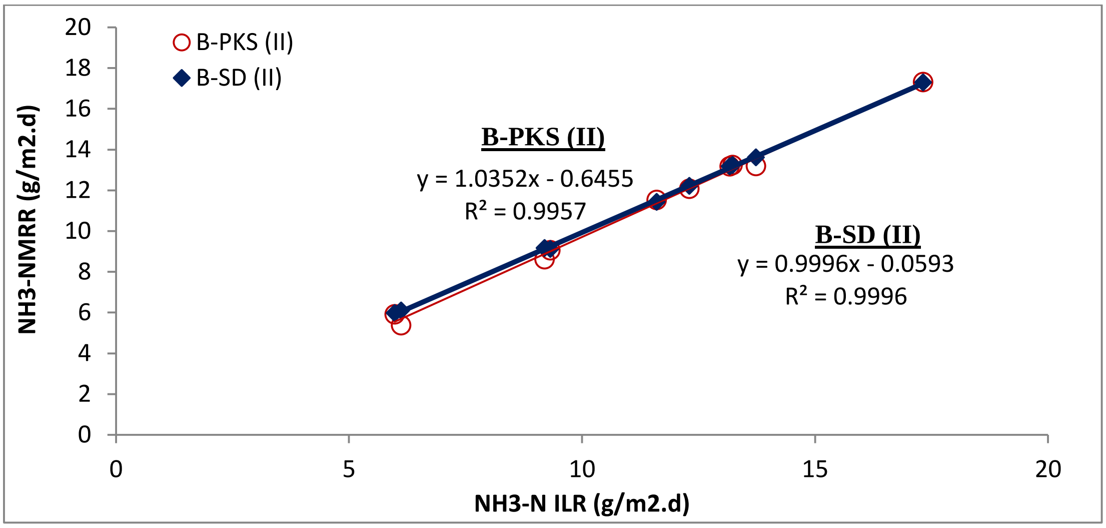


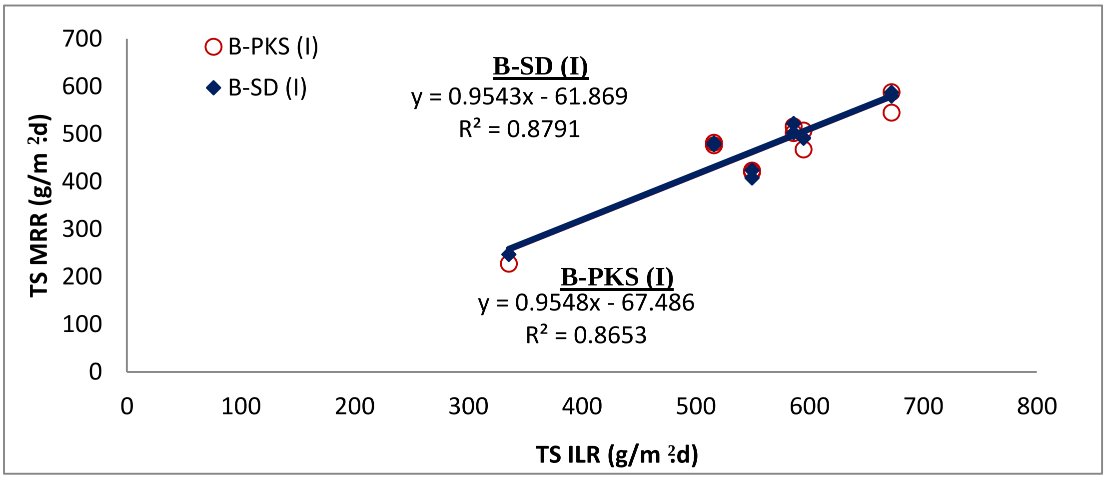
Effect of Substrate Type

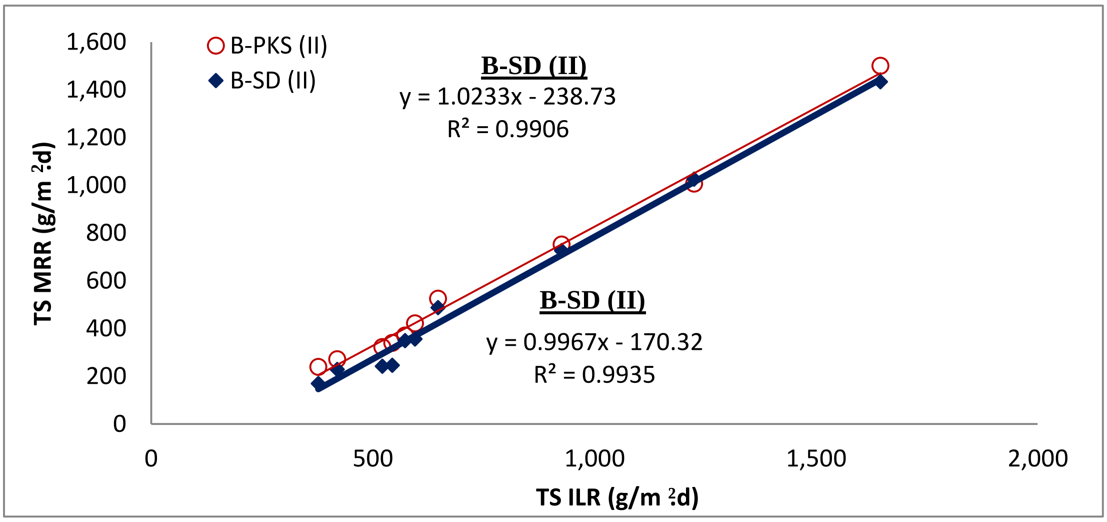


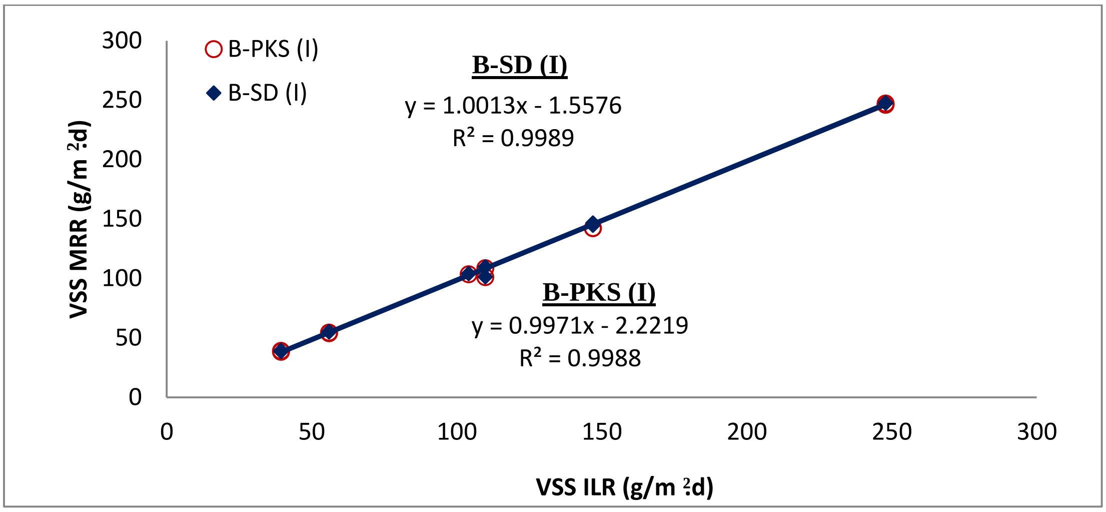


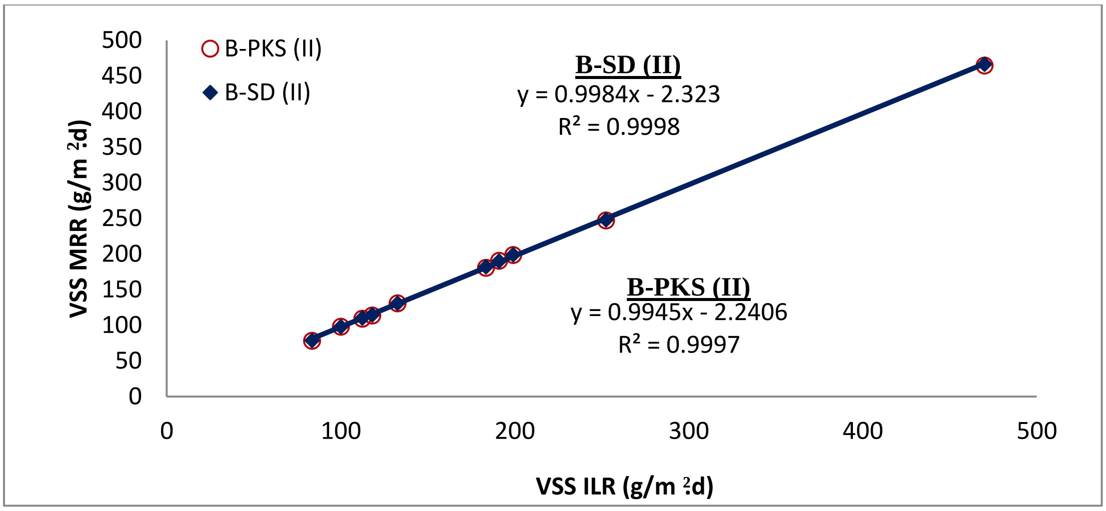



20
18
16
14
12
10
8
6
4
2
0
NH3-NMRR (g/m2.d)
○ B-PKS (II)
◆ B-SD (II)
B-PKS (II)
y = 1.0352x - 0.6455
R² = 0.9957
B-SD (II)
y = 0.9996x - 0.0593
R² = 0.9996
0
5
10
15
20
NH3-N ILR (g/m2.d)

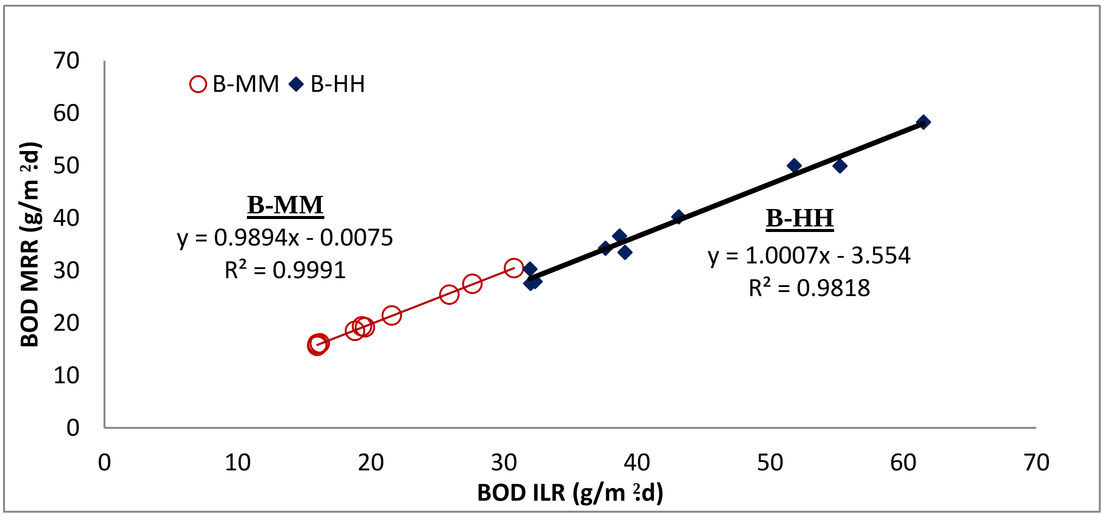

700
600
500
400
300
200
100
0
TS MRR (g/m ²d)
○ B-PKS (I)
◆ B-SD (I)
B-SD (I)
y = 0.9543x - 61.869
R² = 0.8791
B-PKS (I)
y = 0.9548x - 67.486
R² = 0.8653
0
100
200
300
400
500
600
700
800
TS ILR (g/m ²d)


1,600
1,400
1,200
1,000
800
600
400
200
0
TS MRR (g/m ²d)
○ B-PKS (II)
◆ B-SD (II)
B-SD (II)
y = 1.0233x - 238.73
R² = 0.9906
B-SD (II)
y = 0.9967x - 170.32
R² = 0.9935
0
500
1,000
1,500
2,000
TS ILR (g/m ²d)

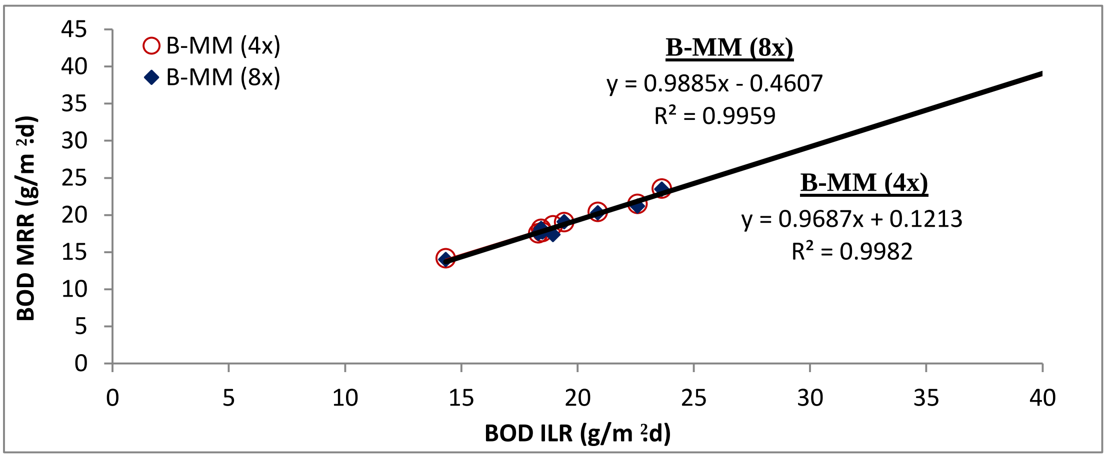


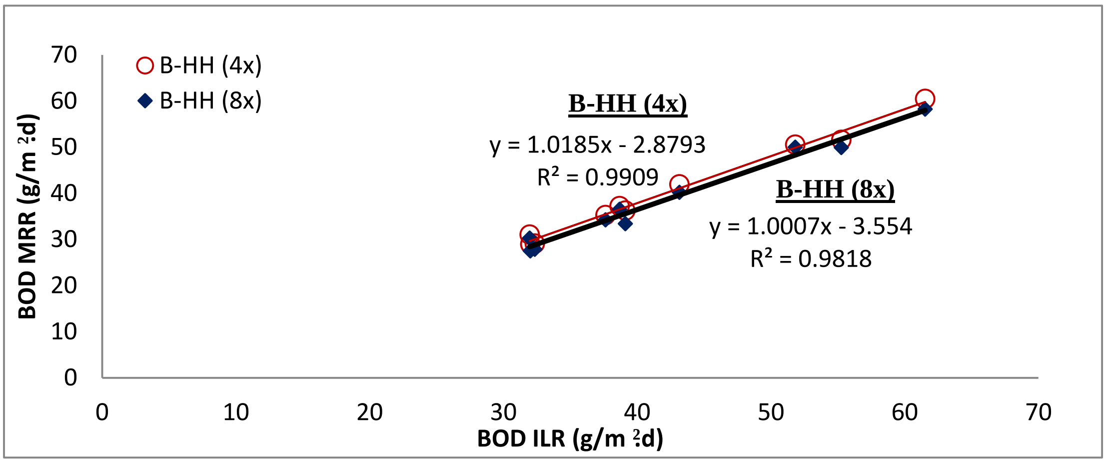


Effect of HLR

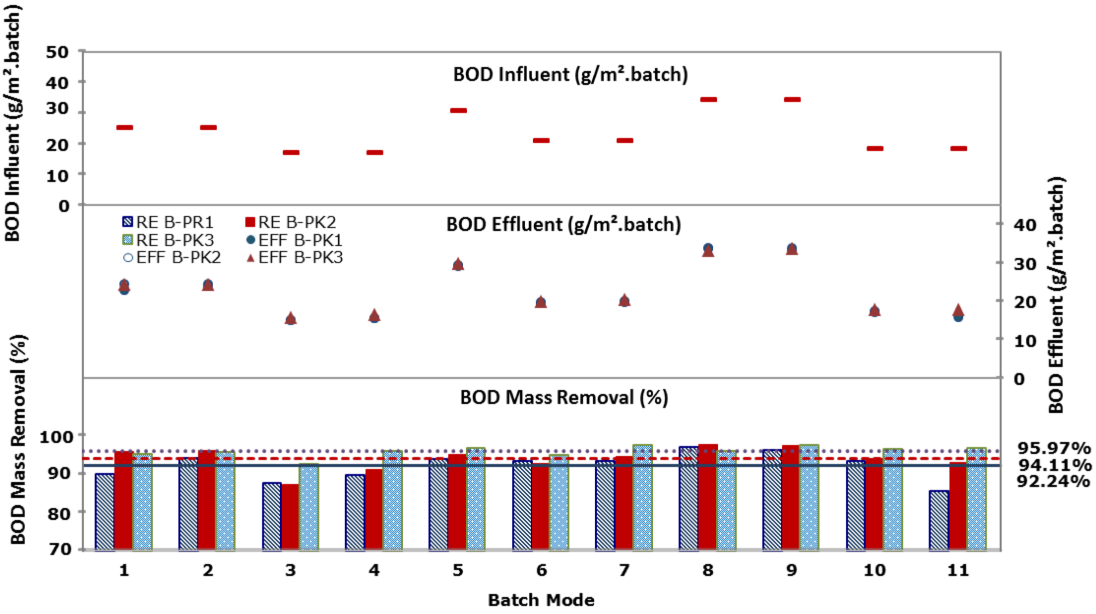


Effect of Dosing Frequency





Mode of Operation



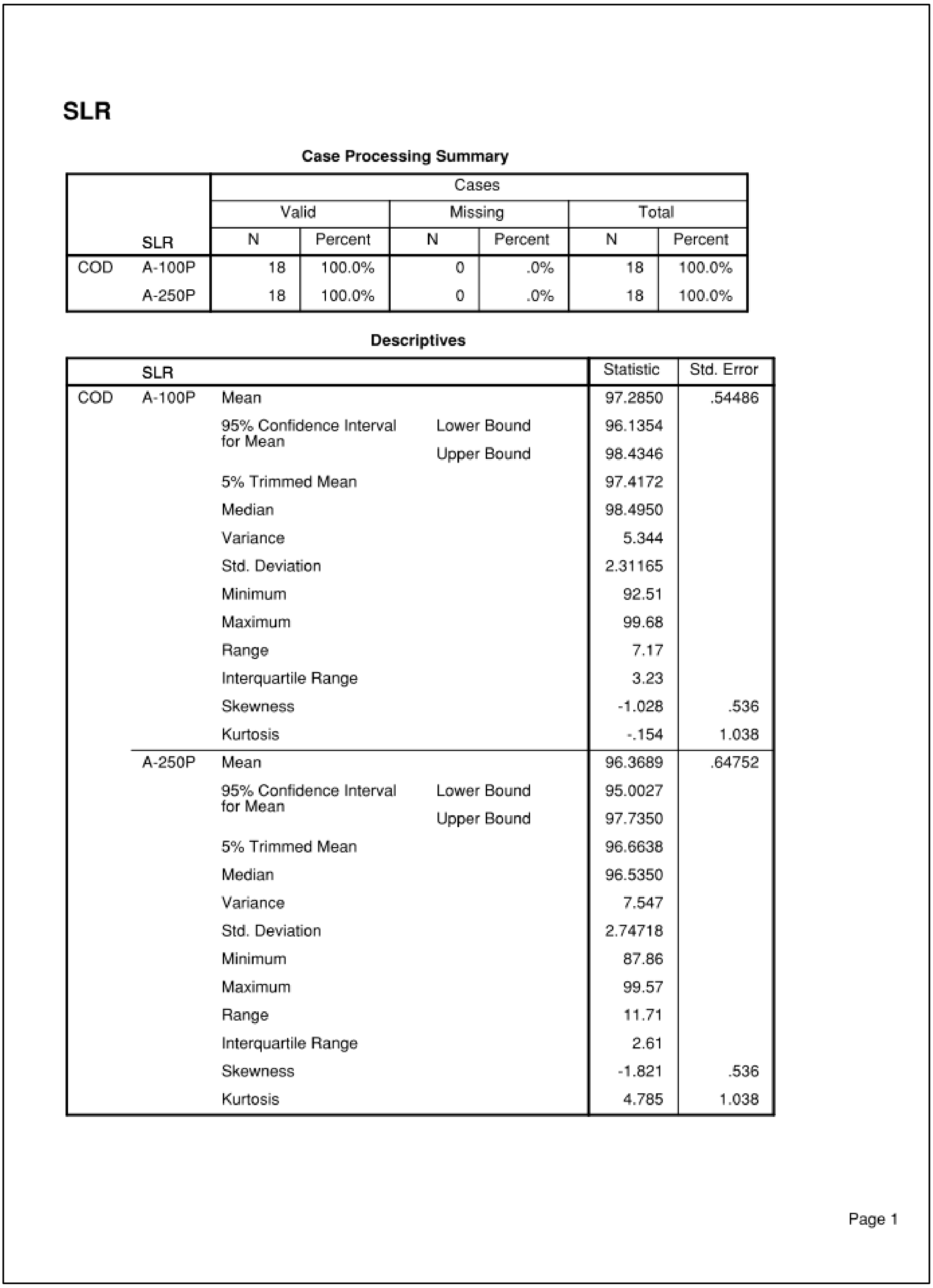
Appendix F: Statistical Analysis

Sample 1: Data Transformation

Untransformed Data (Data normality test)

First Stage Wetlands: SLR 100 Vs SLR 250 (Wetland A-100P Vs A-250P)

COD RE (%)	
SLR 100	**SLR 250**
93.12	95.28
95.93	97.43
99.13	98.80
99.31	99.01
99.23	99.57
98.56	96.60
98.43	96.45
99.68	95.71
93.35	94.41
98.74	87.86
96.25	96.16
95.89	96.41
97.13	97.38
97.11	96.47
92.51	92.79
99.29	99.41
98.71	98.02
98.76	96.88



SLR

Case Processing Summary

	SLR	Cases					
		Valid		Missing		Total	
		N	Percent	N	Percent	N	Percent
COD	A-100P	18	100.0%	0	.0%	18	100.0%
	A-250P	18	100.0%	0	.0%	18	100.0%

Descriptives

	SLR			Statistic	Std. Error
COD	A-100P	Mean		97.2850	.54486
		95% Confidence Interval for Mean	Lower Bound	96.1354	
			Upper Bound	98.4346	
		5% Trimmed Mean		97.4172	
		Median		98.4950	
		Variance		5.344	
		Std. Deviation		2.31165	
		Minimum		92.51	
		Maximum		99.68	
		Range		7.17	
		Interquartile Range		3.23	
		Skewness		-1.028	.536
		Kurtosis		-.154	1.038
	A-250P	Mean		96.3689	.64752
		95% Confidence Interval for Mean	Lower Bound	95.0027	
			Upper Bound	97.7350	
		5% Trimmed Mean		96.6638	
		Median		96.5350	
		Variance		7.547	
		Std. Deviation		2.74718	
		Minimum		87.86	
		Maximum		99.57	
		Range		11.71	
		Interquartile Range		2.61	
		Skewness		-1.821	.536
		Kurtosis		4.785	1.038

Page 1

Tests of Normality

	SLR	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
		Statistic	df	Sig.	Statistic	df	Sig.
COD	A-100P	.245	18	.005	.840	18	.006
	A-250P	.192	18	.078	.841	18	.006

a. Lilliefors Significance Correction

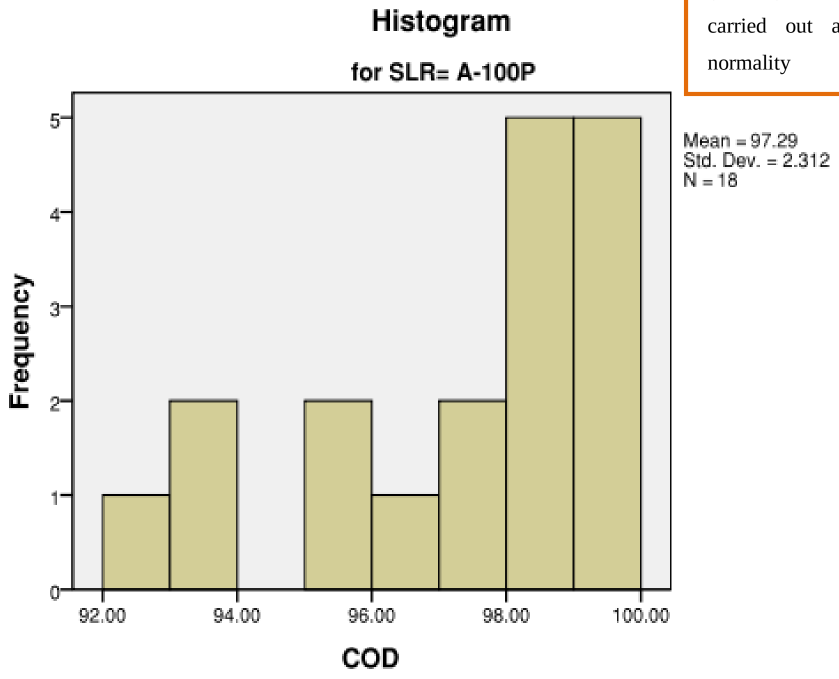
Test of Homogeneity of Variance

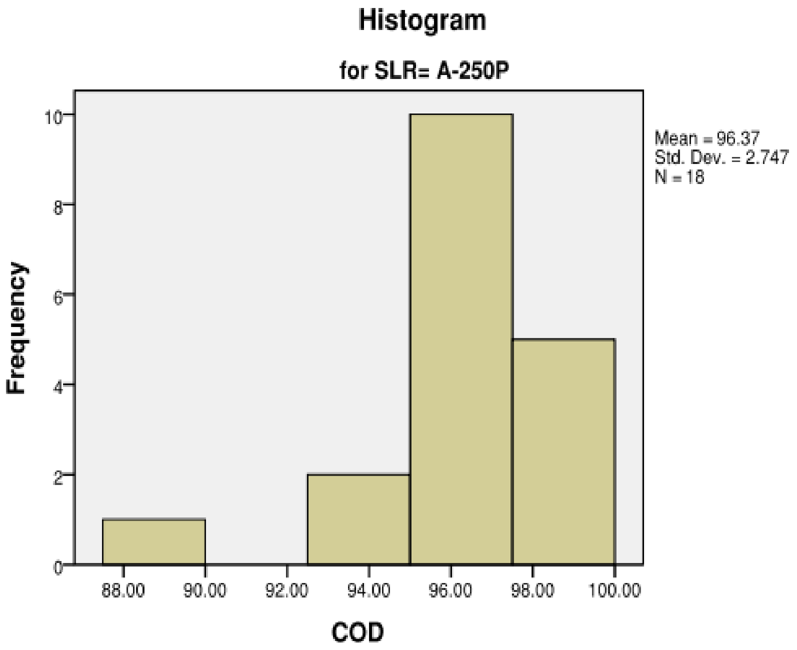
		Levene Statistic	df1	df2	Sig.
COD	Based on Mean	.037	1	34	.848
	Based on Median	.000	1	34	.991
	Based on Median and with adjusted df	.000	1	33.730	.991
	Based on trimmed mean	.038	1	34	.847

Untransformed data for wetland A-100P and A-250P are not normally distributed (P<0.05). Data transformation was carried out and checked again for normality

COD

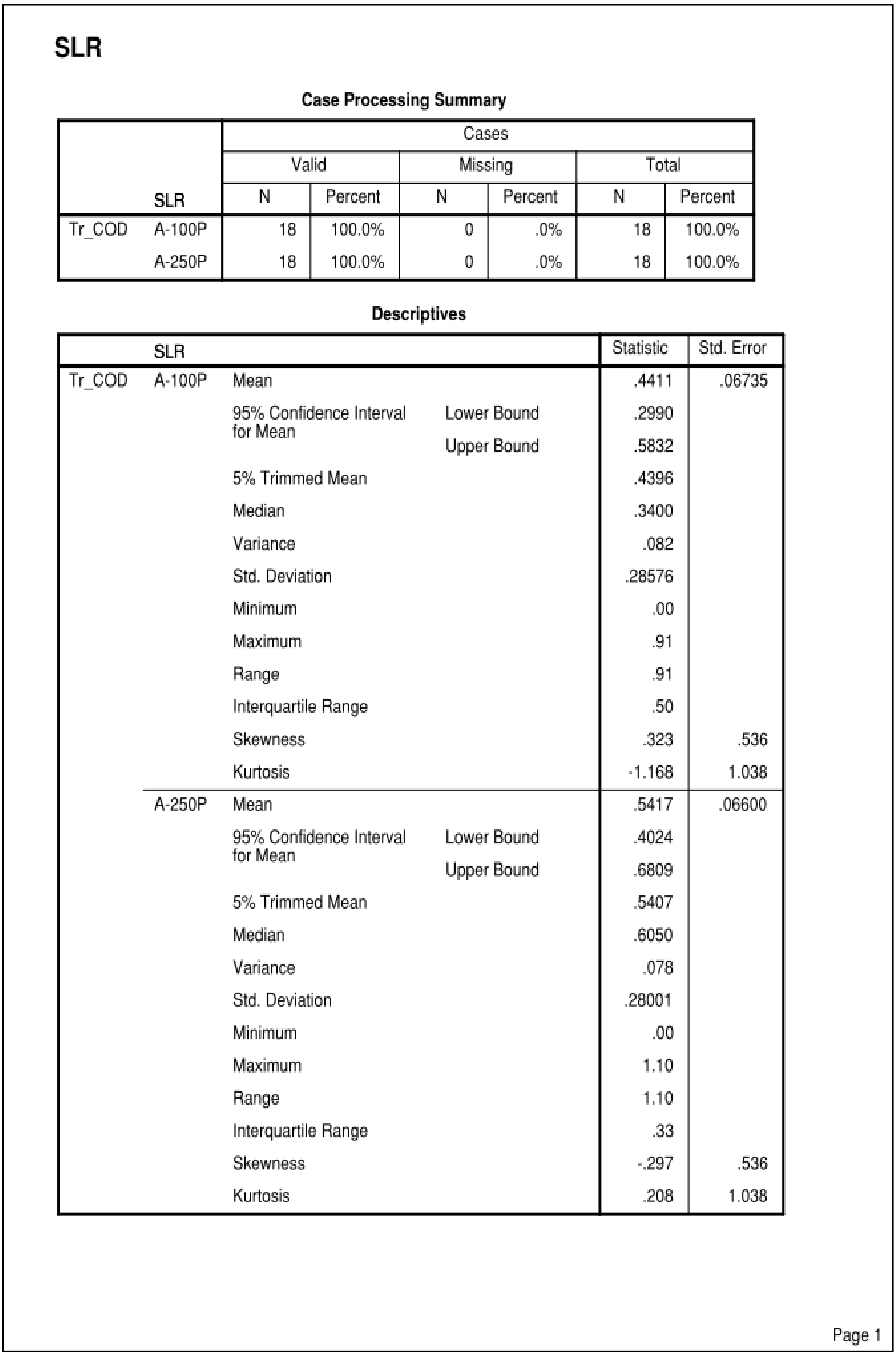
Histograms




Histogram
for SLR= A-250P
Frequency
0
2
4
6
8
10
88.00
90.00
92.00
94.00
96.00
98.00
100.00
COD
Mean = 96.37
Std. Dev. = 2.747
N = 18

Log-transformed data (Data normality test)

COD RE (%)	
SLR 100	**SLR 250**
0.88	0.72
0.68	0.50
0.19	0.25
0.14	0.19
0.16	0.00
0.33	0.60
0.35	0.61
0.00	0.69
0.87	0.79
0.29	1.10
0.65	0.64
0.68	0.62
0.55	0.50
0.55	0.61
0.91	0.89
0.14	0.06
0.29	0.41
0.28	0.57



SLR

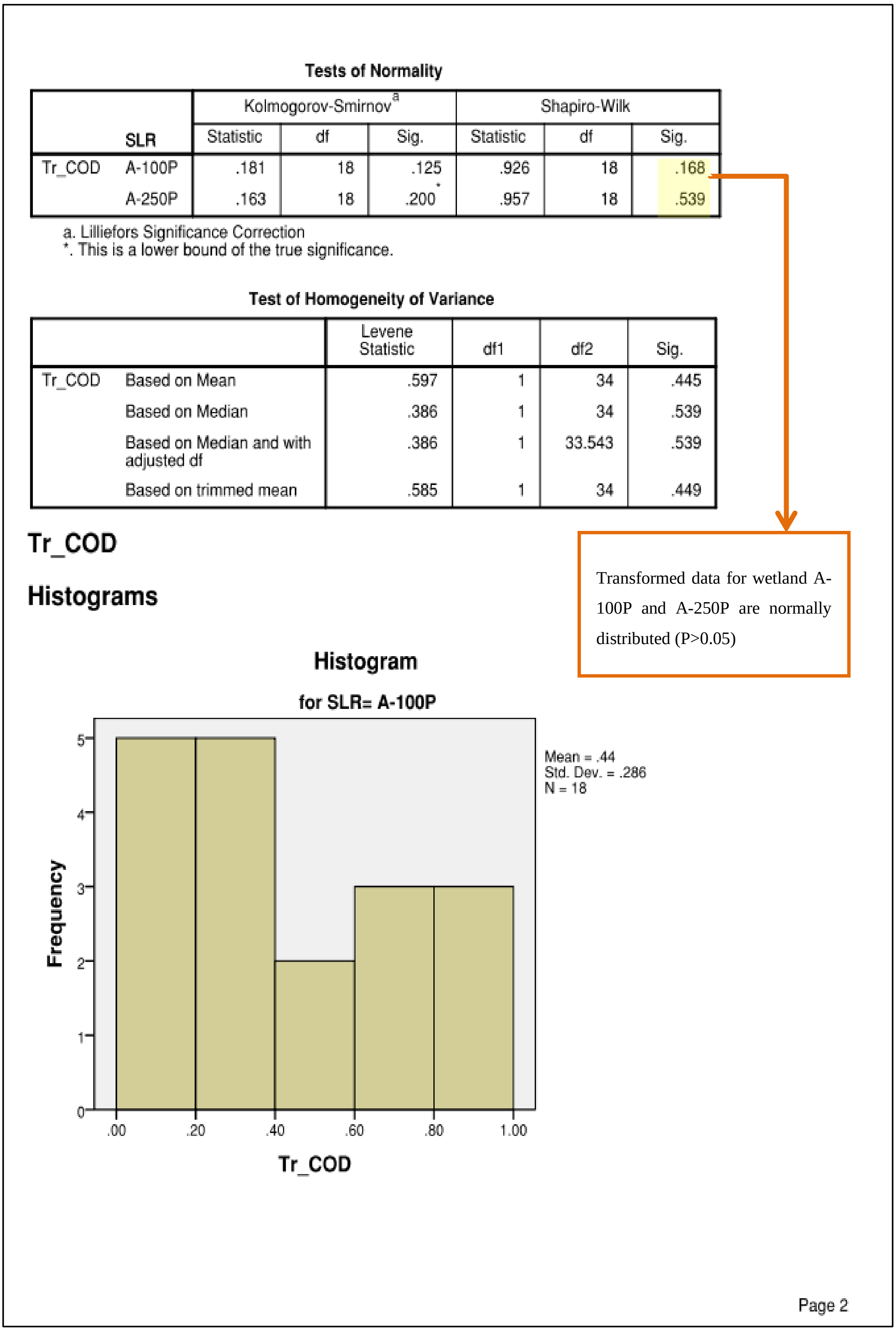
Case Processing Summary

		Cases					
		Valid		Missing		Total	
	SLR	N	Percent	N	Percent	N	Percent
Tr_COD	A-100P	18	100.0%	0	.0%	18	100.0%
	A-250P	18	100.0%	0	.0%	18	100.0%

Descriptives

	SLR			Statistic	Std. Error
Tr_COD	A-100P	Mean		.4411	.06735
		95% Confidence Interval for Mean	Lower Bound	.2990	
			Upper Bound	.5832	
		5% Trimmed Mean		.4396	
		Median		.3400	
		Variance		.082	
		Std. Deviation		.28576	
		Minimum		.00	
		Maximum		.91	
		Range		.91	
		Interquartile Range		.50	
		Skewness		.323	.536
		Kurtosis		-1.168	1.038
	A-250P	Mean		.5417	.06600
		95% Confidence Interval for Mean	Lower Bound	.4024	
			Upper Bound	.6809	
		5% Trimmed Mean		.5407	
		Median		.6050	
		Variance		.078	
		Std. Deviation		.28001	
		Minimum		.00	
		Maximum		1.10	
		Range		1.10	
		Interquartile Range		.33	
		Skewness		-.297	.536
		Kurtosis		.208	1.038

Page 1



Tests of Normality

	SLR	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
		Statistic	df	Sig.	Statistic	df	Sig.
Tr_COD	A-100P	.181	18	.125	.926	18	.168
	A-250P	.163	18	.200*	.957	18	.539

a. Lilliefors Significance Correction
*. This is a lower bound of the true significance.

Test of Homogeneity of Variance

		Levene Statistic	df1	df2	Sig.
Tr_COD	Based on Mean	.597	1	34	.445
	Based on Median	.386	1	34	.539
	Based on Median and with adjusted df	.386	1	33.543	.539
	Based on trimmed mean	.585	1	34	.449

Transformed data for wetland A-100P and A-250P are normally distributed (P>0.05)

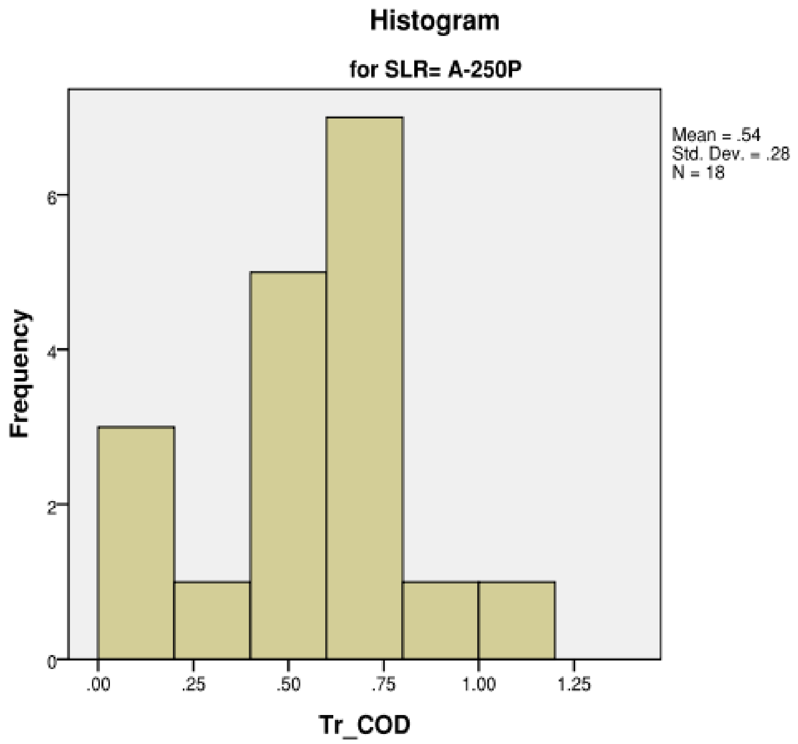
Tr_COD

Histograms

Histogram

for SLR= A-100P

Page 2

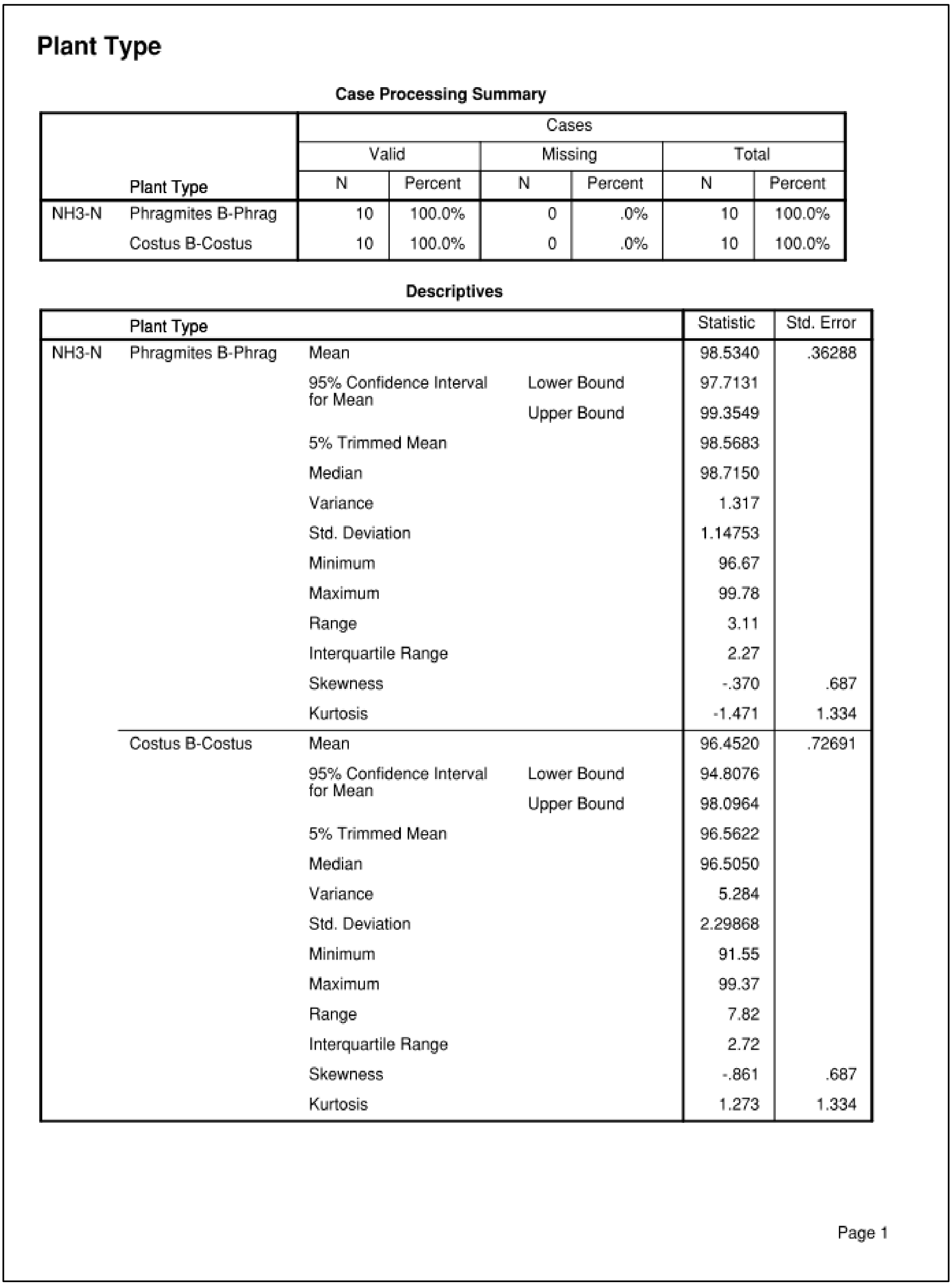

Histogram
for SLR= A-250P
Mean = .54
Std. Dev. = .28
N = 18
Frequency
0
2
4
6
.00
.25
.50
.75
1.00
1.25
Tr_COD

Sample 2: One-way ANOVA ($P<0.05$, Data is statistically different)

Second Stage Wetlands: Plant Phragmites Vs Plant Costus (Wetland B-Phrag Vs B-Costus)

NH_3-N RE (%)	
Phragmites	**Costus**
98.82	91.55
97.35	96.73
98.61	97.75
97.86	95.60
99.62	95.63
96.67	94.74
97.39	97.72
99.75	99.37
99.49	96.28
99.78	99.15

(i) Normality Test



Plant Type

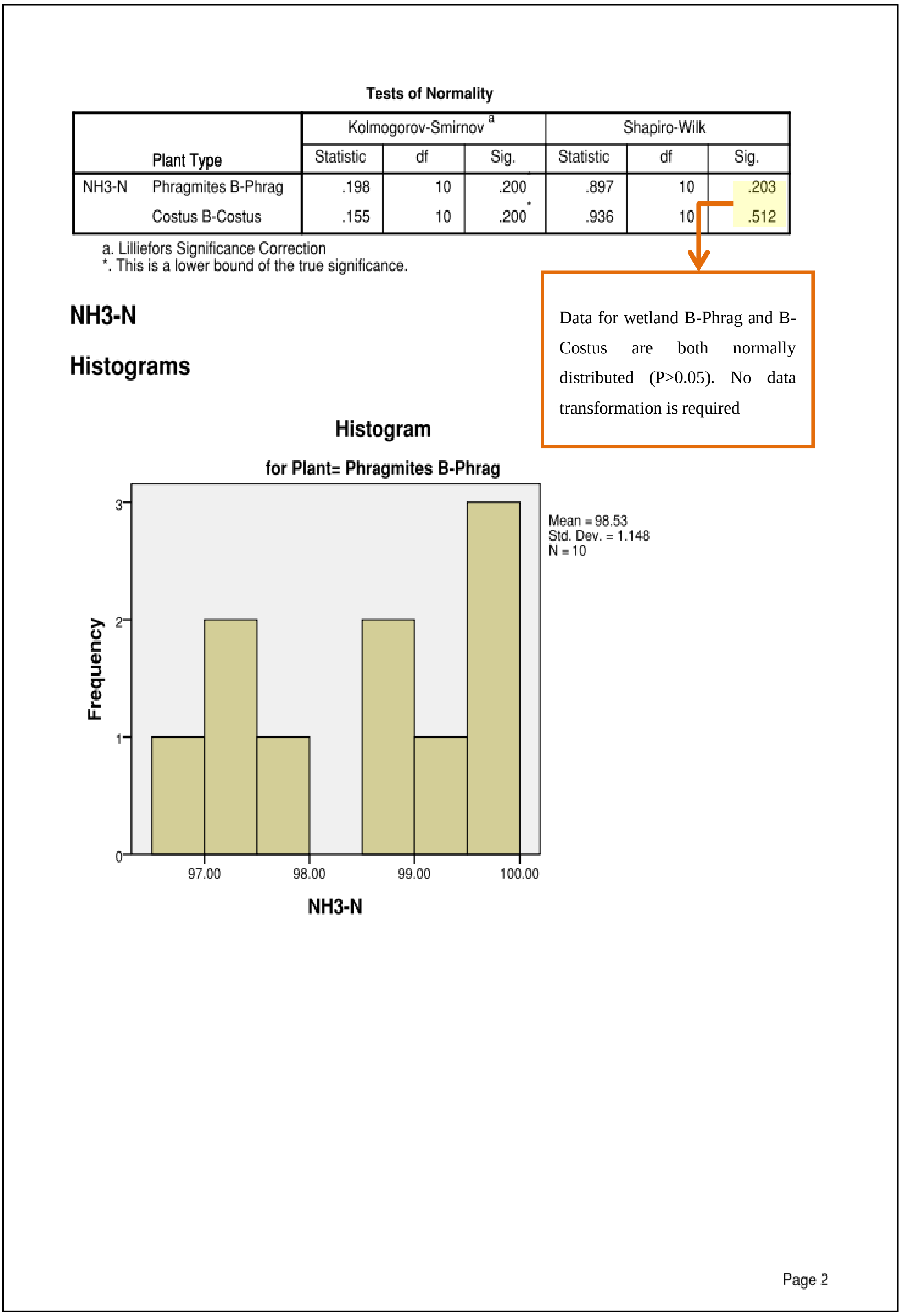
Case Processing Summary

		Cases					
		Valid		Missing		Total	
	Plant Type	N	Percent	N	Percent	N	Percent
NH3-N	Phragmites B-Phrag	10	100.0%	0	.0%	10	100.0%
	Costus B-Costus	10	100.0%	0	.0%	10	100.0%

Descriptives

	Plant Type			Statistic	Std. Error
NH3-N	Phragmites B-Phrag	Mean		98.5340	.36288
		95% Confidence Interval for Mean	Lower Bound	97.7131	
			Upper Bound	99.3549	
		5% Trimmed Mean		98.5683	
		Median		98.7150	
		Variance		1.317	
		Std. Deviation		1.14753	
		Minimum		96.67	
		Maximum		99.78	
		Range		3.11	
		Interquartile Range		2.27	
		Skewness		-.370	.687
		Kurtosis		-1.471	1.334
	Costus B-Costus	Mean		96.4520	.72691
		95% Confidence Interval for Mean	Lower Bound	94.8076	
			Upper Bound	98.0964	
		5% Trimmed Mean		96.5622	
		Median		96.5050	
		Variance		5.284	
		Std. Deviation		2.29868	
		Minimum		91.55	
		Maximum		99.37	
		Range		7.82	
		Interquartile Range		2.72	
		Skewness		-.861	.687
		Kurtosis		1.273	1.334

Page 1



Tests of Normality

Plant Type		Kolmogorov-Smirnov[a]			Shapiro-Wilk		
		Statistic	df	Sig.	Statistic	df	Sig.
NH3-N	Phragmites B-Phrag	.198	10	.200*	.897	10	.203
	Costus B-Costus	.155	10	.200*	.936	10	.512

a. Lilliefors Significance Correction
*. This is a lower bound of the true significance.

Data for wetland B-Phrag and B-Costus are both normally distributed (P>0.05). No data transformation is required

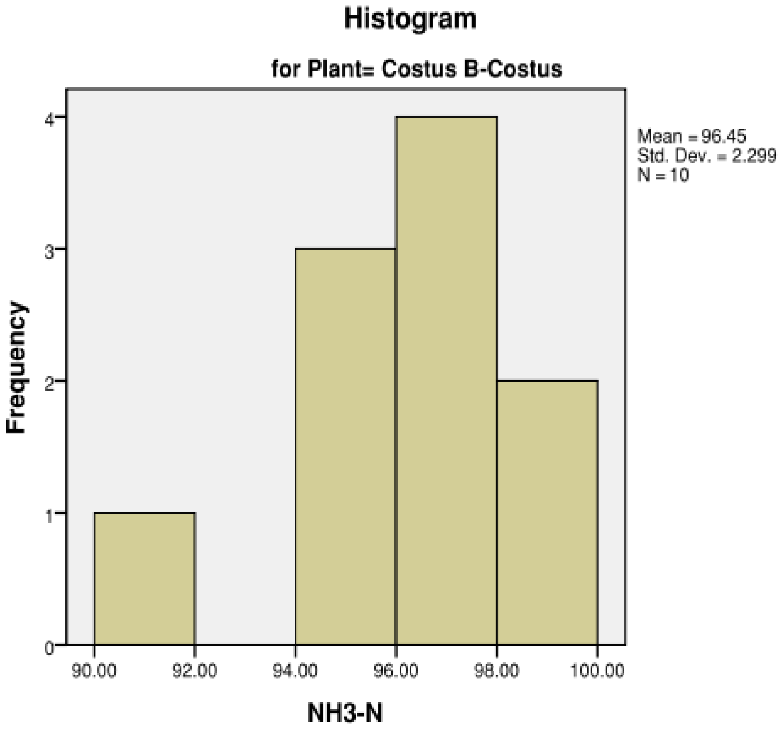
NH3-N

Histograms

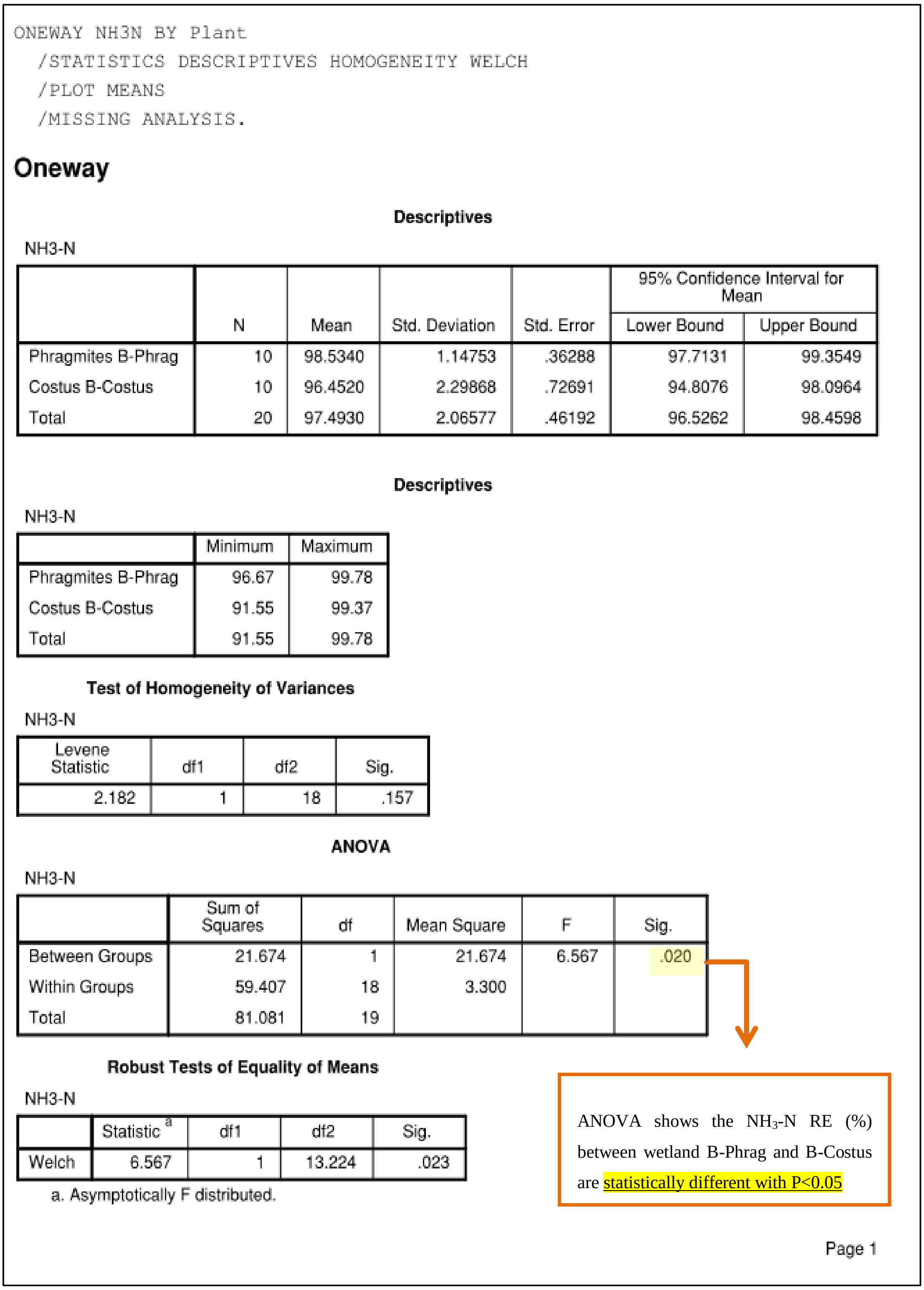
Histogram

for Plant= Phragmites B-Phrag

Page 2


Histogram
for Plant= Costus B-Costus
Frequency
0
1
2
3
4
90.00
92.00
94.00
96.00
98.00
100.00
NH3-N
Mean = 96.45
Std. Dev. = 2.299
N = 10

(ii) One-way ANOVA



```
ONEWAY NH3N BY Plant
  /STATISTICS DESCRIPTIVES HOMOGENEITY WELCH
  /PLOT MEANS
  /MISSING ANALYSIS.
```

Oneway

Descriptives

NH3-N

	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean	
					Lower Bound	Upper Bound
Phragmites B-Phrag	10	98.5340	1.14753	.36288	97.7131	99.3549
Costus B-Costus	10	96.4520	2.29868	.72691	94.8076	98.0964
Total	20	97.4930	2.06577	.46192	96.5262	98.4598

Descriptives

NH3-N

	Minimum	Maximum
Phragmites B-Phrag	96.67	99.78
Costus B-Costus	91.55	99.37
Total	91.55	99.78

Test of Homogeneity of Variances

NH3-N

Levene Statistic	df1	df2	Sig.
2.182	1	18	.157

ANOVA

NH3-N

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	21.674	1	21.674	6.567	.020
Within Groups	59.407	18	3.300		
Total	81.081	19			

Robust Tests of Equality of Means

NH3-N

	Statistic[a]	df1	df2	Sig.
Welch	6.567	1	13.224	.023

a. Asymptotically F distributed.

ANOVA shows the NH_3-N RE (%) between wetland B-Phrag and B-Costus are statistically different with P<0.05

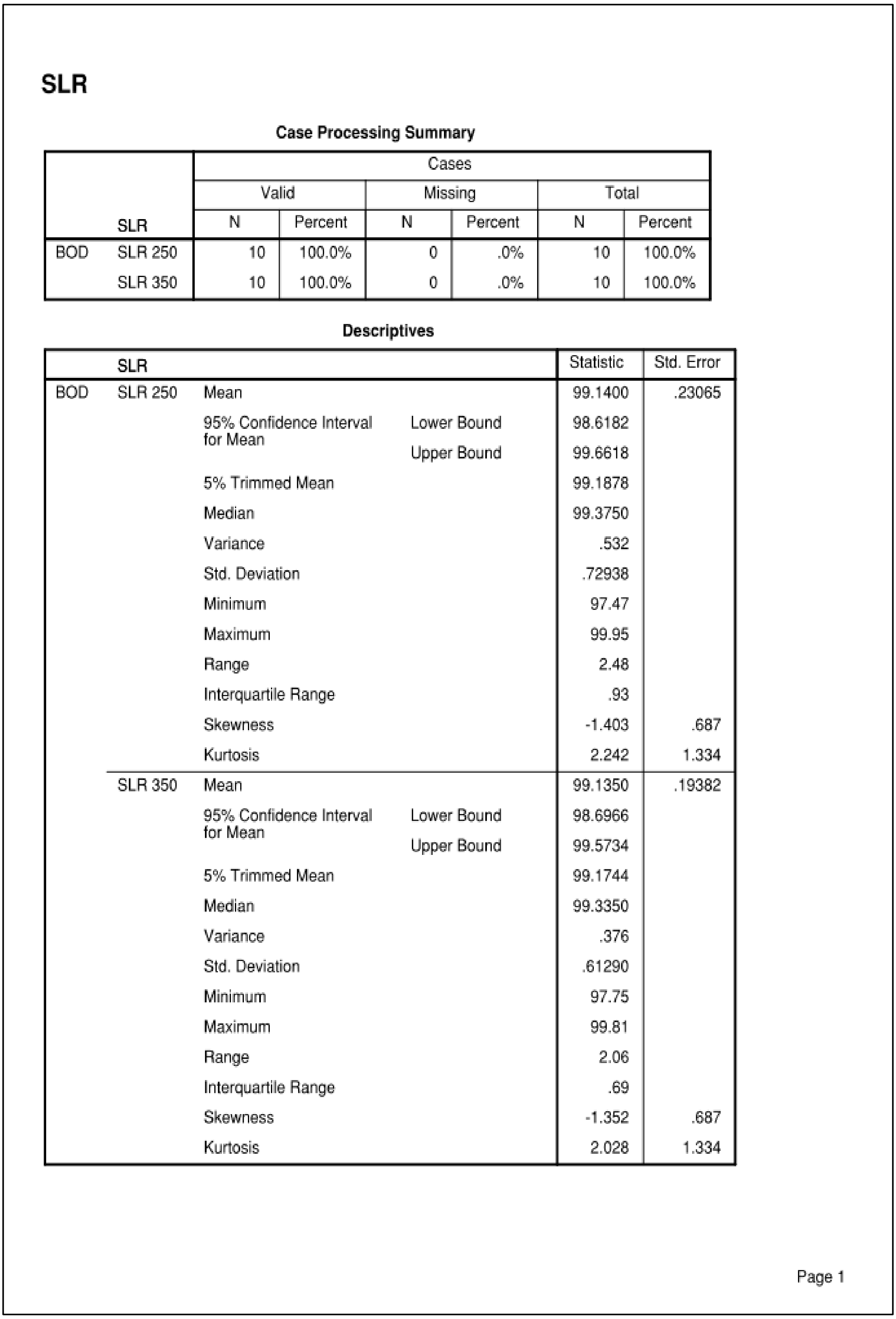
Page 1

Sample 3: One-way ANOVA (P>0.05, Data is not statistically different)

First Stage Wetlands: SLR 250 Vs SLR 350 (wetland A-250P Vs A-350P)

BOD RE (%)	
SLR 250	**SLR 350**
97.47	97.75
98.99	98.59
99.53	99.71
99.72	99.45
98.77	99.27
99.23	98.93
99.63	99.40
99.95	99.81
98.59	98.96
99.52	99.48

(i) Normality Test



SLR

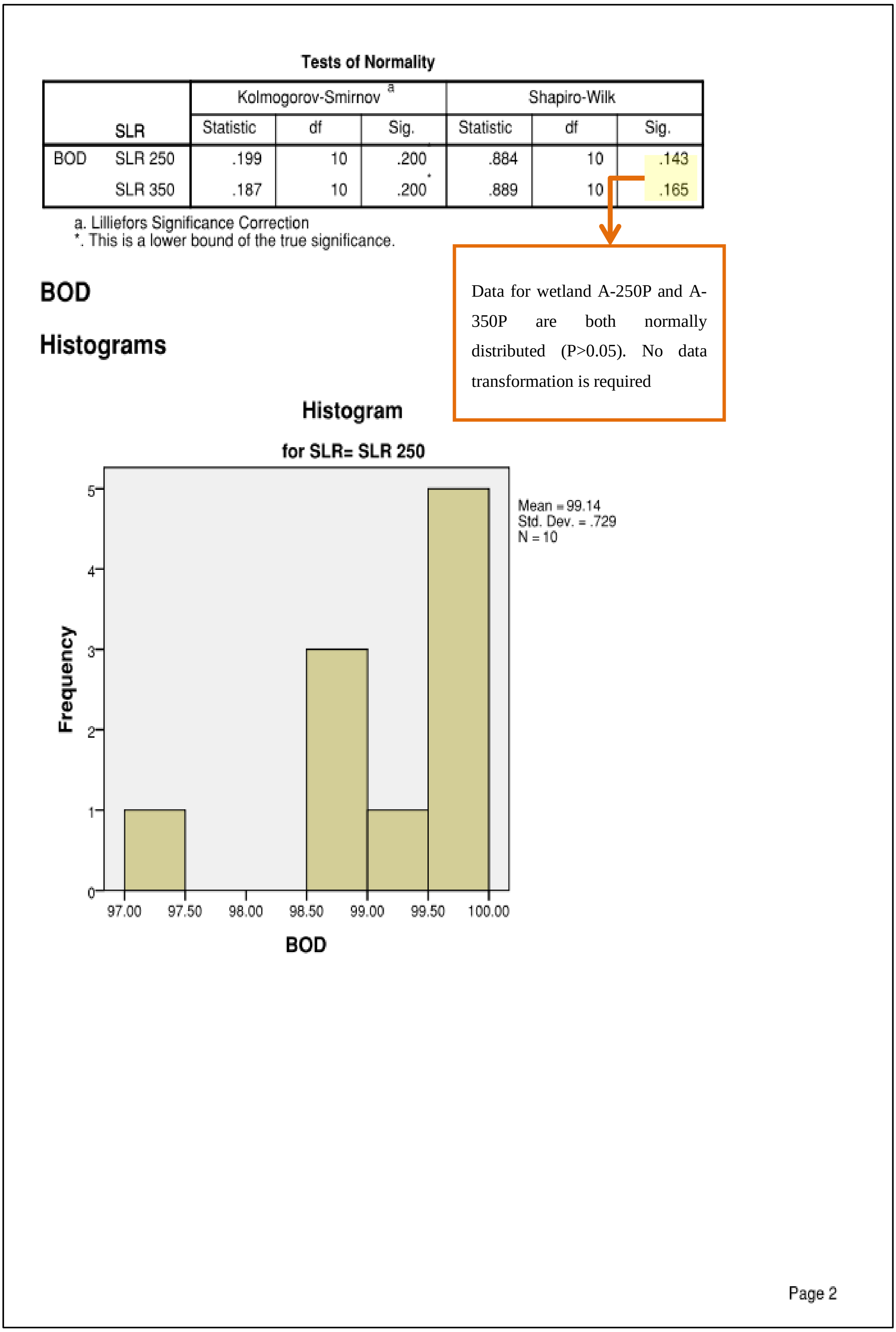
Case Processing Summary

		Cases					
		Valid		Missing		Total	
	SLR	N	Percent	N	Percent	N	Percent
BOD	SLR 250	10	100.0%	0	.0%	10	100.0%
	SLR 350	10	100.0%	0	.0%	10	100.0%

Descriptives

	SLR			Statistic	Std. Error
BOD	SLR 250	Mean		99.1400	.23065
		95% Confidence Interval for Mean	Lower Bound	98.6182	
			Upper Bound	99.6618	
		5% Trimmed Mean		99.1878	
		Median		99.3750	
		Variance		.532	
		Std. Deviation		.72938	
		Minimum		97.47	
		Maximum		99.95	
		Range		2.48	
		Interquartile Range		.93	
		Skewness		-1.403	.687
		Kurtosis		2.242	1.334
	SLR 350	Mean		99.1350	.19382
		95% Confidence Interval for Mean	Lower Bound	98.6966	
			Upper Bound	99.5734	
		5% Trimmed Mean		99.1744	
		Median		99.3350	
		Variance		.376	
		Std. Deviation		.61290	
		Minimum		97.75	
		Maximum		99.81	
		Range		2.06	
		Interquartile Range		.69	
		Skewness		-1.352	.687
		Kurtosis		2.028	1.334

Page 1



Tests of Normality

	SLR	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
		Statistic	df	Sig.	Statistic	df	Sig.
BOD	SLR 250	.199	10	.200*	.884	10	.143
	SLR 350	.187	10	.200*	.889	10	.165

a. Lilliefors Significance Correction

*. This is a lower bound of the true significance.

Data for wetland A-250P and A-350P are both normally distributed (P>0.05). No data transformation is required

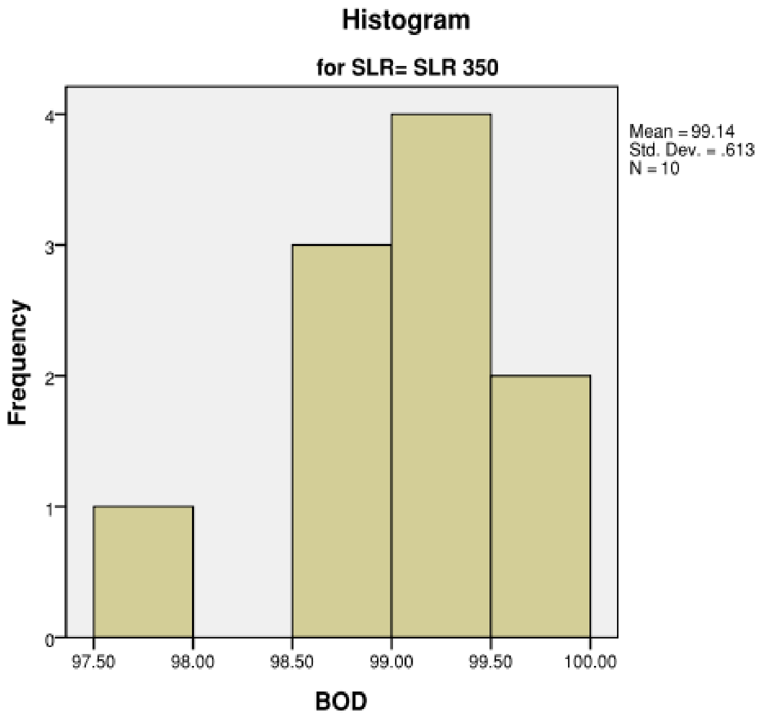
BOD

Histograms

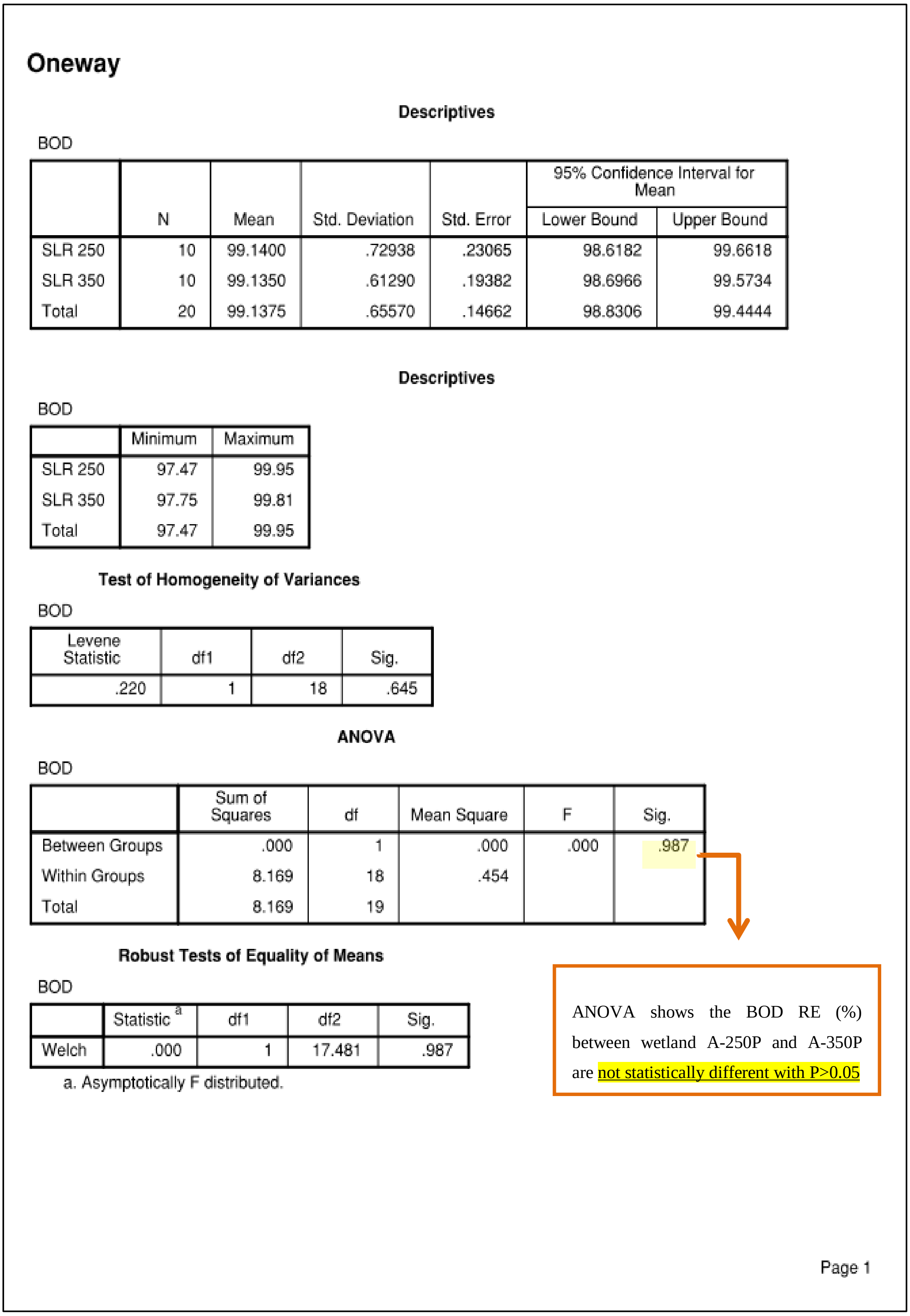
Histogram

for SLR= SLR 250

Page 2


Histogram
for SLR= SLR 350
Mean = 99.14
Std. Dev. = .613
N = 10
Frequency
0
1
2
3
4
97.50
98.00
98.50
99.00
99.50
100.00
BOD

(ii) One-way ANOVA



Oneway

Descriptives

BOD

	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean	
					Lower Bound	Upper Bound
SLR 250	10	99.1400	.72938	.23065	98.6182	99.6618
SLR 350	10	99.1350	.61290	.19382	98.6966	99.5734
Total	20	99.1375	.65570	.14662	98.8306	99.4444

Descriptives

BOD

	Minimum	Maximum
SLR 250	97.47	99.95
SLR 350	97.75	99.81
Total	97.47	99.95

Test of Homogeneity of Variances

BOD

Levene Statistic	df1	df2	Sig.
.220	1	18	.645

ANOVA

BOD

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	.000	1	.000	.000	.987
Within Groups	8.169	18	.454		
Total	8.169	19			

ANOVA shows the BOD RE (%) between wetland A-250P and A-350P are not statistically different with P>0.05

Robust Tests of Equality of Means

BOD

	Statistic[a]	df1	df2	Sig.
Welch	.000	1	17.481	.987

a. Asymptotically F distributed.

Page 1