High school and preservice chemistry teacher education students' understanding of voltaic and electrolytic cell concepts: Evidence of consistent learning difficulties across years

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Abstract

High school students learn the basic voltaic and electrolytic cell concepts during their last year prior to entering an undergraduate teacher-education science degree. During the four years of university, students complete a sequence of topics designed to build on conceptual understanding presented in previous years. At the end of their degrees, graduating students are expected to have developed a comprehensive understanding of the subject that they are required to teach. In this research, we designed and developed a 12- item diagnostic instrument which addressed 10 propositional content knowledge statements based on the Grade 12 chemistry curriculum that will be taught. In this cross-section study, 50 Grade 12 high school students and 216 preservice chemistry teacher education undergraduates in Years 1-4 responded to the Electrochemistry Conceptual Test (ECT) consisting of 12 two-tier multiple-choice items. The instrument was content validated by authors and peers prior to administration and when implemented had a Cronbach alpha reliability coefficient of 0.64. Overall, the students across years possessed basic knowledge about electrochemical cells but frequently were unable to explain their knowledge. While the grand mean trend in understanding electrochemistry concepts from high school through university study did show some improvement, the mean scores remained relatively low and the year group means per item showed no such trend exacerbated by items having varying levels of difficulty. Based on this research, the lack in understanding about electrochemical concepts suggests that instruction in high school and ongoing university chemistry education faces ongoing challenges.

Keywords: electrochemistry; electrolytic cells; electrode reactions; voltaic cells

Introduction

Rationale for the Study

Most studies of students' understanding of science concepts documented in the research literature concern a specific year level and identification of alternative conceptions held by students and how the implementation of different conceptual change strategies for that year level can enhance learning outcomes (Soeharto, Csapo, Sariminah, Dewi & Sabri, 2019; Lee & Osman, 2017). This information is very useful for teachers and researchers. Other studies that investigate learning over multiple years can provide useful information for teachers, researchers and for curriculum planning by illustrating the effectiveness of educational programs and identifying any consistent learning problems as well as teaching opportunities. This style of research has led to programs investigating learning progressions (see for example, Alonzo & Gotwals, 2012; Shepard, 2018).

In their three or four-year undergraduate science degree programs, universities offer a sequence of topics that are designed to build on conceptual understanding presented in previous years so that at the end of their degree graduating students have developed a comprehensive understanding of the subject. This situation applies to the concepts of electrochemistry that is the focus of this research. This study involved a five-year cross age study comparing understanding of electrochemical concepts of Indonesian Grade 12 high school students and undergraduate chemistry education students in years 1 to 4 of their university education. Although the study was conducted with Indonesian high school students and undergraduates, the findings could be relevant to any cohort of undergraduates. To the best of our knowledge no similar studies to ascertain undergraduates' understanding of basic electrochemical concepts, first learned in high school, as they progressed through university have been documented in the extant literature.

Literature Review

Studies of Electrochemistry Concepts

Electrochemistry is a topic that is included in the high school curriculum in most countries. Research in chemistry education conducted over the past 30-40 years indicates that students experience difficulty in understanding several key chemistry concepts, one of which is electrochemistry (Authors, 2002; Childs & Sheehan, 2009; Tsaparlis, 2019). During this period, numerous studies have been conducted at different levels to elucidate students' understanding of electrochemical concepts (e.g., Authors, 2012; Günter & Alpat, 2017; Niaz & Chacón, 2003; Özkaya, 2002) or teaching these ideas in innovative ways to engender a deeper understanding (Keen, Coutoure, El Meseh & Sevian, 2020; Sanders, Crettol, Brown, et al., 2018). Research has shown that students who develop alternative conceptions about electrochemistry in the early stages of instruction can limit their understanding as they continue their studies at higher levels (Sanger & Greenbowe, 1997). However, knowledge about students' misrepresentations of electrochemical concepts can help in developing more appropriate instructional materials and strategies (Authors, 2002).

One reason that electrochemistry is considered as one of the difficult topics both at the high school and undergraduate levels is because most processes occur at the submicroscopic level that cannot be observed directly. That visualization of invisible processes raises difficulties for many students is well-known (Garnett, Garnett & Hackling, 1995) and continues to be investigated (Herga, Čagran, & Dinevski, 2016; Lee & Osman, 2017). Several similar alternative conceptions about the behaviour of galvanic and electrolytic cells have been identified in various studies involving high school students as well as undergraduates and preservice teachers. Most studies documented in the research literature in the field of electrochemistry concern a specific year level and identify alternative conceptions held by students (Akram, Surif & Ali, 2014; Cheung, 2011; Garnett, Garnett & Hackling, 1995; Huddle & White, 2000; Özkaya, Üce, Sarıçayır & Sahin, 2006) or recommend implementing either conceptual change strategies at a particular year level that could help overcome students' difficulties (Amponsah, Kotoka, Beccles, & Dlamini, 2018; Önder, 2017; Niaz, 2002) or provide alternative approaches involving animations (Yang, Andre, Greenbowe, & Tibell, 2003) or multimedia (Osman & Lee, 2014; Lee & Osman, 2017). In a large-scale study with a random sample of high school students, multiple-choice items showed their difficulties in learning electrochemistry were based on four general alternative conceptions related to electric current during electrolysis producing ions, electrons migrating through the solution, the cathode being a minus pole, and the plus and minus poles having net electronic charges (Schmidt, Marohn & Harrison, 2007).

Building on this research and from our own former work (Authors, 2011, 2012) we developed an instrument comprising two-tier items to examine the development of students' understanding of electrochemical concepts across the last year of high school and four years of university chemistry education. This research extends existing research in terms of (a) the range of research subjects - Germany Grades 11-13 high school students (Schmidt et al., 2007), Indonesian and Japanese Grades 11- 12 students (Authors, 2011), Malaysian Grade 10 students (Authors, 2012) and Singapore Grade 10 students (Loh & Subramaniam, 2018); (b) the approach for collecting data – interviews (Bradley, & Ogude, 1996; Rosenthal, & Sanger, 2012), multiple choice test where students justify their choice in writing (Schmidt et al. 2007), multiple choice test without justification for students' choice (Authors, 2011), and an open-ended questionnaire (Loh and Subramaniam, 2018); (c) a more extended concept coverage than only oxidation–reduction reaction (Rosenthal, & Sanger, 2012), the basic concepts of electrolysis (Authors, 2012), and the knowledge structure of Galvanic cells (Loh & Subramanian, 2019).

Studies Across Years

In the chemistry domain, investigations across years have included US high school and university students' understanding of molecular structure and bonding (Birk & Kurtz, 1999), Turkish students' conceptions of the particulate nature of matter from secondary to tertiary levels (Ayas, Ozmen & Calik, 2010), and progression and consistency of thermal concepts held by Turkish grade 8 and grade 10 students (Adadan & Yavuzkaya, 2018). Birk and Kurtz (1999) used a 15 two-tier test on molecular structure and bonding to diagnose alternative conceptions over a time span of 10 years of student experience, along with the development of accepted conceptions, from high school to faculty. The results from this sample showed that at high school students had little understanding of molecular structure and bonding, students in their first year of college began to show some understanding but revealed a lack of comprehension, at the advanced graduate and faculty level, alternative conceptions were mostly not evident although performance was still not at 100%.

In a similarly designed study, students' understanding of the particulate nature of matter over five years, ranging from first year of senior high school to second year university educational levels, was investigated by Ayas et al. (2010) using a questionnaire with five open-ended questions. The results indicated that the understanding of the students was mixed and not linear at all educational levels. The research findings also suggest that most of the students, including those at the university level, held alternative conceptions, could not make sense of knowledge and link their theoretical knowledge to daily phenomena. The authors commented that these students are likely rote rather than conceptual learners and chemistry may not have been linked to everyday life.

The extent of conceptual development and the patterns of consistency in 656 Turkish students' understanding of thermal concepts across distinct age groups from grade 8, grade

10, to first year of college was examined by Adadan and Yavuzkaya (2018). Data were collected using all 19 items of the Thermal Concept Evaluation (TCE) (Yeo & Zadnik, 2001) which consisted of four conceptual groups, namely: (I) heat transfer and temperature changes (II) boiling (III) heat conductivity and equilibrium, and (IV) freezing and melting. The findings indicated a substantial development of students' scientific understanding of thermal concepts across grade levels but the participants in each group did not develop the four thermal concepts in a similar extent. Similarly, the conceptual development of the four thermal concepts occurred in an uneven manner across grade levels. Students' alternative conceptions about thermal concepts generally decreased in frequency across grade levels but certain alternative conceptions were observed in every grade level to a similar extent. The number of students who consistently used scientific ideas increased across grade levels, while the number of students who consistently used non-scientific ideas decreased across grade levels. However, the number of students who used scientific and non-scientific ideas inconsistently generally increased each year of the science curriculum. These findings can be associated with either fragmentation or alternative conceptions that result from the gradual enrichment processes students experience when they try to integrate scientific concepts into their conceptual frameworks.

These studies across years of education broadly show that while development through schooling does improve from year to year, such change is not linear and that earlier identified alternative conceptions remain or recur. This is the departure point for this cross-age study that examines learning electrochemistry concepts across five years of education.

Methodology

Sample and Curriculum Context

In Indonesia, electrochemistry first taught in high school in grade 12 lays the foundation for more advanced study at university level when the basic concepts are taught during the first and second years of university chemistry education studies and continued in third year as applications of the concepts and in fourth year strengthening an understanding for their future teaching of the concepts. The course content in grade 12 and the four years of university are shown Table 1.

Table 1 Electrochemistry curriculum content for Senior High School grade 12 and Years 1-4 of the preservice chemistry education program

Grade/Year	Course	Content
Senior High School grade 12	Chemistry	The concepts of oxidation-reduction Balancing redox reactions Galvanic/Voltaic cells Notation for cells Standard reduction potentials Corrosion Electrolytic cell Application of electrolysis process in industry
Year 1	Basic Chemistry	Review of oxidation-reduction concept Review of balancing redox reactions Galvanic/Voltaic cells Standard reduction potentials Corrosion (protect against corrosion of iron) Electrolytic cells Application of electrolytic process, predicting the product of electrolysis, electroplating and purifying metals
Year 2	Physical Chemistry	Migration of ions: transport number using Hittorf and moving boundary methods, electric current, ion mobility and ionic conductivity Equilibrium Electrochemistry: half reactions and electrodes, electromotive force, variety of cells, cell potentials, application of standard reduction potentials
Year 3	Analytical Chemistry & Instrumentation	Electrochemical Cells and Electrode Potentials: redox reaction, electrochemical cells, NERST equation, effects of concentrations on potentials Potentiometric Electrodes and Potentiometry: redox electrode, voltaic cell, reference electrodes Redox and Potentiometric Titrations: balance redox reactions, redox titration curve, titration with oxidizing/reducing agents, potentiometric titrations Voltametric measurement: current migration/electrochemical technique

Year 4	Review of Senior High School Chemistry curriculum content	The concepts of oxidation-reduction Balancing redox reactions Galvanic/Voltaic cells Notation for cells Standard reduction potentials Corrosion Electrolytic cell Application of electrolysis process in industry

Research Question

The research question that guided the study was: How does students' understanding of basic voltaic and electrolytic cell concepts develop across the last year of high school and four years of an Indonesian university chemistry education program?

Research Design and Participants

Using a quantitative case study approach (Creswell, 2012), data were collected from students who were readily accessible to the first author who is a member of the staff at the university where the undergraduate students were enrolled and has access to high schools through the university's preservice teacher preparation program. The sample comprised 50 high school students in grade 12 and 216 preservice chemistry teacher education undergraduates as follows: Year 1– 58, Year 2- 51, Year 3– 45 and Year 4 – 62. The high school students and the undergraduates were informed that they would be asked to take a conceptual test on electrochemistry, the results of which would be used for writing an article for submission to a journal. The data were collected at the end of the second semester of each year of schooling when electrochemistry curriculum content provided in Table 1 was covered by participants of respective Year. The data was collected within 1– 2 weeks after electrochemistry instruction finished. Permission to conduct the study was sought from the Ethics Review Board in the local Municipality and the university. Permission was received from the Head of Chemistry Department and the lecturers who provided the schedule for students to take the electrochemistry test and from the students. The students were also informed about the purpose of the questionnaire and that they had a choice whether or not to participate.

Teaching Program for Electrochemistry for High School and Preservice Chemistry Teacher Education Students

An electrochemical cell is a system which consists of a voltaic/galvanic cell or an electrolytic cell; the former uses spontaneous redox reactions to produce electrical energy while the latter uses an electric current to produce a chemical reaction. The electrochemistry topic is taught in the Indonesian language to students in the last year of high school and for each year of the program for preservice chemistry teacher education undergraduates. In high school, the electrochemical concepts are commonly taught using a conventional strategy, such as lecture aided by power-point slides, algorithm problem solving and two or three laboratory experiments over the duration of 20, 45-minutes sessions. Teachers usually provide worksheets and also most of students have Indonesian Chemistry textbooks.

At university, the topic is generally delivered using a conventional strategy, such as lecture, algorithm problem solving, and collaborative discussion over a duration of four 150 minutes sessions. Students took laboratory session (4 x 50 minutes) for the electrochemistry topic in separate course (Practicum of General Chemistry course) in the same semester. In General Chemistry, the dominantly used textbooks in the English language are those written by Chang and Overby (2011), McMurray, Fay and Robinson (2016), or Brown et al. (2018). An Indonesian language translated version of the Chang and Overby textbook is available from the university bookstore so students use the translated version to more easily understand the chemistry concepts in the Indonesian language rather than in English.

The electrochemistry topic is taught in the Indonesian language to Year 2 preservice chemistry teachers who took Physical Chemistry II in the fourth semester. The content of electrochemistry in this semester is more advanced compared to the electrochemistry in general chemistry over a duration of 16 x 100 minutes sessions. In Physical Chemistry, lecturers used mainly textbooks written by Ball (2015), Castellan (1983) and Levine (2009). There is no translation of these textbooks in the Indonesian language but students are provided with module material in Indonesian by lecturers based on the textbooks.

In Year 3 of the preservice chemistry teacher education program, the Analytical Chemistry and Instrumentation course comprises applied electrochemistry concepts and principles in the fifth semester (see Table 1). Lecturers used the Analytical Chemistry textbook written by Christian, Dasgupta, & Schug (2014) and Harvey (2000) and provided module material in the Indonesian language. In Year 4 of the preservice chemistry teacher education program, at the end of seventh semester, the undergraduate students go to the senior high school for their Practicum. Before visiting the high school, at the university, they prepare and review all high school chemistry topics, including electrochemistry. The university also provides an elective course 'Review of Senior High School Chemistry Curriculum Content' with the purpose to strengthen students' necessary/basic knowledge for teaching chemistry at the high school level as shown in Table 1. Although preservice chemistry teachers are already equipped with General Chemistry course, more advanced chemistry course and application of some basic concepts in other course during the university study, it was evident from comments by lecturers that students sometimes still faced difficulty in understanding basic concepts that needed for teaching high schools.

Development of the Research Instrument

The Electrochemistry Conceptual Test was developed by the authors to investigate the learning in this program based on 10 major propositional content knowledge identified in the literature as shown in Table 2 and consists of 12 two-tier multiple-choice items. The 12 items in the Electrochemistry Conceptual Test were defined by 10 propositional content knowledge statements needed to understand the five major concepts. Most items stated in Table 2 were developed by the authors as well as other sources, such as Schmidt et al. (2007) and Authors (2012). Schmidt et al. (2007) implemented a multiple-choice test from which we took four items, used the items as the first tiers in our test and then developed the second tiers. We also took a two-tiers item from Authors (2012) and modified it so that it matched with the concept assessed and propositional content knowledge statement. The instrument (in the English and Indonesian languages) is presented as the Electronic Supplementary Materials #1.

Table 2 Electrochemistry Conceptual Test and Sources of Items

Concepts assessed	Propositional content knowledge statements	Item no.	Source
Arrangement of the components of a voltaic cell and their functions.	1. The electrode that is involved in the reaction of a voltaic cell is called an active electrode while the electrode that is not involved in the reaction is an inactive electrode.	1	Authors
	2. The salt bridge in a voltaic cell enables ions to move between the half-cells.	2, 3	Authors
Generation of electrical energy from redox reactions in a voltaic cell.	3. When a voltaic cell is established, electrons produced at the anode (where oxidation occurs) are conducted through the external circuit and are consumed at the cathode (where reduction occurs).	4	Authors
	4. For the electrolyte to remain neutral, cations migrate from the anode half-cell towards the cathode half-cell while anions migrate in the opposite direction.	5, 6	Schmidt et al., 2007 Authors
Working principles of electrolytic cells.	5. In an electrolytic cell an external current source (e.g., a battery) is used to produce a chemical change.	7	Schmidt et al, 2007
	6. The solution that is electrolyzed in an electrolytic cell is a strong electrolyte which consists of freely moving cations and anions.	8	Schmidt et al., 2007
	7. The cathode of the electrolytic cell is connected to the negative pole of the battery so it has a negative charge, while the anode is connected to the positive pole and has positive charge.	9	Authors

Redox reactions in electrolytic cells	8. The electrons that are released at the anode by the anions migrate through the metallic wire to the cathode via the battery.	10	Authors
	9. During electrolysis, the concentration of the electrolyte may change depending on which species reacts at the anode and the cathode.	11	Authors
	10. In the process of electroplating the metal that is to be coated is the cathode and the metal that is used as the coating metal is the anode.	12	Modified from Authors (2012)

The two tiers of the items are multiple-choice in nature. The first tier provides a content response to the question with one scientifically correct response and a number of incorrect responses, often alternative conceptions known to be held by students. The second tier solicits a reason for the answer to the first tier. This multiple-choice tier also consists of one scientifically correct response and other responses that were commonly known alternative conceptions. The items that were developed by the authors were based on the method proposed by Author (1988). When students can answer correctly in both tiers, this meant that they are more likely to fully understand the concept/sub-concept measured. The test was carefully designed based on previous research for the first and the second tiers based on misconceptions in the literature and conducting interviews by the authors to complete the options. As shown in Table 2. the instrument comprises two parts to assess understanding of voltaic cells (items 1- 6) and electrolytic cells (items 7-12).

Data Analysis Procedures

In this research, the instrument was used to diagnose learning outcomes of students' understanding of electrochemistry concepts. We report item difficulty and discrimination indices and item analysis to compare the student scores on the instrument. We also analysed the data to identify any alternative conceptions that would appear to be limiting the students' further understanding these concepts.

Pilot study

In developing the items, a pilot study was conducted. A multiple-choice instrument with open-ended responses was given to a class of 32 preservice chemistry education students. These open-ended responses were analysed and the most common alternative conceptions were used as responses to construct the second tier of the multiple-choice items. One of the responses in the second tier was the scientifically correct response. The first version of the two-tier instrument had 55 items. The two-tier instrument was piloted with a sample of two classes, comprising a different group of 67 preservice science education teachers who took General Chemistry at that time. The curriculum of preservice science teachers is similar to the curriculum of the preservice chemistry education teachers in this university. The test had a reliability of 0.91 with 50 valid items, later reduced to 12 items as a manageable number to be administered to students in one class period. Analysis with these 12 items which has a Cronbach alpha reliability coefficient of 0.64 is described below.

Validity

The 12 items in the Electrochemistry Conceptual Test were validated by two chemistry academics from the Chemistry Department of the first author's university. Each validator was given a list of the items and a scoring sheet using a rubric shown in Table 3. They were asked to examine each item in terms of communicativeness of the language of the item and the correctness of the item corresponding to the concept in the specification grid that was provided. The first validator scored 1 for three items and 2 for nine items. The second validator scored 2 for all items. After discussing with each other and making changes to the three items, the two validators reached complete agreement (Lavrakas, 2011).

Table 3 Rubrics for Validation of the Electrochemistry Conceptual Test

Score	Explanation
2	The item was both easily understood AND corresponds to the content knowledge statements written in the specification grid.

1	The item was either easily understood OR corresponds to the content knowledge statements written in the specification grid.
0	The item was neither easily understood nor corresponds to the content knowledge statements written in the specification grid.

Reliability

The items involved the principles related to the working of voltaic cells and electrolytic cells. The Cronbach's alpha reliability value for the whole instrument of 0.64 was over the threshold value of 0.50 recommended by Nunally and Bernstein (1994). Adams and Weiman (2010) argue that for Formative Assessment of Instruction (FASI) tools, a low reliability can be reasonable and a high value an indication of redundant items in the assessment tool. An example of an item each about voltaic cells and electrolytic cells in the Electrochemistry Conceptual Test is shown in Figures 1 and 2, respectively. The complete instrument is in the Electronic Supplementary Materials #1 (ESM1 in English version and ESM2 in Indonesian version).

Item 1
Several transition metal elements are usually used as electrodes in electrochemical cells.
Zn and Cu in the voltaic cell in Figure 1 can be considered as:

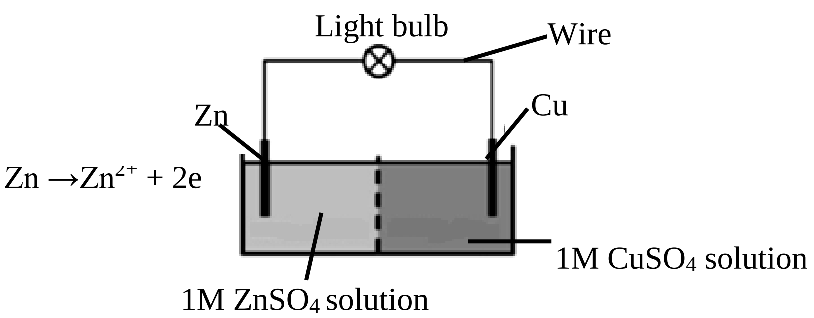

Figure 1

A*. Active electrodes. B. Inert electrodes.

The reason for my answer is:

1. Zn and Cu are transition metals that have strong tendency to be oxidized.
2. The Zn and Cu electrodes do not change when the cell is operating.
3*. Zn and Cu are involved in the redox reactions that occur in the cell.
4. The masses of the electrodes decrease during the reaction.

(* represents correct responses)

Fig. 1. Item #1 on voltaic cells from the Electrochemistry Conceptual Test

Item 9

Consider th

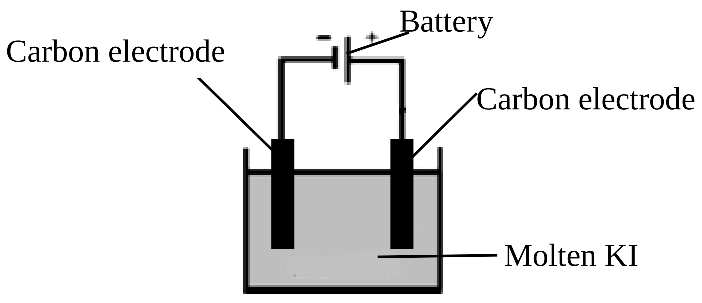

Figure 6

How are the anode and the cathode of the cell determined?
A. By determining the electrode at which a deposit is produced.
B* By considering the poles of the battery that are connected to the electrodes.
C. By comparing the standard reduction potentials of K and I.

The reason for my answer is:
1. As both the electrodes are the same, either one could be the anode or the cathode.
2*. The anode is connected to the positive pole of the battery and the cathode to the negative pole.
3. The element with the higher reduction potential is reduced and deposited at the cathode.

Fig. 2. Item #9 on voltaic cells from the Electrochemistry Conceptual Test

Item difficulty and discrimination indices

Item difficulty indices and discrimination indices of the 12 items are summarised in Table 4.

Table 4 Item difficulty and discrimination indices for the items in the Electrochemistry Conceptual Test

Item No.	Item difficulty index	Item discrimination index	Item No.	Item difficulty index	Item discrimination index
1	0.66	0.60	7	0.61	0.43
2	0.48	0.38	8	0.30	0.53
3	0.67	0.40	9	0.52	0.59
4	0.36	0.69	10	0.21	0.48
5	0.45	0.57	11	0.38	0.71
6	0.18	0.41	12	0.36	0.45

Item difficulty is measured by the number of respondents who provided a correct answer for an item divided by the total number of responses. The smaller the number obtained, the more difficult the item. The discrimination index of an item is a measure of how well the item is able to discriminate between high achieving and low achieving respondents. The index is computed from equal-sized (usually 27%), high and low scoring groups on a test. The difference between the number of successes of the high scoring group and the low scoring group divided by the size of the group, gives the discrimination index. Values of 0.4 and above are considered as highly discriminating while values below 0.2 are low and do not discriminate well between the two groups of respondents. The data in Table 4 show a spread of difficulty indices ranging from 0.18 to 0.66 for the 12 items. Three items (1, 3 and 7) may be considered easy with difficulty indices of 0.66. 0.67 and 0.61, respectively. Items 6 and 10 with difficulty indices of 0.18 and 0.21, respectively, are moderately difficult. The remaining seven items are moderately easy with difficulty indices ranging from 0.30 to 0.52. As for the discrimination indices, all the 12 items with discrimination indices close to or above 0.4 discriminate well between the higher achieving 27% of students and lower achieving 27% of students.

Results

Number of items correct across five years of study

Students' responses to the items were analysed using SPSS software (Version 22). The two-tier items were considered correctly answered if students provided correct responses to both tiers of each item. Correctly answered responses were coded '1' while incorrect responses were coded '0'. The total maximum score for tier 1 was 12. The total maximum score for the combined tiers was 12, calculated when students' responses for both tiers were correct. (When one tier was incorrect or both tiers were incorrect, it was coded '0'). The

Electrochemistry Conceptual Test consisted of two main categories of items involving voltaic cells (6 items) and electrolytic cells (6 items). The mean scores of tier 1 and the combined tiers were analysed for the total test and the two categories are shown in Table 5 and Figure 3.

Table 5 Electrochemistry Conceptual Test mean scores by year level for the total test and the Voltaic cells (6 items) and Electrolytic cells (6 items)

Year Level Max Score	N	Total Tier 1 12	Total Both Tiers 12	Voltaic Tier 1 6	Cells Both Tiers 6	Electrolytic Tier 1 6	Cells Both Tiers 6
Grade12	50	5.84	3.98	3.14	2.10	2.70	1.88
1	58	5.81	3.78	3.10	2.07	2.71	1.71
2	51	7.33	5.24	3.98	3.00	3.35	2.24
3	45	7.29	5.53	3.69	2.89	3.60	2.64
4	62	8.15	6.19	4.39	3.27	3.76	2.92

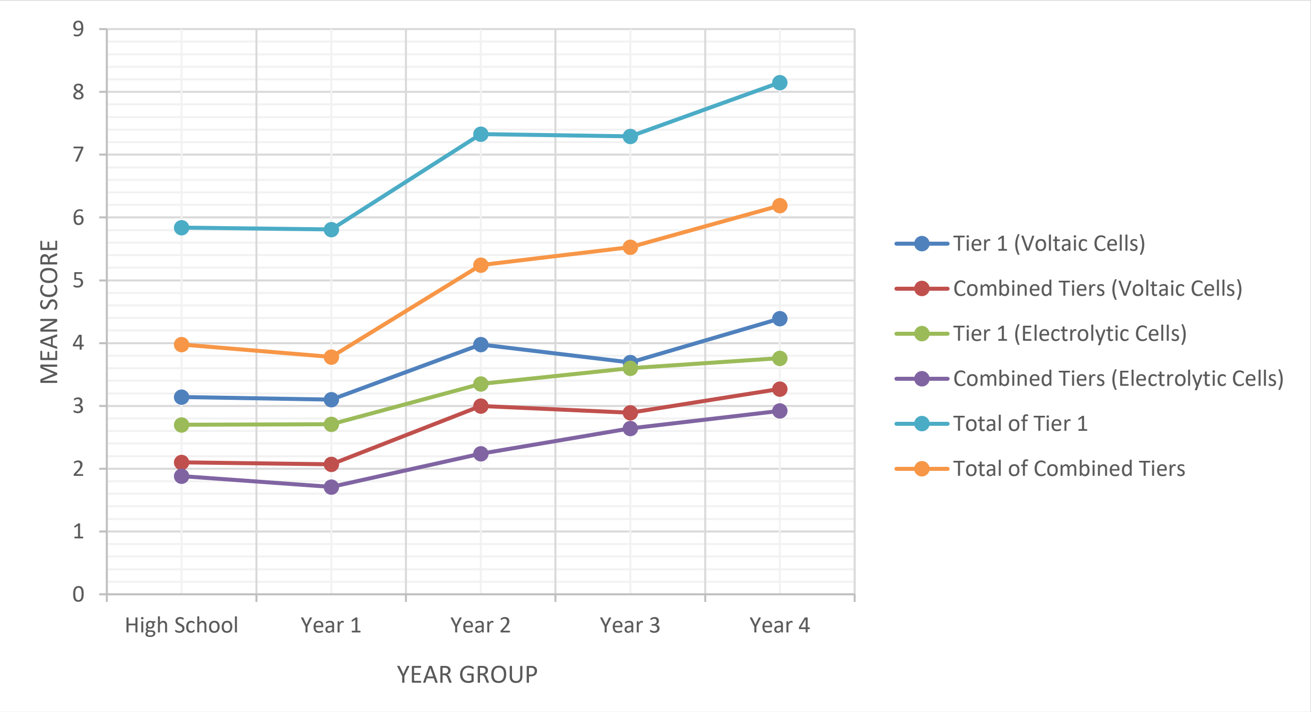

Fig. 3. Mean score of tier 1, combined tiers and total of tier-1 and total of combined tiers in each year group

To ascertain whether or not the difference in the mean scores between the groups was significant, a one-way between-groups analysis of variance (ANOVA) was performed to explore the effect of year level on the total scores. The results of the ANOVA analysis involving the overall scores of each group showed that there were statistically significant differences after making changes for a Bonferroni adjustment in understanding between students in the different year levels [$F(3, 212) = 10.77$, $p = 0.000$]. However, the statistical differences in the combined tiers mean scores were between undergraduates in (a) Year 1 and Year 3 [($M_{yr1} = 3.78$, $SD_{yr1} = 2.48$; $M_{yr3} = 5.53$, $SD_{yr3} = 2.13$); $p = 0.002$; eta-squared = 0.78], and (b) Year 1 and Year 4 [$M_{yr1} = 3.78$, $SD_{yr1} = 2.48$; $M_{yr4} = 6.19$, $SD_{yr4} = 2.50$); $p = 0.000$; eta-squared = 0.97]. There were no statistical differences between mean scores for other combinations of years nor for scores between Grade 12 and Year 1. The finding is positive with these changes between Year 1 and Year 3 and 4 showing eta squared (Cohen's d) (Cohen, 1988) large effect sizes of 0.78 and 0.98, respectively.

Students' overall understanding of electrochemical concepts as reflected in the combined tiers mean scores shows that there is an improvement in students' understanding from Year 1 to Year 4 (ranging from 3.78 to 6.19 as shown in Table 5) but these scores are low compared to a maximum possible score of 12. A similar increase in understanding is displayed for electrolytic cells (see Table 5). For voltaic cells, however, the increasing trend is disrupted when comparing the performance of Years 2 and 3 undergraduates. Tables 5 also shows that the tier 1 mean scores were always higher than the mean scores for the combined tiers suggesting that the students may have learned the answers to the questions without clear understanding; they had selected the correct response to the first tier but were unable to explain their choice of answer.

Percentage of Student Correct Responses for the 12 Items Across Five Years of Study

A comparison of students' responses to the first tier and the combined tiers of each of the 12 items is summarised in Table 6 for high school students and undergraduates from each of the four years. Graphs of these results in Figures 4 and 5 illustrate the unevenness of scores from year to year with these Indonesian students.

Table 6 Comparison of tier 1 and combined tier correct responses to the Electrochemistry Conceptual Test for high school students and the undergraduates from each year

Level	Item no.	Tier 1(%)	Combined tiers (%)	Item no.	Tier 1(%)	Combined tiers (%)
High School (N= 50)						
	1	86 (A)	36 (A3)	7	60 (B)	45 (B2)
	2	62 (B)	54 (B3)	8	60 (B)	38 (B3)
	3	82 (C)	72 (C2)	9	56 (B)	56 (B2)
	4	38 (B)	12 (B4)	10	20 (C)	2 (C2)
	5	36 (C)	28 (C3)	11	26 (C)	18 (C1)
	6	10 (A)	8 (A2)	12	48 (A)	30 (A1)
Year 1 (N = 58)						
	1	78	54	7	74	55
	2	45	31	8	50	21
	3	76	71	9	55	48
	4	60	21	10	19	9
	5	31	21	11	31	21
	6	21	12	12	41	17
Year 2 (N = 51)						
	1	88	74	7	80	60
	2	65	41	8	40	24
	3	69	59	9	67	57
	4	71	47	10	37	22
	5	80	65	11	53	31
	6	26	16	12	59	33
Year 3 (N = 45)						
	1	91	76	7	78	62
	2	71	53	8	60	38
	3	82	76	9	58	53
	4	44	24	10	38	16
	5	49	42	11	60	51
	6	31	18	12	67	44
Year 4 (N = 62)						
	1	90	69	7	79	68
	2	87	66	8	69	39
	3	73	65	9	50	50
	4	77	48	10	57	36
	5	69	55	11	63	52
	6	42	26	12	58	49

Note: 1. The correct responses for each item are shown in parentheses in the high school level 2. The responses are to the nearest whole percent.

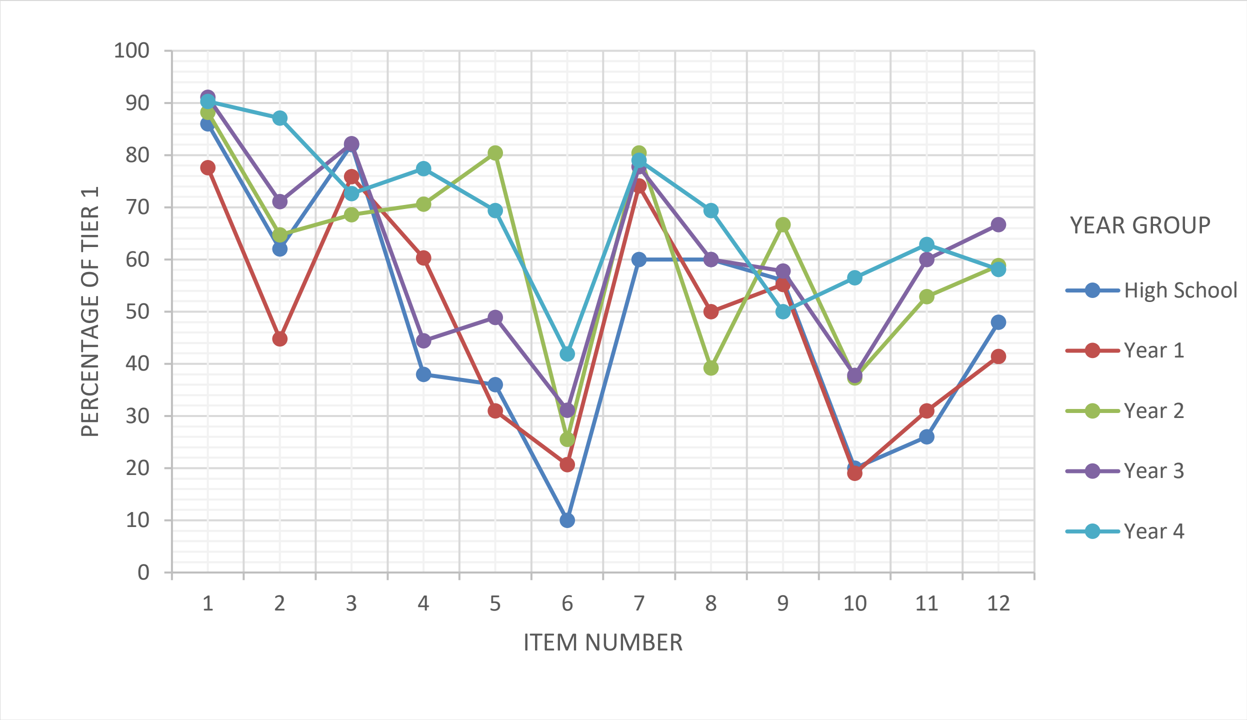

Fig 4. Percentage score of tier 1 of each item test for high school and year 1-4 preservice chemistry education groups

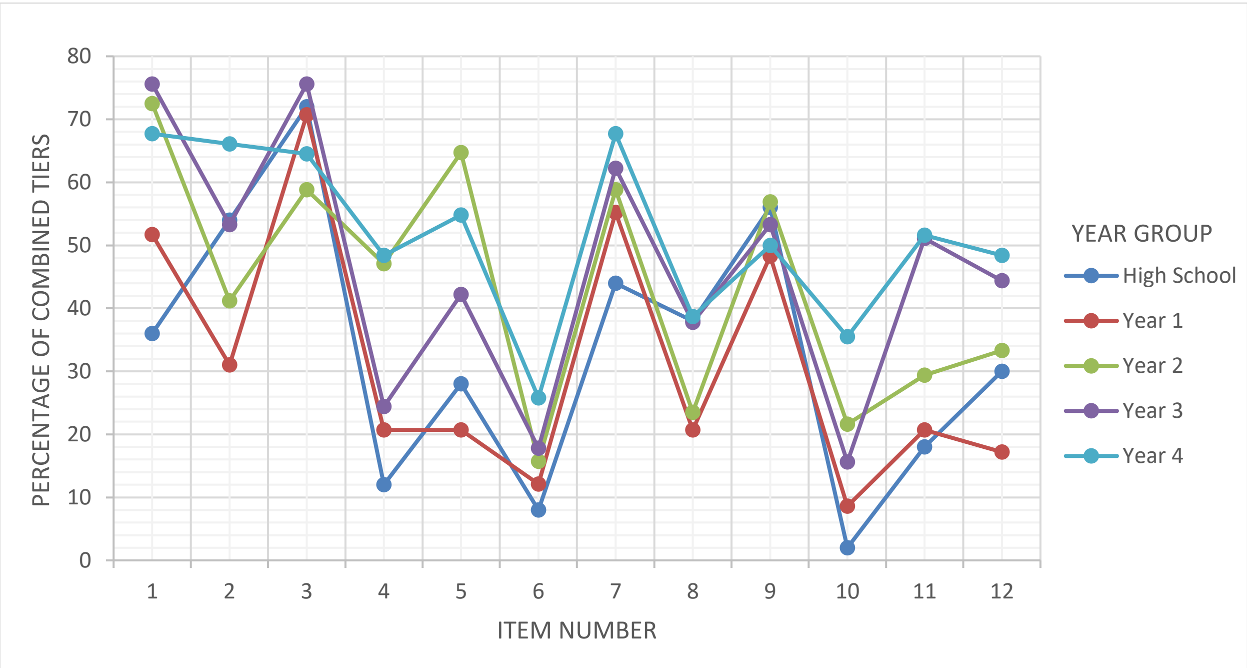

Fig. 5. Percentage score of combined tiers of each item test for high school and Year 1-4 preservice chemistry education groups

The trend of unevenness of scores was also observed for students' responses to each of the items in each of the years (see Table 6 and Figues 4 and 5). There was only one exception to this trend: in Item 9, Year 4 students scored the same percentage (50%) for both the first and the combined tiers of the question.

Discussion of Results

The electrochemical test was shown to be both valid and reliable and identified students' understanding of the learning concepts at the end of high school studies and across the four years of university studies but the findings raise concerns about the level of understanding. The discussion of results from the instrument are presented in terms of the four Concepts Assessed shown in Table 2, namely, *Arrangement of the components of a voltaic cell and their functions* (see Items 1, 2 and 3), *Generation of electrical energy from redox reactions in a voltaic cell* (Items 4, 5 and 6), *Working Principle of electrolytic cells* (Items, 7, 8, 9) and *Redox reactions in an electrolytic cell* (Items 10, 11, 12). Detailed tabulated results are presented in the Electronic Supplementary Materials #2.

Arrangement of Components of a Voltaic Cell and their Functions (Items 1-3)

Item 1 is shown in Figure 1. The results in Table 6 show that students' correct answers increased steadily from high school to Year 1 till Year 3 and slightly decrease in Year 4 (36%, 54%, 74%, 76%, and 69%, respectively). By Year 2, approximately 70% of students understand the concept but the notion of transition metals remains a strong choice for some students. Students have increasingly sound understanding of the function of electrodes in voltaic cells, when they were exposed directly to the concepts. As shown in Table 1, the students were taught the voltaic concepts in grade 12, general chemistry, physical chemistry, and its application in analytical chemistry. In Year 4, although the Chemistry Department provides elective course (i.e., Review of Senior High School Chemistry curriculum content), not all students enrol in the course. There are similar patterns of students' answers from grade 12 in high school to Year 4 at university. Besides the trend of students' increased sound understanding of concepts, they also hold alternative conceptions, such as "understanding that Cu and Zn are active electrodes as transition metals that have strong tendency to be oxidized".

Item 2 is questioning about function of salt bridge: what will happen if the salt bridge was replaced by a piece of Pt wire that is a conductor of electricity? Even though there is an increased sound understanding from Year 1 to Year 4, correct responses are less than 70% of students, 31%, 41%, 53%, and 66%. Most high school students have better understanding than Year 1 and Year 2. It seems this concept is difficult for almost all students. Many students in high school (20%) and Year 1 (33%) held the alternative conception that electricity is produced because there is a continuous flow of electrons through the platinum wire. However, students who hold this alternative conception decreased in Years 2 and 3 and was not evident in Year 4. A similar pattern of students' conception happened from grade 12 to Year 3 of students. Students responded that electricity is produced because there is a continuous electron flow from the external wire and go to solution in voltaic cells, then pass through platinum wire. Both the answer and the reason are incorrect. If the salt bridge is replaced by a piece of platinum wire, no electricity is produced. The basic misunderstanding is the function of the salt bridge combined with students' understanding that platinum is an element with high electrical conductivity. Similar results are reported by Sanger and Greenbowe (1997) and Author (2011). In the study by Amposah (2020, p.365) who explored grade-12 students' conceptions regarding electrochemistry in South Africa, fsimilar results were found where students conceptions about electron movement hampered their conception of the function of the salt bridge.

Item 3 enquires about the function of gelatine of salt bridge if a strong electrolyte is replaced by a weak electrolyte. Students' responses of correct answers are varied between 59% - 76% from Year 1 till Year 4. Even, most grade 12 students (74%) have sound understanding of this concept. However, there is similar pattern of alternative conceptions hold by students from high school to Year 4, that is "an electric current will not be produced, because a weak electrolyte does not ionise completely and so the charge at the cathode and anode is not neutralised."

Generation of Electrical Energy from Redox Reactions in a Voltaic Cell (Items 4-6)

Items 4 and 5 which refer to the voltaic cell in Figure 1 enable teachers or researchers to identify students' understanding of the role of the electrons and ions, respectively, when the voltaic cell is operating. It is clear form these two items that this sample of grade 12 and university preservice chemistry education students have not developed a good understanding of the workings of a voltaic cell with wide range of possible choices selected for both items with responses ranging from 12% and 28% in high school to 48% and 54% in Year 4.

Responses to item 6 that examined electron flow with a salt bridge between two electrolytes had even lower correct responses from 12% to 26%., These same learning difficulties in electrochemistry related to electric current during electrolysis producing ions, electrons migrating through the solution, the cathode being a minus pole, and the plus and minus poles having net electronic charges were identified by Schmidt et al. (2007) with secondary-school students' responses to multiple choice test items. In a study to examine the effectiveness of an interactive multimedia module on students' learning of the electrochemistry, Tien and Osman (2017) noted that students assumed that the electrons flowed in the electrolyte to complete the circuit, a similar finding to the study with Pakistani students by Akram et al. (2014).

Working Principle of Electrolytic Cells (Items 7-9)

Item 7 required students to identify the cathode in electrolytic cells and provide the correct reason. A slight majority of the students increasingly have the correct concept from grade 12 to Year 4, 45%, 55%, 60%, 62% and 68%, respectively. The same pattern of alternative conceptions that exist from grade 12 to Year 4, ranged from 12% to 18% of the students. These students do not recognise that in an electrolytic cell, the source of the electrons is the external power source which must draw electrons away from the anode; thus, the anode must be connected to the positive terminal of the battery. Meanwhile, the power source drives electrons toward the cathode, so the cathode must be connected to the negative terminal of the battery. Other researchers have reported similar scientifically inappropriate understandings about the electrodes in electrolytic cells in Japan, Malaysian and the US (Authors, 1992; 2002; Sanger & Greenbowe, 1997).

Item 8, with four content choices and four reasons, showed that the students' sound understanding was not linier, in which, grade 12 students and Years 3-4 students had similar understanding (38 - 39%), and Years 1- 2 responded lowest (21-24%). There is a consistent alternative conception across years. Students gave correct answer for the tier-1 but were unable to provide the correct reason in tier-2. The alternative concept is that "at the negative electrode two H^+ ions bond together to form H_2". Students are unable to recognize that reduction occurs in the negative electrode not covalent bonding of H_2. Authors (2012) investigated the nature of redox reaction at an electrode was investigated with 330 Malaysian students; only 32% answered correctly those items that were related to anode and cathode in electrolytic cells. The study showed that the electrolysis reaction seems difficult for students to understand because of the abstractness of the concept that needs formal explanations of invisible interactions at the particulate level of representations (Carr, 1984)

Item 9 required students to determine the anode and the cathode in an electrolytic cell and give the reason for this choice (see Figure 2). Less than 70% of students in each level (ranged between 48% - 57%) provided the correct answer to consider the poles of the battery that are connected to the electrodes, because the anode is connected to the positive pole of the battery and the cathode to the negative pole. Some students from grade 12 to Year 4 (except Year 3), ranged from 12% - 24%, hold the alternative conception that the anode and the cathode of the cell are determined by which electrode has a deposit. From item 9, an alternative conception identified in Years 1- 4 university students was not understanding that the anode and the cathode of the cell are determined by comparing the standard reduction potentials of K. This difficulty of understanding has been identified in other research when students were unable to understand the role of the anode and cathode in electrolytic cells (Authors, 2012, Acar & Tarhans, 2007; Bong & Lee, 2016).

Redox Reactions in Electrolytic Cell (Items 10-12)

The responses to items 10 - 12 with four content choices (except item 12) and four reasons, showed that the students responded similarly to items 4 and 5 with a lot of variability of responses so little can be determined about this sample of students. In both items, although less than 53% students increasingly possess content knowledge about electrolysis process there were no consistent explanations for the changes that had occurred. All possible alternative conceptions were chosen across the five years. That there are consistent difficulties with this concept was identified by Amponsah (2020) and Loh and Subramaniam (2018) and is consistent with Author (2012) where, based on their selection of the items correctly, less than 45% of students displayed an understandings of electrolysis.

Especially for item 10, students' responses were random and there was no consistency which implied that the students had difficulty concerning the abstract concepts of ions, cations and anions. The particulate nature of matter (e.g ions, cations, anions) is one of fundamental concepts to learning chemistry (Abraham, Williamson, & Westbrook, 1994; Nakhleh, 1992). If the students do not understand the fundamental concept, they will find electrochemistry concepts difficult (Sirhan, 2007). Another issue that may have accounted for the random responses for Item 10 is that the referring Figure 5 was on a previous page and the student did not refer to that figure.

Conclusion

The results of the study suggest that these Indonesian students in grade 12 high school and Years 1-4 undergraduate preservice chemistry teacher students have not fully understood the electrochemical concepts at the end of their teacher education program. In Indonesia, students learn electrochemistry concepts in Grade12 in high school and during their first and second years at university and are shown applications of electrochemistry concepts in later years of the course. Also, the basic electrochemistry concepts are reviewed before their practicum in senior high school. Despite these learning opportunities, these students' knowledge and understanding of basic electrochemistry concepts appears to remain limited throughout the university studies. However, there was a general trend of increase in understanding of electrochemical concepts as students proceeded from first to fourth year in university as shown Table 5 and Figure 3. While Year 4 undergraduates displayed the best understanding of these concepts, their overall scores for both voltaic and electrolytic cells were below the maximum possible scores.

The overall results of this study also indicate that students' scores for the combined tiers of each item were less than those for the first tier indicating that although students possessed correct knowledge about several concepts, they were unable to explain the reasons for their particular answers. This trend suggests that students may have learned several concepts by rote without understanding. Based on the findings of this study, we can conclude that there was insufficient development of students' understanding of electrochemical concepts from high school and through the four years of university education. The expectation is that the electrochemistry curriculum at university level should build on what students have learned at grade 12. The limited progress is likely partly due to students retaining the alternative conceptions which they may have first developed from high school. Nevertheless, similar to the investigation of students' scientific understanding of thermal concepts across grade levels by Adadan and Yavuzkaya (2018), the conceptual development occurred in an uneven manner across grade levels, as shown in Table 6 and Figures 4 and 5, even though there was a general mean increase.

Implications for teaching

The findings of this study suggest that there are inherent weaknesses in the implementation of the electrochemistry curricula at the high school and university level, at least in this Indonesian sample, but that the overall results have similarities with studies of students in other countries who are learning electrochemistry concepts. It is likely that the university lecturers in this study assumed that students in their chemistry education classes already learned the electrochemical concepts from their high school studies. Unfortunately, there is no opportunity to address students' alternative conceptions in the General Chemistry course due to the dense content to be taught in this course. Also, students enter the Preservice Chemistry Teachers program from many different public and private high schools and municipalities in East Java. Similarly, these undergraduate students may still have difficulties and hold alternative conceptions when they learn more advanced electrochemistry in Physical Chemistry II. In this course, there was no special treatment also for students' alternative conceptions and teaching strategy is similar to that for General

Chemistry. Given what science educators know about diagnosing and improving learning, we recommend that the university chemistry lecturers modify their instruction to facilitate more meaningful learning. Administering a diagnostic test may be useful to identify students' understanding or alternative conception of electrochemistry concepts in the General Chemistry course (Year 1), or even in the Physical Chemistry (Year 2) and Analytical Chemistry (Year 3) courses, and more importantly in the course of Review of senior high school topics. Especially in the course that reviews senior high school topics, a teacher candidate should be aware of some alternative conceptions held by students and be prepared how to accommodate these conceptions in their teaching before going to schools. Further some education in-service with the lecturers would be helpful to advice on using research findings on this topic by implementing conflict cognitive strategy, an animation, or modelling. This in-service education could include computer animations at the particulate level to help students develop and improve their conceptual understanding of electrochemistry topics (Cole, Rosenthal, & Sanger, 2019; Tsaparlis, 2019). However, care needs to be made so inaccurate visual images are avoided; even accurate visual images should be scrutinised for avoiding alternative conceptions by the students viewing them (Cole, Fuller, & Sanger, 2021).

Limitations of the Study

The advantages of using two-tier multiple-choice items are that students recall their knowledge and have the opportunity to compare a correct answer with several incorrect ones in both tiers. Also, the test is time-efficient with large samples. However, the second tier is mostly difficult for students if they do not have a clear understanding of the concept behind the first tier. Making the correct choices, especially when there is no opportunity for discussion, with a large number of choices in both tiers can result in very diverse response patterns which was the case for item 8 on the working principle of electrolytic cells and items 10-12 concerning redox reactions in electrolytic cells. Especially, items with three or four content choices and three or four reasons choices may be too difficult to answer in the allocated time for completing the instrument. Another limitation of this study is that the data were collected in one university in Indonesia where the focus is teacher education, in this case chemistry teacher education. Nevertheless, there are many universities with the same goals across all provinces in Indonesia and many countries around the world. Hence, it is likely there are similar teaching approaches and the same student learning outcomes with limited understanding of electrochemical cells.

Acknowledgements

References

Abraham, M. R., Williamson, V. M., & Westbrook, S. L. (1994). A cross-age study of the understanding of five chemistry concepts. *Journal of Research in Science Teaching, 31*(2), 147–165. https://doi.org/10.1002/tea.3660310206

Acar, B. & Tarhan, L. (2007). Effect of cooperative learning strategies on students' understanding of concepts in electrochemistry. *International Journal of Science and Mathematics Education, 5*, 349–373. https://doi.org/10.1007/s10763-006-9046-7

Adadan, E., & Yavuzkaya, M. N. (2018). Examining the progression and consistency of thermal concepts: A cross age study. *International Journal of Science Education, 40(*4), 371-396. https://doi.org/10.1080/09500693.2018.1423711.

Adams, W. K. & Wieman, C. E. (2011). Development and validation of instruments to measure learning of expert-like thinking. *International Journal of Science Education, 33*(9), 1289-1312. https://doi.org/10.1080/09500693.2010.512369.

Akram, M., Surif, J. & Ali, M . (2014). Conceptual difficulties of secondary school students in electrochemistry. Asian Social Science, 10 (19), 276-281.10.5539/ass.v10n19p276

Alonzo, A. C. & Gotwals, A. W. (2012). *Learning progressions in science: Current challenges and future directions*. Rotterdam, The Netherlands: Sense Publishers. http://dx.doi.org/10.1007/978-94-6091-824-7.

Amponsah, K. D. (2020). South African twelfth grade students' conceptions regarding electrochemistry. *Journal of Education and Learning, 14*(3), 362-368. https://doi.org/10.11591/edulearn.v14i3.16273

Amponsah, K. D., Kotoka, J. K., Beccles, C. & Dlamini, S. N. (2018). Effectiveness of collaboration on low and high achieving school students' comprehension of electrochemistry in South Africa. *European Journal of STEM Education, 3*(2), 04. https://doi.org/10.20897/ejsteme/2685.

Ayas, A., Ozmen, H., & Calik, M. (2010). Students' conceptions of the particulate nature of matter at secondary and tertiary level. *International Journal of Science and Mathematics Education, 8*(1), 165-184. https://doi.org/10.1007/s10763-009-9167-x.

Ball, D.W. (2015). *Physical chemistry* (2nd ed.). USA: Wadsworth Cengage Learning.

Birk, J. P. & Kurtz, M. J. (1999). Effect of experience on retention and elimination of misconceptions about molecular structure and bonding. *Journal of Chemical Education, 76,* 124-128.https://doi.org/10.1021/ed076p124.

Bong, A.Y. L & Lee, T. T. (2016). Form four students' misconceptions in electrolysis of molten compounds and aqueous solutions. Asia-Pacific Forum on Science Learning and Teaching, 17 (1). https://www.eduhk.hk/apfslt/

Bradley, J. D., & Ogude, N. A. (1996). Electrode processes and aspects relating to cell emf, current, and cell components in operating electrochemical cells: Precollege and college student interpretation. *Journal of Chemical Education, 73*(12),1145. https://doi.org/10.1021/ed073p1145

Brown, T.L., LeMay, H. E., Bursten, B.E., Murphy, C.J., Woodward, P. M., Stoltzfus, M.W., & Lufaso, M.W. (2018). *Chemistry: The central science*. Malaysia: Pearson.

Carr, M. (1984). Model confusion in chemistry. *Research in Science Education,* 14, 97–103. https://doi.org/10.1007/BF02356795

Castellan, G.W. (1983). *Physical chemistry* (3rd ed.). Boston, MA: Addison-Wesley.

Chang, R. & Overby, J. (2011). *General chemistry: The essential concepts* (6th ed.). New York: McGraw Hill.

Cheung, D. (2011). Using diagnostic assessment to help teachers understand the chemistry of the lead-acid battery. *Chemistry Education Research and Practice, 12*(2), 228-237. https://doi.org/10.1039/C1RP90028E.

Childs, P. E. & Sheehan, M. (2009). What's difficult about chemistry? An Irish perspective. *Chemistry Education Research and Practice, 10*(3), 204-218. https://doi.org/10.1039/B914499B.

Christian, G. D., Dasgupta, P.K., & Schug, K. A (2014*). Analytical chemistry* (Seventh ed.). Arlington, TX: Wiley.

Cohen, J. (1988). *Statistical power analysis for the behavioural sciences* (2nd ed.). Hillsdale, NJ: Lawrence Erlbaum Associates.

Cole M. H., Rosenthal D. P. and Sanger M. J., (2019), Two studies comparing students' explanations of an oxidation- reduction reaction after viewing a single computer animation: The effect of varying the complexity of visual images and depicting water molecules, *Chemistry Education Research & Practice, 20*, 738–759.https://doi.org/10.1039/C9RP00065H

Cole, M. H., Fuller, D. K., & Sanger, M. J. (2021). Does the way charges and transferred electrons are depicted in an oxidation–reduction animation affect students' explanations? *Chemistry Education Research and Practice, 22*(1), 77–92. http://doi.org/10.1039/d0rp00140f

Creswell, J. W. (2012). *Educational research* (4th ed.), Upper Saddle River, NJ: Pearson Education Inc.

De Jong, O., & Treagust, D. F. (2002). The teaching and learning of electrochemistry. In Gilbert, J. G., De Jong, O., Justi, R. Treagust, D. F. & van Driel, J. H. (Eds.). *Chemical education: Towards research based practice* (pp. 317-338). Dordrecht, The Netherlands: Kluwer

Garnett, P. J. & Treagust, D. F. (1992). Conceptual difficulties experienced by senior high school students of electrochemistry: electrochemical and electrolytic cells. *Journal of Research in Science Teaching, 29,* 1079-1099.https://doi.org/10.1002/tea.3660291006

Garnett, P. J., Garnett P. J. & Hackling M. W. (1995). Students' alternative conceptions in chemistry: A review of research and implications for teaching and learning. *Studies in Science Education, 25*(1), 69-96.DOI: https://doi.org/10.1080/03057269508560050.

Günter, T. & Alpat, S. K. (2017). The effects of problem-based learning (PBL) on the academic achievement of students studying 'Electrochemistry'. *Chemistry Education Research and Practice*, *18*, 78-98. DOI: https://doi.org/10.1039/C6RP00176A.

Harvey, D. (2000). *Modern analytical chemistry*. New York, NY: McGraw-Hill.

Herga, N. R, Čagran, B., & Dinevski, D. (2016). Virtual laboratory in the role of dynamic visualisation for better understanding of chemistry in primary school. *Eurasia Journal of Mathematics, Science and Technology Education, 12*(3), 593-608. https://doi.org/10.12973/eurasia.2016.1224a.

Huddle, P. A. & White, M. D. (2000). Using a teaching model to correct known misconceptions in electrochemistry. *Journal of Chemical Education, 77*(1), 104-110. https://doi.org/10.1021/ed077p104.

Keen, C., Couture, S., El Meseh, N.A. & Sevian, H. (2020). Connecting theory to life: Learning greener electrochemistry by taking apart a common battery. *Journal of Chemical Education*, *97* (4), 934-942. https://doi.org/10.1021/acs.jchemed.9b00840.

Lavine, I. N. (2009). *Physical chemistry* (6th ed). New York, NY : McGraw-Hill.

Lavrakas, P. J. (2011). Interrater reliability. In Lavrakas (Ed.), *Encyclopedia of survey research methods* (pp. 360-362). Thousand Oaks, CA: Sage Publications.

Lee, T. T. & Osman, K. (2017). Misconceptions in electrochemistry: How do pedagogical agents help? In M. Karpudewan, A. N. Md Zain and Chandrasegaran (Eds.). *Overcoming students' misconceptions in science: Strategies and perspectives from Malaysia* (pp. 91-110). Singapore: Springer.

Loh, A. S. L., & Subramaniam, R. (2018). Mapping the knowledge structure exhibited by a cohort of students based on their understanding of how a galvanic cell produces energy. *Journal of Research in Science Teaching*, *55*(6), 777-809. https://doi.org/10.1002/tea.21439

McMurray, J. E., Fay, R. C., & Robinson, J.K. (2016). *Chemistry* (7th ed). New York: Pearson.

Nakhleh, M. B. (1992). Why some students don't learn chemistry: Chemical misconceptions. Journal of Chemical Education, 69(3), 191-196. https://doi.org/10.1021/ed069p191

Niaz, M. (2002). Facilitating conceptual change in students' understanding of electrochemistry. *International Journal of Science Education, 24*(4), 425-439. https://doi.org/10.1080/09500690110074044.

Niaz, M., & Chacón, E. A. (2003). Conceptual change teaching strategy to facilitate high school students' understanding of electrochemistry. *Journal of Science Education and Technology 12*, 129–134. DOI: https://doi.org/10.1023/A:1023983626388.

Nunally, J. C. & Bernstein, I. H. (1994). *Psychometric theory* (3rd ed.). New York: McGraw-Hill.

Önder, İ. (2017). The effect of conceptual change texts supplemented instruction on students' achievement in electrochemistry. *International Online Journal of Educational Sciences*, *9* (4), 969 -975. http://dx.doi.org/10.15345/iojes.2017.04.006.

Osman, K. & Lee, T.T. (2014). Impact of interactive multimedia module with pedagogical agents on students' understanding and motivation in the learning of electrochemistry. International *Journal of Science and Mathematics Education*, *12*, 395–421. https://doi.org/10.1007/s10763-013-9407-y.

Özkaya, A. R. (2002). Conceptual difficulties experienced by prospective teachers in electrochemistry: Half-cell *potential, cell potential, and chemical and electrochemical equilibrium in galvanic cells. Journal of Chemical Education, 79*(6), 735-738. https://doi.org/10.1021/ed079p735.

Özkaya, A. R., Üce M., Sarıçayır, H. & Sahin, M. (2006). Effectiveness of a conceptual change-*oriented teaching strategy to improve students' understanding of galvanic cells. Journal of Chemical Education, 83*(11), 1719-1723. https://doi.org/10.1021/ed083p1719.
Rahayu, S., Treagust, D.F., Chandrasegaran, A.L., Kita, M. & Suhadi Ibnu, S. (2011). Assessment of electrochemical concepts: A comparative study involving senior high school students in Indonesia and Japan. Research in Science & Technological Education, 29(2), 169-188. https://doi.org/10.1080/02635143.2010.536949
Rosenthal, D. P., & Sanger, M. J. (2012). Student misinterpretations and misconceptions based on their explanations of two computer animations of varying complexity depicting the same oxidation–reduction reaction. *Chemistry Education Research & Practice*, *13(*4), 471–483. https://doi.org/10.1039/C2RP20048A
Sanders, R. W., Crettol, G. L., Brown, J. D., Plummer, P. T., Schendorf, T. M., Oliphant, A., Swithenbank, S. B., Ferrante, R. F., & Gray, J. P. (2018). Teaching electrochemistry in the general chemistry laboratory through corrosion exercises. *Journal of Chemical Education*, *95* (5), 842-846. https://doi.org/10.1021/acs.jchemed.7b00416.
Sanger M. J. & Greenbowe T. J. (1997). Students' misconceptions in electrochemistry: current flow in electrolyte solutions and the salt bridge. *Journal of Chemical Education*, *74*(4), 819-823. https://doi.org/10.1021/ed074p819.
Schmidt H. J., Marohn A. & Harrison A. G. (2007). Factors that prevent learning in electrochemistry. *Journal of Research in Science Teaching*, *44*(2), 258–283. https://doi.org/10.1002/tea.20118.
Shepard, L. A. (2018). Learning progressions as tools for assessment and learning, *Applied Measurement in Education*, *31*(2), 165-174. https://doi.org/10.1080/08957347.2017.1408628
Sia, D. T., Treagust, D. F. & Chandrasegaran, A. L. (2012). High school students' proficiency and confidence levels in displaying their understanding of basic electrolysis concepts. International Journal of Science and Mathematics Education, 10 (6), 1325-1345.10.1007/s10763-012-9338-z
Sirhan G. (2007). Learning difficulties in chemistry: An over- view, Journal of Turkish Science Education, 4, 2–20. https://www.tused.org/index.php/tused/article/view/664
Soeharto, Csapo, B., Sariminah, E., Dewi, F. I. & Sabri, T. (2019). A review of students' common misconceptions in science and their diagnostic assessment tools. *Jurnal Pendidikan IPA Indonesia*, *8*(2), 247-266. http://dx.doi.org/10.15294/jpii.v8i2.18649.
Tien, L. T., & Osman, K. (2017). Misconceptions in electrochemistry: how do pedagogical agents help? In Karpudewan M., Md Zain A., Chandrasegaran A. (Eds), *Overcoming students' misconceptions in science* (pp. 91-110). Singapore: Springer. https://doi.org/10.1007/978-981-10-3437-4_6
Treagust, D. F. (1988). Development and use of diagnostic tests to evaluate students' misconceptions in science. *International Journal of Science Education*, *10*(2),159-169. DOI: 10.1080/0950069880100204
Tsaparlis, G. (2019). Teaching and learning electrochemistry. *Israeli Journal of Chemistry*, *59*, 478-492. https://doi.org/10.1002/ijch.201800071
Yang E-M., Andre, T., Greenbowe, T. J. & Tibell, L. (2003). Spatial ability and the impact of visualization/animation on learning electrochemistry. *International Journal of Science Education*, *25*(3), 329-349. http://dx.doi.org/10.1080/09500690210145738b.
Yeo, S., & Zadnik, M. (2001). Introductory thermal concept evaluation: Assessing students' understanding. *The Physics Teacher*,*39*(8), 496–504. https://doi.org/10.1119/1.1424603