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ORIGINAL ARTICLE

Evaluating Chinese Secondary School Students' Understanding of Green Chemistry

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ABSTRACT

This study aimed to examine the understanding of secondary school students about green chemistry-related concepts, to include raw materials, solvent, and atom economy. Interviews were conducted with secondary school students from Grades 9 to 12 to acquire their descriptive understanding of the corresponding concepts. Based on the systematic analysis of the collected data, a semi-structured two-tier diagnostic instrument was proposed, which was then administered to secondary school students. Some options that were less often selected by respondents were eliminated. Using the revised instrument, a pilot survey was conducted among secondary school students, and the similar elimination procedure was followed. The final instrument was used to conduct a survey among secondary school students from Grades 9 to 12 for examining their understanding of various concepts related to green chemistry. The results showed that secondary school students' understanding of green chemistry-related concepts and the term "green chemistry" was low. However, the older students' understanding of the corresponding concepts was significantly superior to that of the younger students. No noticeable differences were found between male and female students. The findings of this study can help teachers to better examine the knowledge mastered by their students and evaluate progression in learning green chemistry.

KEY WORDS: chemical science, conceptual understanding, green chemistry, students, two-tier diagnostic instrument

INTRODUCTION

After the intensification of the conflicts between chemical production and the natural environment, chemists have re-examined and reformed conventional chemistry from the perspective of resource preservation and pollution prevention to reduce environmental damages. In 1990, the United States Congress introduced the concept of "green chemistry" in the Pollution Prevention Act (EPA, 1990), which was primarily based on "atom economy." Green chemistry, which is a new concept guiding the development of chemical science, provides a fundamental solution to the aforementioned problem from the perspective of molecular science. Rather than reducing environmental harm by "patching" the existing damage, green chemistry aims to prevent the pollution to ensure that such an issue never endangers human life (Anastas and Warner, 1998). Karpudewan et al. (2012) noted that green chemistry is not a new branch of science, but a new and responsible approach of thinking about science.

Green chemistry is significant in supporting the sustainable development of chemistry (Anastas and Zimmerman, 2018). As a vital part of chemistry education, green chemistry is crucial in training students to become responsible chemists and citizens. At the 3rd Green and Sustainable Chemistry Conference, Berlin, Germany in 2018, experts exchanged scientific insights, challenges, and perspectives on green issues, including topics, such as energy conversion and storage, biological resources, environmental science, and sustainable chemistry in pharmacy and education (Elschami and Bazzanella, 2019). China's 2017 edition of the General Senior Secondary School Chemistry Curriculum Standard (The Ministry of Education of the People's Republic of China, 2018) explicitly emphasizes the education of "green chemistry" and requires students to develop an awareness of green chemistry and a sense of sustainable development as well as to take responsibility and actively participate in the decisions on social issues related to chemistry. Such requirements set high expectations for the students' involvement in sustainable development (The Ministry of Education of the People's Republic of China, 2018). This approach is reinforced in the textbook Senior Secondary School Chemistry (Compulsory 2) published by the People's Education Press (Song et al., 2004), which systematically introduces the concepts of green chemistry, the atom economy, and the "twelve principles of green chemistry."

Secondary school students from Grades 9 to 12 are in an early stage of learning green chemistry-related theories. Therefore, an assessment of students' understanding of and awareness on green chemistry is crucial to achieve the corresponding educational goals. The existing instruments related to green chemistry mainly used to assess students' environmental and green chemistry awareness are mostly based on interviews (Mandler et al., 2012; Karpudewan et al., 2015b;

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Shamuganathana and Karpudewan, 2017), questionnaire surveys (Qiao et al., 2013; Aubrecht et al., 2015), tests (Karpudewan et al., 2015a), and student self-report surveys (Gron et al., 2013; Aubrecht et al., 2015; Kennedy, 2016; Shamuganathana and Karpudewan, 2017). Unfortunately, there is a lack of a reliable tool to comprehensively evaluate the understanding of green chemistry concepts among secondary school students.

Research Objectives

This study aimed to develop an instrument to assess students' understanding of green chemistry concepts from Grades 9 to 12. The two-tier diagnostic instrument is a simple method accessible to science teachers for examining the understanding of a scientific concept among a large number of students, as it can be conducted using a paper and pen it is easy to conduct and time-efficient for teachers (Treagust, 1988). The two-tier diagnostic instrument was first proposed by Treagust in 1985 and has been used by numerous researchers (Treagust, 1988; Peterson and Treagust, 1989; Krishnan and Howe, 1994; Odom and Barrow, 1995; Zhang and Zhang, 2007; Mcclary and Bretz, 2012) to evaluate students' understanding of their existing scientific concepts. Therefore, a two-tier diagnostic instrument was developed in this study to investigate secondary school students' understanding of green chemistry concepts, such as raw materials, solvents, and catalysts, as well as green chemistry principles, applications, synthetic processes, and social and economic significance. The research addresses the following questions:

1. How well do Chinese secondary school students understand the concepts of green chemistry?
2. Are there differences between the understandings of students in different year groups and genders?

Green Chemistry

Green chemistry is the design of chemical products and processes that reduce or eliminate the use or generation of hazardous substances. Green chemistry applies across the lifecycle of a chemical product, including its design, manufacture, use, and ultimate disposal. Green chemistry is also known as sustainable chemistry (EPA, 1996). In 1990, the Environmental Protection Agency (EPA) (1996) coined the term "green chemistry" and defined pollution prevention as a national policy. Pollution prevention refers to eliminating the generation of waste for resolving the problem of waste disposal and for minimizing the consumption of raw materials and energy, with the maximization of production. Trost (1991) first proposed and defined the concept of the "atom economy" and was awarded the 1998 Green Chemistry Award in recognition of his contribution to selectivity and the atom economy. This work was reinforced by Sheldon (1992) with his concept of the "E-factor." These two concepts, which are considered the foundation of green chemistry, received considerable attention and marked the emergence of green chemistry as an independent concept. In 1998, Anastas and Warner built on this foundation by systematically proposing the "twelve principles of green chemistry," which provide evaluation indicators regarding the development of new synthetic methods and analytical techniques, and these remain the primary internationally-recognized principles for green chemistry. The 12 principles triggered a new wave of green chemistry research. Hjeresen et al. (2000) summarized the 12 principles using 12 keywords. However, Gałuszka et al. (2013) reported that the 12 principles were not completely applicable to analytical chemistry, and thus, they were revised based on the current requirement of chemical engineering, production, and green analytical chemistry to develop the "twelve principles of green analytical chemistry."

Over the past 20 years, sustainability has become a predominant challenge. Green chemistry guides chemical production by applying the principles of scientific methodologies, such as re-examining, redesigning, and recreating theories, to achieve more sustainable development in the future (Li and Anastas, 2012).

Green Chemistry Education

Green chemistry is a critical component of chemistry education. Green chemistry is interdisciplinary in that it provides an opportunity for the sustainable development of the three pillars of a nation (economic, social, and environmental development) (Karpudewan et al., 2015b). In 1996, the University of Scranton incorporated green chemistry into their curriculum of environmental chemistry; in 2000, they developed an independent curriculum to promote the development of green chemistry throughout the country. Thereafter, other countries started incorporating green chemistry courses into chemistry education in colleges (Zhu, 2001; Shen and Wang, 2006). Participation in green chemistry education programs in formal (Kennedy, 2016; Hudson et al., 2016) or non-formal (Garner et al., 2015; Aubrechtet et al., 2015) learning environments has been found to influence students' attitudes toward sustainability. In terms of formal educational environments, Kennedy (2016) conducted a study, wherein he encouraged students with the advanced knowledge of green chemistry to develop dynamic undergraduate textbooks, thus allowing them to learn to apply the principles of green chemistry through a dynamic learning process and contribute to the development of green chemistry. Various other teaching methodologies have been developed, such as asking students to explore various green chemistry principles using interlocking building block molecular models (Hudson et al., 2016) and focusing on the reaction process when evaluating chemical reaction efficiency (Dicks, 2018). In terms of non-formal educational environments, Garner et al. (2015) and Aubrecht et al. (2015) designed informal experimental environments and organized field trips for students to learn more about green chemistry principles. Non-formal education not only stimulates students' enthusiasm and professional interest in chemistry but also contributes to curriculum reforms, innovation, and the professional development of teachers. To increase students' awareness on resolving environmental problems, Karpudewan et al. (2015b) integrated green chemistry into education programs for pre-service and in-service teachers. Furthermore, Wihardjo et al. (2017) and Shamuganathana and Karpudewan

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(2017), respectively, established environmental awareness and literacy models to observe changes in students' environmental awareness and literacy throughout the learning process.

Green chemistry education in China comprises three primary teaching models: Teaching courses, laboratory experiments, and published texts (Wang et al., 2018). In secondary school chemistry courses, the knowledge and mentality of green chemistry are generally conveyed through texts or implicitly embedded in other media (Gu and Wang, 2019). Chinese scholars have proposed various methods to embed the ideas of green chemistry into general classroom teaching (Li and Liu, 2015; Xu et al., 2016; Pan, 2016; Liu, 2018), such as designing green chemistry experiments (Yang et al., 2006; Ma et al., 2007; Zhu, 2009; Fan, 2010; Bai, 2015; Lin, 2015; Qu, 2017; Yan et al., 2018; Ling, 2018; Fan et al., 2019), studying green chemistry teaching strategies (Wang et al., 2010; Ma, 2007; Teng, 2015; Gong, 2013; Ye et al., 2018), and developing teaching cases (Zou, 2015), to improve students' green chemistry awareness, promote the development of green chemistry education in China, and train students to take appropriate actions that contribute to global environmental issues (Karpudewan et al., 2012).

Studies on Evaluating Secondary School Students' Understanding of Green Chemistry

The development of new courses must be strongly associated with course assessment. The assessment data reflect the effectiveness of teaching and are conducive to improving the existing course designs (Armstrong et al., 2018). When students complete the corresponding learning modules, researchers generally select diagnostic instruments to evaluate the learning performance and effectiveness of the curriculum based on the investigated factors (Gron et al, 2013). Green chemistry can be considered updated content in chemistry education, and as such, must be assessed correspondingly. Karpudewan et al. (2015a) utilized the chemistry achievement test with interviews to collect data for an in-depth research involving students' green chemistry learning motivation. After the incorporation of green chemistry into pre-service and in-service teacher education, Karpudewan et al. (2015b) conducted questionnaire surveys and individual interviews to evaluate the relationship between green chemistry and changes in students' learning motivation, environmental awareness, and environmental values. Mandler et al. (2012) embedded environmental issues into high school chemistry education and conducted structured interviews with the students to evaluate the affective and cognitive aspects as well as the relevance of the subject to the students in their everyday lives. The results showed that the students were more interested and willing to solve the environmental problems after the learning process.

The Likert scale is one of the most prevalently used tools (Armstrong et al., 2018) among researchers of green chemistry education (Gron et al., 2013; Aubrecht et al., 2015; Garner et al., 2015) to eliminate complicated written exams from the learning process (Gron et al., 2013; Aubrecht et al., 2015) and to design formative and summative instruments for assessing students' learning performance. With the assistance of data collected through large-scale questionnaire surveys, some scholars found that Chinese students lack the awareness of green chemistry (Qiao et al., 2013; Jia, 2018), have insufficient understanding of green chemistry (He et al., 2013; Wang et al., 2017), and possess a limited ability to apply green chemistry-related knowledge (Gu and Wang, 2019). Furthermore, promoting microchemistry experiments among Chinese students were difficult (Liu, 2005; Shi et al., 2006; Tang et al., 2014).

These findings revealed the challenges encountered by green chemistry education in China (Han and Liu, 2011; Chen and Qin, 2016; Shan, 2017). Numerous types of assessment instruments are available for determining the effectiveness of green chemistry in education; however, each instrument has its own assessment orientation (Gron et al., 2013). Therefore, the present authors intended to develop a more comprehensive and systematic instrument to evaluate students' understanding of green chemistry to ensure that science teachers can accurately examine students' green chemistry knowledge and behaviors, design improved teaching methods to facilitate learning, and further enhance sustainable development education (Armstrong et al., 2018; Karpudewan et al., 2015a).

METHODOLOGY

Participants

According to the chemistry textbooks published by the People's Education Press, Chinese students are exposed to green chemistry-related knowledge from the 9th grade. Since the researcher was teaching in a high school in Min County, Gansu Province, to facilitate sampling, in this study, secondary school students from Grades 9 to 12 from Min County, Gansu Province were selected for research. A stratified sampling method was adopted to select samples. Min County comprises four senior secondary schools of comparable sizes, two of which have lower entrance requirements ("conventional" schools), whereas the other two have higher entrance requirements ("excellent" schools). Therefore, the researchers selected a group of students per grade (from Grades 10 to 12), with one from each of the conventional and excellent schools as research subjects. Junior secondary school education is mandatory in China; therefore, the overall performance of the students was similar among schools. Thus, students from two classes in Grade 9 were randomly selected as research subjects. A total of 416 students participated in the study, among whom 392 provided valid responses to the instrument, yielding a valid response rate of 94.2%. Table 1 exhibits the descriptive data of the participants. Before the test, we reported the purpose of the study to school administrators, classroom teachers, and students who participated in the test, and we conducted research after their approval.

Developing the Research Instrument

The diagnostic instrument in this study was developed based on the development principles and procedures of the two-tier diagnostic instrument proposed by Treagust (1988). The development process included three stages and ten steps.

Stage 1: Defining the assessment criteria of the students' understanding of green chemistry

- Step 1: Drafting the Proposition Statements

Green chemistry-related books, secondary school chemistry curriculum standards (2017 edition), and secondary school chemistry textbooks published by the People's Education Press were referred to for compiling a database of green chemistry knowledge. The definition for green chemistry proposed by Anastas and Warner (1998) as well as the 12 principles of green analytical chemistry proposed by Gałuszka et al. (2013) were then referred to for compiling the proposition statements for green chemistry knowledge suitable for secondary school students (Table 2).

- Step 2: Composing the concept map

A concept map was composed to illustrate the relationship between the 15 concepts (i.e., green chemistry, raw materials, atom economy, energy, solvent, extraction agents, catalysts, products, evaluates, micro-experiments, green awareness, and energy awareness) based on their definitions and scopes (Figure 1).

Table 1: Descriptive data of the research samples

Gender	Grade 9	Grade 10	Grade 11	Grade 12	Total
Male	53	52	61	42	208
Female	44	47	44	49	184
Total	97	99	105	91	392

- Step 3: Connecting the proposition statements to the concept map

The proposition statements were linked with the concept map to ensure the internal consistency of the assessed content, which served as a reliability check to ensure that the basic concepts and proposition statements belonged to the same subject area.

- Step 4: Content validity

One university expert on green chemistry, two people with doctorates in chemistry education, and five secondary school chemistry teachers were invited to validate the contents of the proposition statements and concept map. Corrections and revisions were performed according to their comments and suggestions.

Stage 2: Collecting students' misconceptions

- Step 5: Reviewing corresponding studies

In this step, the existing research on green chemistry was reviewed to collect the misconceptions of students to be used as a basis for developing the instrument.

- Step 6: Conducting student interviews

To assess students' general understanding of green chemistry, an interview outline was designed, which included green chemistry, atom economy, 12 principles, energy awareness, environmental awareness, learning interests, and knowledge acquisition channels. Here, 12 students from Grade 9 to 12 from Min County (including students with good, medium-level, and unsatisfactory academic performance) were invited to participate in the unstructured recorded interviews. The findings of the interviews were then

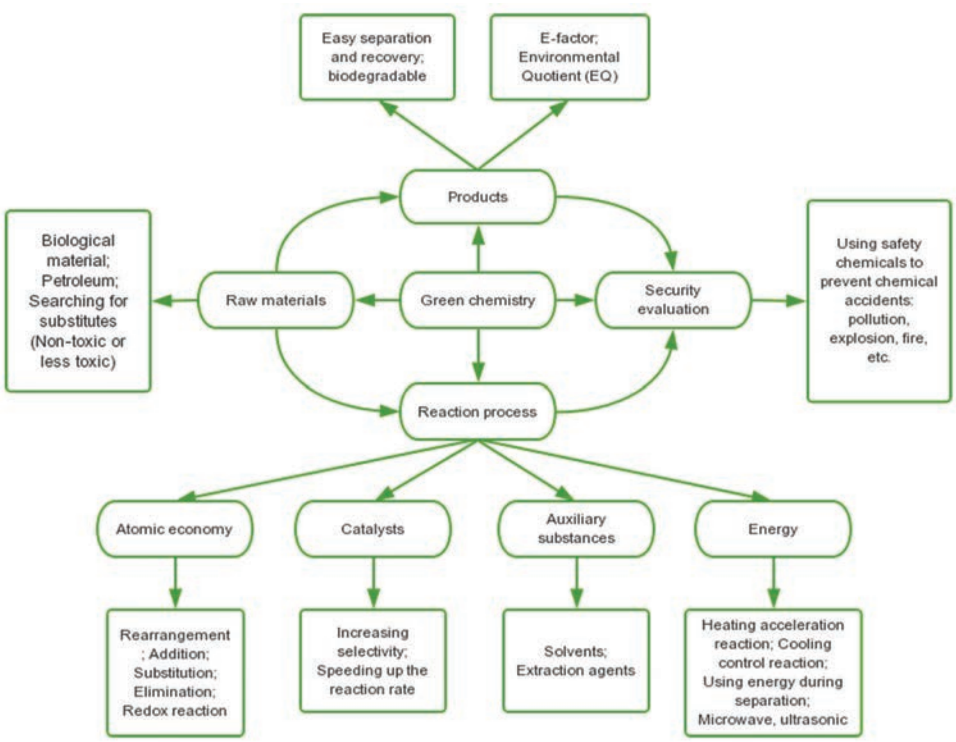

Figure 1: Concept map of green chemistry concepts

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Table 2: Proposition statements of green chemistry-related concepts

Conceptual field	Conceptual theme	Green chemistry concepts proposition statement
Definitions	Green chemistry	Green chemistry: Refers to the use of a range of principles to reduce or eliminate the use and production of hazardous materials in the design, production, and application of chemical products
Principles	Principles	Follow the twelve principles of green chemistry
	Raw materials	Raw materials: Raw fossil materials, raw biomass materials, and alternative resources
	Reaction process	The atom economy: The use of chemical principles to reduce and eliminate the environmental pollution of industrial production from the atomic source. The idea is that the molecule of the reactants is converted into a desired final product; that is, it has an "atomic utilization rate of 100%."
		E-factor: It is the mass ratio of waste to the target product
		Reaction type: Compounding reaction, addition reaction, substitution reaction, elimination reaction, redox reaction
		Energy: Heating to accelerate the reaction, cooling to control the reaction, use energy separation, ultrasonic, microwave
		Auxiliary substances: Solvent, supercritical fluid, aqueous phase, solid phase
		Separation and purification: The product is easy to be separated and purified
		Catalyst: Accelerate reaction rate, increase selectivity, and productivity
	Product	Product: Not only retain the efficacy, and non-toxic
		Derivatives: Completed by molecular modification or group protection, which consumes resources and energy and produces waste
	Evaluate	Raw materials: Source, whether it is regenerated, toxic, environmental impact
		Type of reaction: Maximizing "atom economy."
		Energy: Minimize energy use
		Auxiliary substances: Avoid using as much as possible, if used, non-toxic
		Product: Non-toxic, degradable to organisms, and the environment
		Reaction process: Minimize the occurrence of chemical accidents: For example, leaks, explosions, and fires
Application	Green awareness	Micro-experiment: Reduce the use of raw materials and energy, reduce waste, and pollution
		Green awareness: Environmental protection, air pollution, greenhouse effect, hole in the ozone layer, white pollution, garbage disposal
		Energy awareness: Solar energy, biomass energy, tidal energy, water energy, wind energy clean fuel, hydrogen energy, nuclear energy, fuel cell

Remarks: Since E-factors and auxiliary substances are not included in the secondary school curriculums, they are marked in italics and not included in the assessment instrument

used to identify students' misconceptions and misunderstandings regarding green chemistry and to subsequently improve the options in the instrument. The interview primarily comprised open-ended questions, such as "What is green chemistry?" "Is green chemistry the same as conventional chemistry?" "What does green chemistry focus on?" and "Do you think our chemistry textbooks include green chemistry-related contents?"

- Step 7: Drafting the semi-structured two-tier diagnostic instrument

The initial instrument comprised 17 items, which were developed based on the aforementioned proposition statements to resolve the misconceptions encountered during the interviews and literature review and to further collect other likely misconceptions. Each item was followed by a blank space for the respondents to provide a reason for their selection of the first-tier option. One example of the items is as follows:

We are going to produce a batch of ethanol (alcohol). Both of the following raw materials can produce ethanol. Which one will you choose?

① CO_2 and H_2; ② Fermented sweet potatoes, corn, sorghum, etc.

Please state your reasons: ____________________

The first part of the question was based on objective options, and the second part was aimed to elicit subjective answers to collect as many reasons from the students as possible. Two groups of Grade-9 students from junior secondary school X, and one group of students from Grades 10 and 11 each from senior secondary school Y were selected. In total, 207 students participated in the survey, yielding 200 valid responses. Reasons that were used by more than 10% of the participants were included in the two-tier instrument. Four items had unsatisfactory reliability and validity and were thus eliminated from the instrument.

Stage 3: Developing the diagnostic instrument

- Step 8: Developing the two-tier diagnostic instrument for green chemistry

The first part of each item provided multiple choices, where each question was followed by 2–3 options. The second part of each item comprised four possible options covering reasons to support the decision. The multiple-choice items included one correct answer, an answer based on conventional established misconceptions, and an obviously wrong answer. The reason options were developed based on the findings from the semi-structured instrument, interviews, and literature review in the previous section. An example of the items is as follows:

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We are going to produce a batch of ethanol (alcohol). Both of the following raw materials can produce ethanol. Which one will you choose?

① CO_2 and H_2; ② Fermented sweet potatoes, corn, sorghum, etc.

Please select your reason for choosing this option: ______

a. Crops are easy to grow and have high yield and low cost, whereas naturally fermented ethanol is healthy for humans and harmless to the environment
b. The raw materials are easy to access and are conducive to reducing CO_2 content in the air and environmental protection
c. Although using CO_2 and H_2 do not generate pollution, CO_2 is a greenhouse gas
d. H_2 is difficult to prepare and store and is highly flammable when exposed to an open flame
e. We must avoid using chemical substances as raw materials to reduce environmental pollution
f. Others (please specify): ______

- Step 9: Designing a two-way specification table (Table 3)

A two-way specification table was designed to ensure that the items of the instrument uniformly included all concepts in the proposition statement of the concepts to be assessed.

- Step 10: Revising and improving the instrument

Treagust (1985) stated that each test successfully improves the instrument and its diagnostic function. To further examine the reliability and validity of the instrument, in December 2018, the research team invited three senior secondary school students and two Grade-9 students (with basic chemistry knowledge) to participate in an interview. Each participant was asked to read the questions aloud and provide the corresponding answers. Items were revised or eliminated from the instrument based on the results. This step allowed the researchers to ensure the content validity of the items and further examine students' understanding of the questions. In January 2019, 155 students from Grades 9 to 12 (one group per grade) were invited to participate in a pilot survey. The reasons that were selected by <10% of the respondents were eliminated, and the instrument was revised accordingly. The completed instrument comprised 13 items.

In general, Cronbach's alpha was used to indicate the reliably of an instrument in measuring the same construct. Although the instrument developed in this study primarily examined green chemistry-related concepts, the concepts belonged to different fields of chemistry and involved multiple constructs. Therefore, Cronbach's alpha was not suitable for assessing the reliability of the instrument (Adams and Wieman, 2011). Thus, in this study, item difficulty and discrimination were employed to analyze the reliability of the instrument (Adams and Wieman, 2011; Towns, 2014). Item difficulty, which is measured using the proportion of students that accurately answer the question, reflects the difficulty of the test. Table 4 shows that the difficulty index ranged from 0.138 to 0.668, thereby revealing that the instrument included items with various difficulty levels. Odom and Barrow (1995) suggested that for a conventional four-option multiple-choice question, the likelihood of guessing the correct answer is 25%. The items in this study included four options in the first tier and five options in the second tier, and thus, the likelihood of guessing the correct combination of answers was 0.05. Since 0.1 was the minimum acceptable value, no revision was required. Item discrimination refers to the relationship between each respondent that correctly answered the question and their

Table 3: Two-way specification table of the two-tier diagnostic instrument

Conceptual field	Concept	Item												
		I	2	3	4	5	6	7	8	9	10	11	12	13
Definitions	Green chemistry	*	*									*		*
Twelve principles of green chemistry	Raw materials			*		*					*			
	Atom economy						*							
	Energy												*	
	Solvents							*						
	Extraction agents									*				
	Catalysts								*					
	Products					*					*			
	Evaluates		*	*	*	*	*	*	*	*	*	*	*	*
Application	Microexperiments											*		
	Green awareness		*									*	*	*
	Energy awareness				*							*	*	

Table 4: Results of item difficulty and discrimination analysis

Item	1	2	3	4	5	6	7	8	9	10	11	12	13
Difficulty index	0.138	0.477	0.168	0.194	0.485	0.204	0.301	0.263	0.258	0.668	0.260	0.166	0.625
Discrimination index	0.249**	0.435**	0.373**	0.377**	0.457**	0.338**	0.313**	0.271**	0.377**	0.519**	0.259**	0.356**	0.476**

Remark: **=All data are significantly correlated at a 0.01 level (both sides)

Table 5: Descriptive statistics of the test results by grade

Grade	n	Mean	Std. deviation	Standard error	Min.	Max.	Range
G9	97	3.3093	2.07345	0.21053	0	9	9
G10	99	4.0606	1.88343	0.18929	0	8	8
G11	105	4.3048	1.92216	0.18758	0	9	9
G12	91	5.2088	2.17315	0.22781	0	10	10
Total Headcount	392	4.2066	2.11090	0.10662	0	10	10

overall score in the test, ranging from −1.00 to 1.00. The point-biserial correlation method was used to measure item discrimination (Huang, 2002). The correlation coefficients between the scores of each item and the total score ranged from 0.249 to 0.519 ($p < 0.01$) (Table 4), thus indicating that the items were highly differentiated.

Data Collection and Analysis

The qualitative data collected in this study were acquired through interviews with students. A preliminary analysis of the content was performed after each interview to comprehend the students' understanding of green chemistry-related knowledge. Moreover, the interview data were used to develop a semi-open two-tier diagnostic instrument to collect reasons for selecting the corresponding answers. The reasons that were selected by <10% of the respondents and four items with unsatisfactory reliability and validity were eliminated, and a two-tier diagnostic instrument was developed. The developed instrument was then used for a pilot survey, and reasons that were selected by <10% of the respondents were eliminated. The revised instrument was used in the formal survey. The items with correct answers for both tiers were scored "1," otherwise, the score was "0." The maximum score was 13. The SPSS software package (version 17.0) was used to analyze the collected data.

RESULTS

Comparing the Overall Understanding of Green Chemistry Concepts among Students of Different Grades

Table 5 shows that the highest value was obtained from students in Grade 12, whereas the lowest values were observed in all four grades. The mean value of the overall score was 4.0048, which is noticeably lower than the highest score of 13. However, the mean value per year group increased with the grade.

The analysis of variance (ANOVA) method was used to compare the significance of mean differences among students from the four grades. Table 6 shows that variances were homogeneous; therefore, the least significance difference analysis was performed. Table 7 reveals significant differences among students from different grades, with the only exception being students from Grades 10 and 11.

Comparing the Understanding of Three Knowledge Categories among Students of Different Grades

Table 8 shows that the knowledge category with the highest mean scores of all grades was the 12 principles of green chemistry. In addition, the mean scores of the definitions, principles, and applications increased with the increasing grade.

Table 6: Results of ANOVA

Test of homogeneity of variance		ANOVA	
Levene's statistic	Sig.	F	Sig.
0.860	0.462	14.224	0.000

*: The significance level of the mean difference is 0.05

Table 7: Results of least significance difference test

Dependent variable	Grade (I‑J)	Mean difference (I‑J)	Standard error	Sig.
Total Score	G9–G10	−0.75133*	0.28735	0.009
	G9–G11	−0.99548*	0.28326	0.000
	G9–G12	−1.89951*	0.29353	0.000
	G10–G11	−1.89951*	0.28176	0.387
	G10–G12	−1.89951*	0.29209	0.000
	G11–G12	−.90403*	0.28807	0.002

*: The significance level of the mean difference is 0.05

Table 8: Students' performance by knowledge category for different grades

Grade	n	Knowledge category		
		Definitions	Principles	Application
G9	97	1.2474	3.2165	1.2474
G10	99	1.5152	3.9697	1.4848
G11	105	1.5905	4.1238	1.4857
G12	91	1.6484	5.0220	1.9231
Total score	392	1.5000	4.0689	1.5281

Concepts of green chemistry

Figure 2 reveals that the accuracy rate for memorizing the definitions was lower than 20% among all year groups. However, their understanding of green chemistry was superior to the memorized definitions of the corresponding concepts. In addition, the grade of students was directly proportional to their performance.

Principles of green chemistry

Figure 3 illustrated the students' performance in answering questions related to the principles of green chemistry. The accuracy rates of questions related to the selection of unfamiliar

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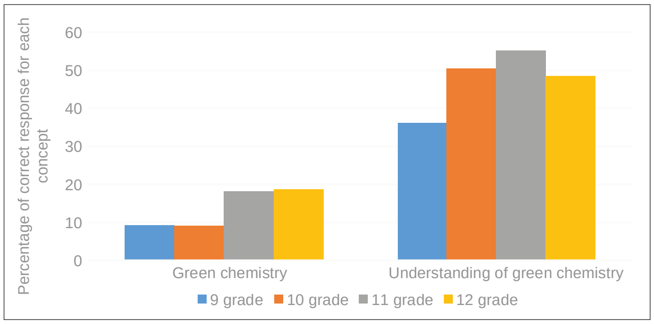

Figure 2: Students' Performance in Answering Definition-Related Questions

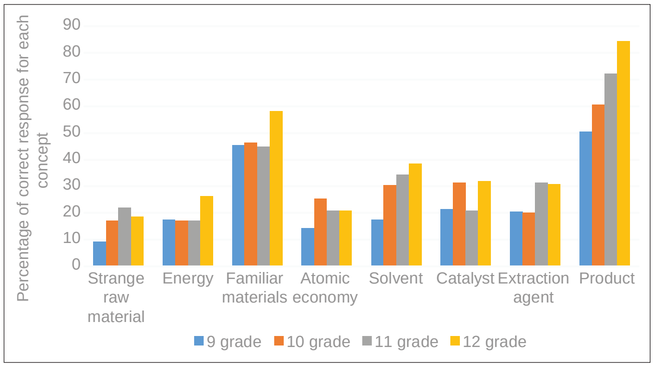

Figure 3: Students' Performance in Answering Principle-Related Questions

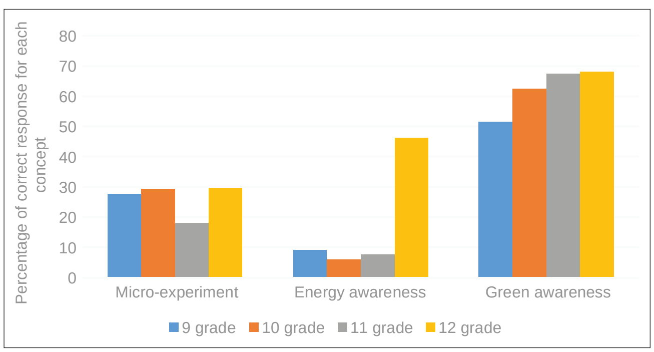

Figure 4: Students' Performance in Answering Application-Related Questions

raw materials, green energy, atom economy, solvents, catalysts, and extraction agents were lower than 40%. However, the accuracy rates of the selection of familiar raw materials were higher than 40%. Moreover, the accuracy rate of the items related to the reaction process was considerably higher, thereby indicating that students had higher environmental awareness because they were concerned about the presence of SO_2 in the products of the reaction. Nevertheless, students' overall understanding of the 12 principles remained insufficient. However, students' understanding of each concept improved with their increasing grade.

Application of green chemistry

Figure 4 shows that students from Grades 9 to 11 had a lower accuracy rate in the questions related to energy awareness, and only students from Grade 12 exhibited suitable performed. Although the accuracy rate of micro experiments was low, the results were satisfactory because secondary school students generally have limited exposure to micro experiments. However, the accuracy rate of questions related to green chemistry awareness was higher than 60% among students from Grades 10 to 12; only students from Grade 9 exhibited unsatisfactory performance. This difference can be attributed to Grade-9 students being exposed to chemistry knowledge for only one semester and thus possessing less theoretical knowledge.

Comparing the Understanding of Green Chemistry between Male and Female Students

To examine the differences in the understanding of green chemistry between male and female students, an independent-samples t-test was conducted using the total scores and the scores from each knowledge category as dependent variables. Table 9 presents the results. The mean scores of male students were slightly higher than that of female students. However, the different was not substantial. No significant differences were observed between male and female students in terms of total scores and the scores related to definitions, principles, and applications.

DISCUSSION AND CONCLUIONS

In this study, a two-tier diagnostic instrument was developed for examining students' understanding of green chemistry

Table 9: Comparing the understanding of green chemistry between male and female students

Knowledge Category	Gender	Head-count	Average score	Std. deviation	F	Sig.	t	p
Total Score	Male	208	4.2692	2.10924	0.215	0.643	0.624	0.533
	Female	184	4.1359	2.11630				
Definitions	Male	208	1.5481	0.94158	0.001	0.974	1.070	0.285
	Female	184	1.4457	0.95086				
Principles	Male	208	4.1298	2.04714	0.192	0.661	0.626	0.532
	Female	184	4.0000	2.05392				
Application	Male	208	1.5625	0.94585	0.684	0.409	0.753	0.452
	Female	184	1.4891	0.98063				

and evaluating the effectiveness of teaching interventions in developing students' understanding of green chemistry. The results showed that students' understanding of green chemistry concepts improved significantly with their increasing grade, thereby indicating that with the improvement of academic knowledge and advancement of cognition, the students' understanding of green chemistry improved. However, no significant differences were noted in the understanding of male and female students, which were consistent with the conclusions of Gu and Wang (2019). Nevertheless, the students of all four grades had a generally insufficient understanding of green chemistry; the response accuracy rate was higher only for items 10 (products) and 13 (green chemistry awareness).

These findings revealed that the students were particularly sensitive toward pollutants in chemical production and could accurately identify common pollutants (e.g. SO_2). In addition, they understood that the goal of green chemistry was to pursue "zero pollution" rather than "zero production" of the pollutants during the chemical production process. Although the involved students had strong environmental and green chemistry awareness, they had difficulties in understanding the conceptual content of green chemistry, such as raw materials, energy, atom economy, solvents, catalysts, and extraction agents.

Based on the aforementioned results and the interviews results, the following conclusions can be drawn: (1) Students have limited opportunities to participate in experimental practices. The students had considerable interest and expectations in participating in chemical experiments. However, because of the constraints of available facilities and equipment, they had limited opportunities to "experience the charm" of chemical experiments. Yang and He (2008) suggested that to achieve the goals of green chemistry education, the courses must be designed to stimulate various senses, such as sight and smell. (2) The channels for students to acquire green chemistry-related knowledge are limited. During the interviews, the students mentioned that they obtained green chemistry-related knowledge through textbooks, the internet, exams, and lectures. Therefore, students were struggling to resolve the situational questions presented in items 3, 8, 9, 11, and 12 because of insufficient access to the corresponding frontier information. (3) Teachers' green chemistry literacy requires improvement. Item 12 (energy) was extracted from the chemistry textbook. However, its accuracy rate was only 16.6%, thereby showing that the students did not understand the new frontiers of chemistry involved in the textbook. This result suggested that green chemistry textbook content was not further explored in classes, which could be attributed to teachers being employing conventional chemistry education and not emphasizing the concepts of green chemistry or lacking the time or energy to improve their green chemical literacy because of heavy workload (Zou, 2015). (4) Students have a biased understanding of green chemistry, particularly in the following three aspects: ① Green chemistry means production without pollution. When responding to item 13, some students selected the option "paper mills can be built both upstream and downstream," which shows that they believed green chemistry means zero pollution and emission. ② Green chemistry increases the workload of students. Students seemed under the impression that green chemistry is a new branch of science. They did not realize that green chemistry is merely a new approach of thinking about science responsibly (Karpudewan et al., 2012), which must be integrated into chemistry education and problem-solving processes. ③ Green chemistry is environmental chemistry. Some students mentioned that "green chemistry is the study of ecological environment" and that "learning green chemistry is conducive to improving the management of local environmental problems." They did not understand that the goal of green chemistry is to prevent damages to the environment by reducing and eliminating the generation of hazardous substances during industrial production and environmental governance.

The present study has certain limitations such as the design of diagnostic instruments and the sampling of subjects. The level of understanding and influencing factors of green chemistry for secondary school students in other regions must be further explored. As with any instrument, it is crucial to explore the reliability and validity of the generated data when used in new contexts and/or when new items are included (Versprille et al., 2017). For future research, we can develop appropriate teaching strategies based on the current research results to promote concept construction among secondary school students and explore the effectiveness of teaching.

DISCLOSURE STATEMENT

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