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Development of teaching material for green and sustainable chemistry in Japan

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Abstract: This study first developed content for a series of textbooks on green and sustainable chemistry (hereinafter referred to as GSC) targeted for university use. The textbooks focus on technology and products that have been awarded prizes in recognition of their contribution and performance toward GSC promotion. We also supplemented the textbooks with a video teaching material on dyeing systems that do not use water. We then surveyed aspiring secondary school teachers about the developed teaching materials using the questionnaire method. The results from university students' questionnaires showed that 82% understood the importance of GSC and were interested in the subject. Second, we developed a series of leaflets on GSC targeted for use in upper secondary schools. Specifically, the content emphasizes the relationship between high school chemistry textbooks and daily life, other subjects, society, and the global environment. The results showed that approximately 60% of the senior high school students' first impression of the leaflet was "interesting." Twenty years after GSC has been defined, it has still not become completely pervasive in Japan. In the future, it will be necessary to foster instructors capable of teaching GSC in secondary education.

Keywords: green and sustainable chemistry (GSC); green chemistry (GC); teaching material; the Japan Association for Chemical Innovation (JACI).

Introduction

There has been considerable progress and growth in science and technology in recent times. The foundation provided in chemistry helps us lead healthy and safe everyday lives, as it allows us to gain correct knowledge about familiar substances, as well as scientific observation and reasoning skills. Its role in the pursuit of life-long learning is also indispensable. Thus, it is important to teach students in standard high school or university chemistry classes the role chemistry plays within modern society (i.e., in what ways it is useful to our lives). Undoubtedly, there are few such roles that are common across various cultures and societies. However, green chemistry (hereinafter referred to as GC) is an exceedingly global concept, and can therefore be used as teaching material within a multicultural chemistry education. To incorporate GC into secondary and post-secondary chemistry education, various studies and praxes, such as curriculum development and microscale experiments, have been conducted globally. In this study, we also developed new green and sustainable chemistry (GSC) teaching materials for upper secondary students and college freshmen/sophomores. This paper provides the details of the developed GSC teaching materials and their evaluation.

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Green chemistry (GC) education in Japan, US, and UK

We focused on the papers of the American Chemistry Society, the Royal Society of Chemistry, and the Chemical Society of Japan in order to understand the current state of education on GC. To do so, we surveyed educational research on GC from 2010 to 2019 in Japanese, American, and British journals. Specifically, we focused on papers with green chemistry (GC), GSC, and sustainable development (SD) as keywords.

Figure 1 shows the co-occurrence network of the Journal of Chemical Education (214 articles). The network of keywords from the JCE reveals that the words “Laboratory Instruction” and “Hands-On Learning/Manipulatives” have a strong co-occurrence with GC (Dicks et al., 2019; Gómez-Biagi & Dicks, 2015; Stark, Ott, Kralisch, Kreisel, & Ondruschka, 2010). The most frequent content target was “Second-Year Undergraduate” with 92 occurrences. The hierarchical cluster analysis showed that “Second-Year Undergraduate” had a tendency for more organic chemistry content (Figure 2).

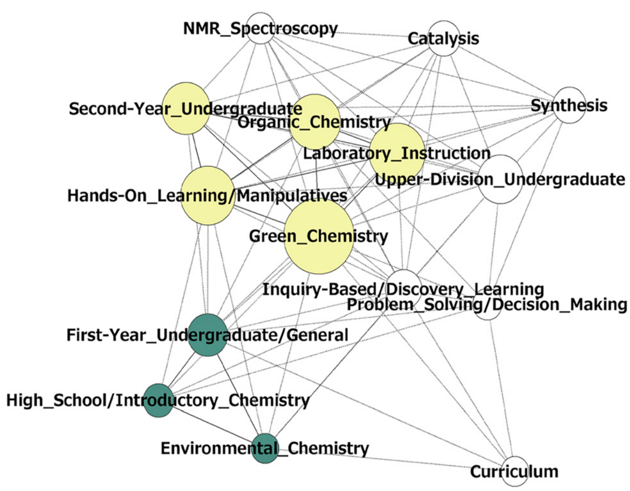

Figure 1: Co-occurrence network (US).

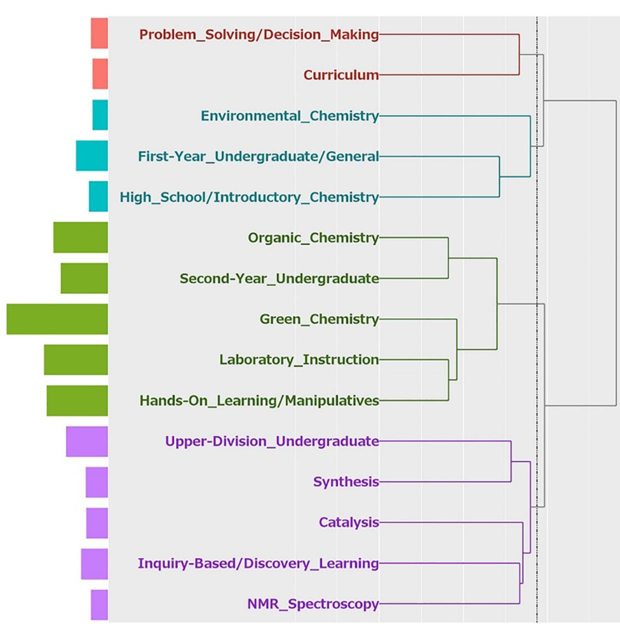

Figure 2: Hierarchical cluster analysis (US).

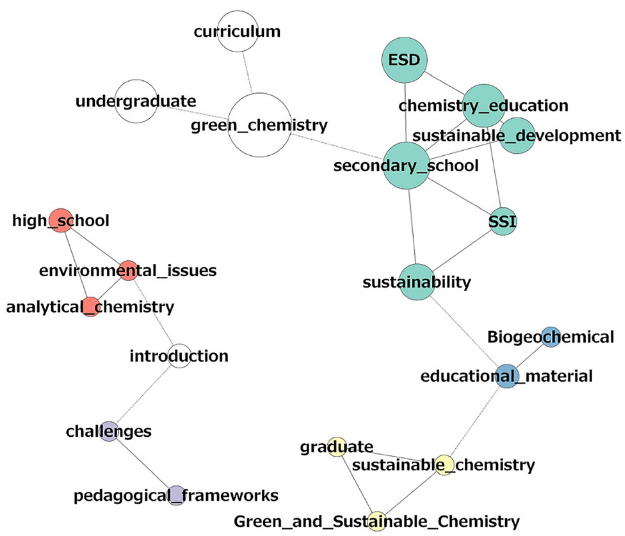

Figure 3: Co-occurrence network (UK).

Next, Figure 3 shows the co-occurrence network of journals in the UK. As can be seen, in Chemistry Education Research and Practice (35 papers), the words “curriculum” and “secondary school” show a strong co-occurrence with GC (Karpudewan, Ismail, & Roth, 2012; Karpudewan, Roth, & Sinniah, 2016; Shamuganathan & Karpudewan, 2017). Additionally, the keywords that have a strong co-occurrence with Education for Sustainable Development are “chemistry education” and “secondary school.”

While there is significant research on microscale experiments in Japan, there is little educational research on GC and GSC. In Japanese journals, “Catalysis” had a strong co-occurrence with GC, while “Development of Teaching Materials” and “High School Chemistry” had a strong co-occurrence with microscale experiments (Figure 4). Therefore, it is necessary to develop teaching methods and curricula that incorporate the GSC perspective.

History of GSC

In September 1998, industry, academia, and government officials consulted and launched the Green Chemistry Liaison Committee. A GC workshop was held in 1999, and GC in Japan was re-named “GSC” to combine

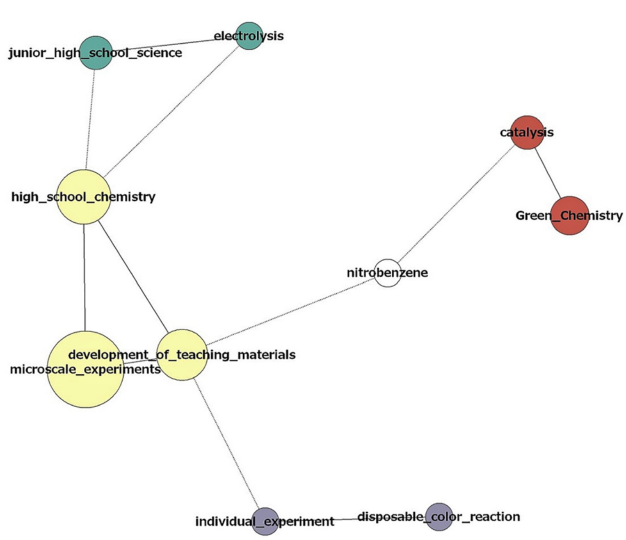

Figure 4: Co-occurrence network (JPN).

"environmental burden reduction" and "sustainable society." GSC has been defined as "chemistry that supports the development of a sustainable society with human beings and the environment." Its activity guidelines advocate for chemical products and technologies to be evaluated from a life-cycle perspective, which was remarkably advanced for its time.

For the development of GSC, the Japan Chemical Society established the Green Chemistry Research Association and held symposiums in 1999 and 2000. In March 2000, the Green and Sustainable Chemistry Network (GSCN), a partnership between industry, academia, and the government to effectively promote GSC activities in Japan was established and reorganized by the Green Chemistry Liaison Committee. The GSCN subsequently established the Green Sustainable Chemistry Award in 2001 to promote GSC. Since 2002, the following awards have been established and are conferred each year: the Minister of Economy, Trade and Industry Award; the Minister of Education, Culture, Sports, Science and Technology Award; and the Minister of the Environment Award.

In 2003, the first GSC International Conference was held in Tokyo, and the Tokyo Declaration was adopted. This declaration places GSC at the center of chemistry and chemical technology for SD Since April 2011, the New Chemical Technology Promotion Association (JACI), which incorporated the GSCN into its organization, has been promoting its activities. In 2015, the 7th GSC International Conference was held in Tokyo, and the Tokyo Declaration of 2015 was adopted. In this declaration, those involved in global chemistry to achieve society's rich and SD, research and development aimed at achieving symbiosis with the global environment, fulfillment of social demands, and economic rationality simultaneously reaffirmed their commitment to the future and to various collaborations that will help solve global, long-term issues.

Introduction to GSC

The Green and Sustainable Chemistry Network Promotion Group of the Japan Association for Chemical Innovation (JACI) has published a series of JACI textbooks (Table 1) known as Introduction to GSC (JACI, 2018). The series aims to encourage students' understanding on the topic (in both humanities/social sciences and natural sciences). The series explores three major concepts: "GSC is achieved when environmental friendliness, sociability, and economy are satisfied," "GSC is complete only when it is implemented in society," and "GSC is realized through stakeholder collaboration."

The second installment in the series is "Novel Non-phosgene Polycarbonate Production Process Using By-product CO_2 as Starting Material." The outstanding part of this technology is that unlike the conventional polycarbonate production process, it does not use toxic phosgene as a starting material. The technology was revolutionary when it was first conceived because it achieved savings of both resources and energy. More than 10 years have passed, and the technology has now been widely commercialized all over the world. This technology was very highly regarded and it was also the first time that a Japanese technology received the Heroes of Chemistry Award from the American Chemical Society in 2014.

Chapter 1: The Path to Technology Development
- What were the intentions that started the development toward realizing the sustainable progress of society?

Chapter 2: Toward Resolution of Issues
- What kind of technological challenges did the developers face, and how did they come up with solutions?

Chapter 3: Contribution to Society
- What kind of values were contributed to the society by the new technology?

Table 1: Structure and content of the series textbooks "Introduction to GSC".

No. 1 Received the Minister of Economy, Trade, and Industry Award at the 12th GSC Awards (2012) **"New Laundry Proposal for Pioneering a Sustainable Society"** Kao Corporation viewed laundry detergent from a life-cycle assessment (LCA) perspective to realize a sustainable society. It developed laundry detergent that dispenses with just one rinse cycle instead of the conventional two cycles. Kao proposes "eco together," a new laundry style that reduces environmental impact together with consumers via a single rinse cycle.
No. 2 Received the Minister of Economy, Trade and Industry Award at the 2nd GSC Awards (2002) **"Novel Non-phosgene Polycarbonate Production Process Using By-product CO_2 as Starting Material"** The Asahi Kasei Corporation successfully produced a polycarbonate resin using the by-product carbon dioxide, which was previously just emitted into the atmosphere, as a starting material. This production process does not use toxic materials such as phosgene as a starting material, which suppresses the generation of wastewater and waste products. This is a breakthrough process with excellent environmental, social, and economic benefits.
No. 3 Received the Minister of Economy, Trade and Industry Award at the 13th GSC Awards (2013) **"Development of Carbon Fiber Composite Materials for Lightweight Commercial Airplanes"** Carbon fiber reinforced plastic (CFRP), a composite material developed by Toray Industries Inc., has realized the weight reduction of airplane structures. Reducing the weight of airplanes allows them to carry more passengers/cargo and fly longer distances. A lightweight airplane can conserve energy and reduce CO_2 emissions, which contributes to the reduction of greenhouse gases that cause global warming.
No. 4 Received the Minister of Economy, Trade, and Industry Award at the 14th GSC Awards (2014) **"Development and Commercialization of High-Performance Transparent Plastics Derived from Plant-Based Raw Material"** Mitsubishi Chemical Corporation succeeded in the development and commercialization of transparent engineering plastics, which is the main raw material of isosorbide derived from renewable resources. Not only was the environmental impact reduced by a unique process utilizing renewable resources, the performance of the product in terms of impact resistance and weathering resistance was radically improved as well.
Special Edition **"Introduction to Sustainable Development Goals (SDGs)"** GSC plays a driving role in SDGs. Let us change the world toward a sustainable future.

GSC-friendly actions toward people and the environment—dyeing systems

We developed a video teaching material entitled "GSC-friendly actions toward people and the environment—dyeing systems" (Imai, 2017a) for dyeing systems that do not use water. We focused on the LCA of products and their relevance in GSC evaluation.

In Section 1, the need to think about the environment in terms of LCA, i.e., evaluating the burden on the environment through the LCA of a product when conducting a GSC evaluation, is described.

In Section 2, the dyeing method is explained while performing a demonstrative experiment, specifically a method of dyeing cloth using natural cochineal dyes. Cochineals are insects that live inside desert cacti; a red pigment is present in the bodies of female cochineals. The pigment is taken from them and used to dye cotton, silk, and wool with a deep crimson or scarlet color. Humans have relied on natural dyes for thousands of years. However, in the 19th century, it became possible to produce the same dyes as those found in nature cheaply in large quantities, as well as synthetic dyes that do not exist in nature, using chemistry. In Section 2, there is also an explanation as to why dyeing methods should be reconsidered because dyeing can use a lot of water, energy, and chemicals.

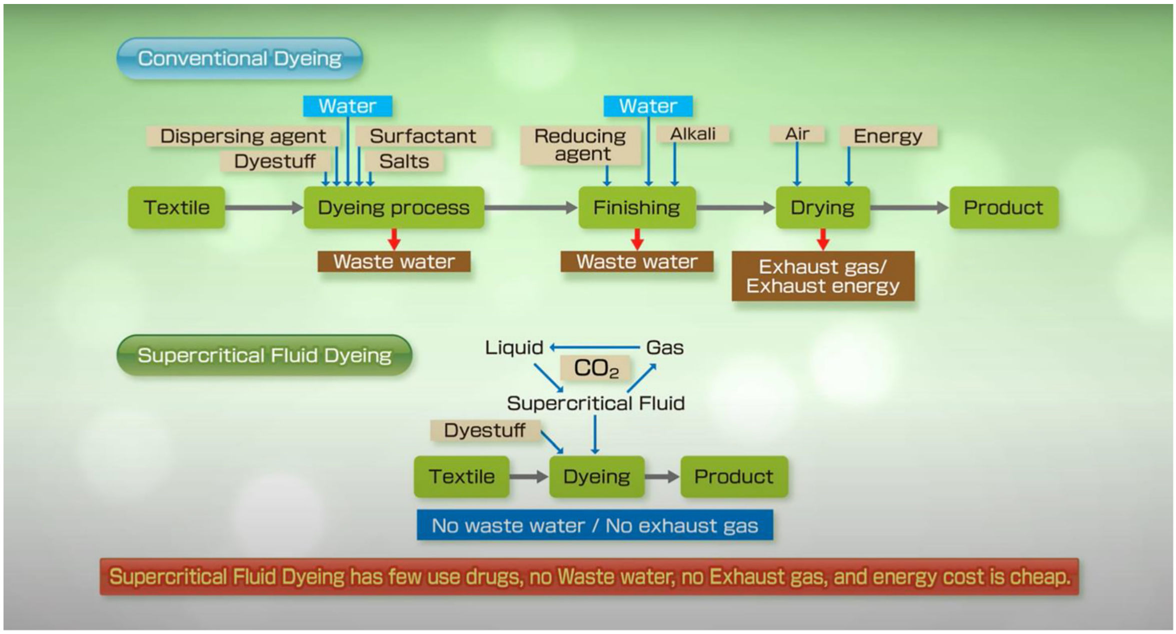

Figure 5: Comparison of conventional dyeing with supercritical fluid dyeing.

In Sections 3 and 4, an environmentally-conscious dyeing method that does not use water is introduced (a dyeing method using supercritical carbon dioxide). Here, the merits of supercritical fluid dyeing over conventional dyeing are explained by a demonstration of the actual dyeing process and thorough discussions with Visiting Professor Hori Teruo from the University of Fukui, who has researched and developed dyeing methods that do not use water for many years. Next, we compared the differences between conventional dyeing methods and supercritical fluid dyeing methods. In conventional methods, an excessive amount of water is used for dyeing and other subsequent processes. This results in the discharge of polluted wastewater. In addition, the drying process consumes an excessive amount of energy. However, supercritical fluid dying does not require water, therefore no polluted liquid waste is produced. In addition, because there is no requirement for drying, no energy is utilized during this process.

Supercritical fluid dyeing is an environmentally friendly dyeing method that does not use water and is a better alternative due to the following five points (Figure 5):

– Does not require auxiliaries to improve the dyeability or prevent uneven dyeing.
– Shortens dyeing time.
– Dyes that do not exhaust fibers are recovered in powder form.
– Requires no drying processes.
– Very little liquid waste is produced. In other words, it is environmentally friendly.

The results from the university students' questionnaires are shown in Figures 6 and 7, indicating that 82% of students (chemistry, biology, physics) understood the conditions under which the GSC was established. Video teaching materials are easy to understand and can be used by different groups of people. Results show that the students were able to understand the LCA after watching the video materials.

"Awarding the GSC Junior Award"

Since 2012, the GSC Junior Award has been given to high school and junior high school students at the Chemistry Club Research Presentation hosted by the Kanto Branch of the Chemical Society of Japan (Table 2).

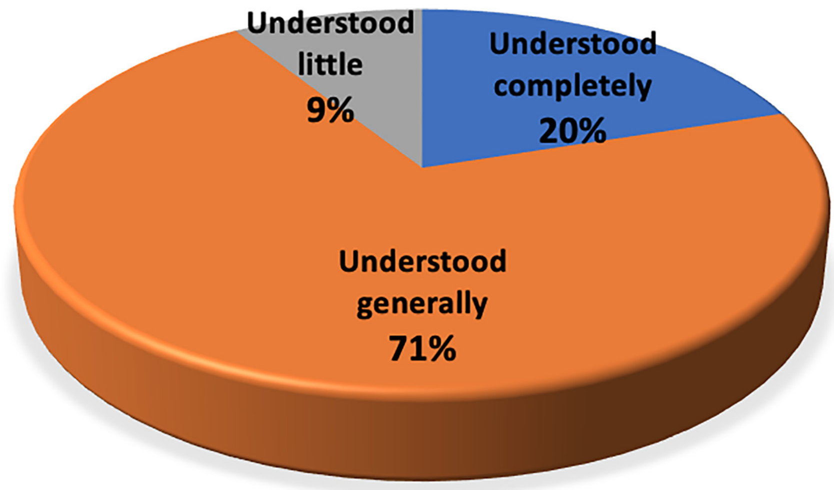

Figure 6: Understanding of the life cycle assessment (LCA) (89 participants).

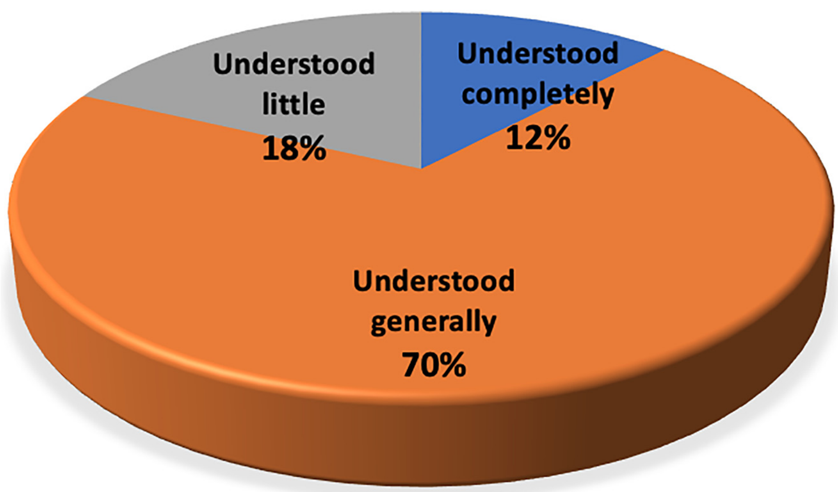

Figure 7: Understanding of the conditions green and sustainable chemistry (GSC) needs to satisfy (90 participants).

From the perspective of disseminating GSC to high school and junior high school students, this initiative is immensely significant. Currently, only chemistry club presentations sponsored by the Kanto branch are held. In the future, we hope to have more opportunities to award junior GSC prizes throughout Japan. We also hope that more high school students are provided with the opportunities to engage in research that incorporates the GSC perspective.

GSC leaflets: "The Power of Chemistry"

The JACI GSCN dissemination and enlightenment group created the chemistry teaching material "GSC Leaflets: The Power of Chemistry, 01–08" (Imai, 2017b). Our aim was to enable high school teachers to teach GSC using leaflets. Specifically, the content structure emphasizes the relationship between the contents of high school chemistry textbooks and daily life, other subjects, society, and the global environment (Table 3). The leaflet can be downloaded directly from the JACI website and is expected to serve as either a self-study task, home-study task, or science research task. The sources of important data are included.

The GSC leaflet "Chemistry Power 02 (Background to GSC)" was distributed in a microscale experiment class (lecturer: Ogino, 43 first- and second-year students) at Sendai Minami High School in Miyagi Prefecture. A survey

Table 2: GSC Junior Awards.

1st
– Purification of domestic wastewater using natto bacteria II (Kanagawa Prefectural Kawasaki Technical High School)
– Safe silver mirror reaction that does not use ammonia (Ichikawa Gakuen Ichikawa High School)
– Environmental purification of hydroxyapatite/titanium oxide composite material (Tokyo Technology University Science and Technology High School)
– Decomposition of organic matter using titanium dioxide (Chiba Prefectural Kashiwa High School)
– Transform konjac flying powder to bioethanol (Meisho Gakuen Jutoku High School)
– Water treatment and algae prevention effect by titanium oxide-supported foamed recycled glass (Ichikawa Gakuen Ichikawa High School)
2nd
– Environmental purification with sludge (Tokyo Metropolitan Science and Technology High School)
– Research on high-efficiency dyes in dye-sensitized solar cells (Shibaura Institute of Technology Junior and Senior High School)
– Research on the atmosphere around Otsuki to determine the causes of photochemical smog (Yamanashi Prefectural Tsuru High School)
– Green chemistry-oriented reduction reaction of nitrobenzene (Ibaraki Prefectural Ryugasaki Daiichi High School)
– Use of a photocatalyst as a polymerization initiator (Tokyo Metropolitan Science and Technology High School)
3rd
– New possibilities for solar cells and earth-friendly energy development using natural pigments (Chiba Municipal Chiba High School)
– Research on environment-friendly lead-acid batteries (Ibaraki Prefectural Ryugasaki Daiichi High School)
– Effects of soil on springs: analyzing soil from the perspective of chemistry (Tokyo Metropolitan Tama High School of Science and Technology)
– Iron-Iron (III) secondary battery saves the world (Ichikawa Gakuen Ichikawa High School)
– Challenge to phytoremediation III: Aiming to recover heavy metals from plants (Tokyo Metropolitan Science and Technology High School)
4th
– Separation of metal ions using silicate (Komaba Toho Junior and Senior High School)
– Creation of super absorbent polymer made from brown algae (Johoku Junior and Senior High School)
– Production of ethylene gas from fallen leaves using zinc chloride and zeolite (Ichikawa Gakuen Ichikawa High School)
– Production of bioethanol from konjac flying powder (Meisho Gakuen Jutoku High School)
– Culture of methane bacteria and analysis of gas (Yokohama City Yokohama Science Frontier High School)
– Environmental purification using photocatalysts for effective use of plastic waste materials (Tokyo Metropolitan Science and Technology High School)
– Research to protect the environment with bamboo-made biodegradable plastic from bamboo (Tokyo Metropolitan Science and Technology High School)
5th
– Performance evaluation of dye-sensitized solar cells using reduced graphene oxide as the positive electrode (Hiroo Gakuen High School)
– Iron-Iron (�) Rechargeable battery saves World—Part 2 (Ichikawa Gakuen Ichikawa High School)
– Safe synthesis of methyl salicylate in a salicylic acid/methanol system (Ibaraki Prefectural Mito 1st High School)
– Research on a simple manufacturing method of lithium-ion secondary batteries (Ichikawa Gakuen Ichikawa High School)
– Improving the performance of original dye-sensitized solar cells (Chiba Prefectural Awa High School)
6th
– Use of agar to stop desertification (Kanagawa Prefectural Atsugi High School)
– Study on the properties of tin compounds (Yamanashi Prefectural Kofu Minami High School)
– Dye-sensitized solar cells using food (Tamagawa Gakuen Junior High School)
– Adsorption of heavy metal ions using dead leaves (Tokyo Metropolitan Tama High School of Science and Technology)
– Kihada's antibacterial ingredient—Kihada versus yeast (Chiba Prefectural Chiba Higashi High School)
7th
– Treatment of Benedict's solution using hydrotalcite (Johoku Gakuen Johoku Junior and Senior High School)
– Production of bioethanol using mushrooms (Kanagawa Prefectural Atsugi High School)
– Preparation of highly water-absorbent polymers using peanut shells (Ibaraki Prefectural Ryugasaki Daiichi High School)

Table 2: (continued)

–	Use of Mottainai as an energy. Conversion of food loss to energy by thermal decomposition (Tokyo Metropolitan Tama High School of Science and Technology)
8th	
–	Electroless copper plating using glucose (Kaisei Junior and Senior High School)
–	Contact hydrogen reduction of nitrobenzene extraction and application of chitin from crayfish (Ibaraki Prefectural Takezono High School)

Table 3: Green and sustainable chemistry (GSC) leaflet ("The Power of Chemistry" 01–08).

01	What is GSC (Green & Sustainable Chemistry)?
02	Background of GSC
03	Solar power generation
04	Metal and hydrogen storage alloy
05	Conductive plastic
06	Weight reduction of automobiles using plastic
07	Haber-Bosch method, the power of catalyst utilization, and equilibrium theory
08	Haber-Bosch process and the dawn of the chemical industry

was conducted. The results showed that approximately 60% of the students answered that their first impression of the leaflet was "interesting" (Figure 8). Among all students, "Minamata disease" ranked first in "content of interest" while "GSC" ranked first in "content that I would like to know more about" (Figure 9). Regarding "reasons for interest," approximately 70% of the students cited "interest in the global environment and sustainability itself" and "connection with other subjects and society" (Figure 10). Conversely, approximately 40% of the students who answered "it seems difficult" in Figure 8 cited "society/connection" as the reason for their interest. In total, 75% of the students answered, "it looks interesting" and were eager for further details. "Environment and sustainability" were cited as reasons for wanting to know more. As shown in Figure 9, two-thirds of the students who cited "environment/sustainability" as their reason for being "interested/wanting to know more" said that their first impression of the leaflet was "interesting." A representative student quoted: "I once again felt the importance of thinking about the global environment and sustainability."

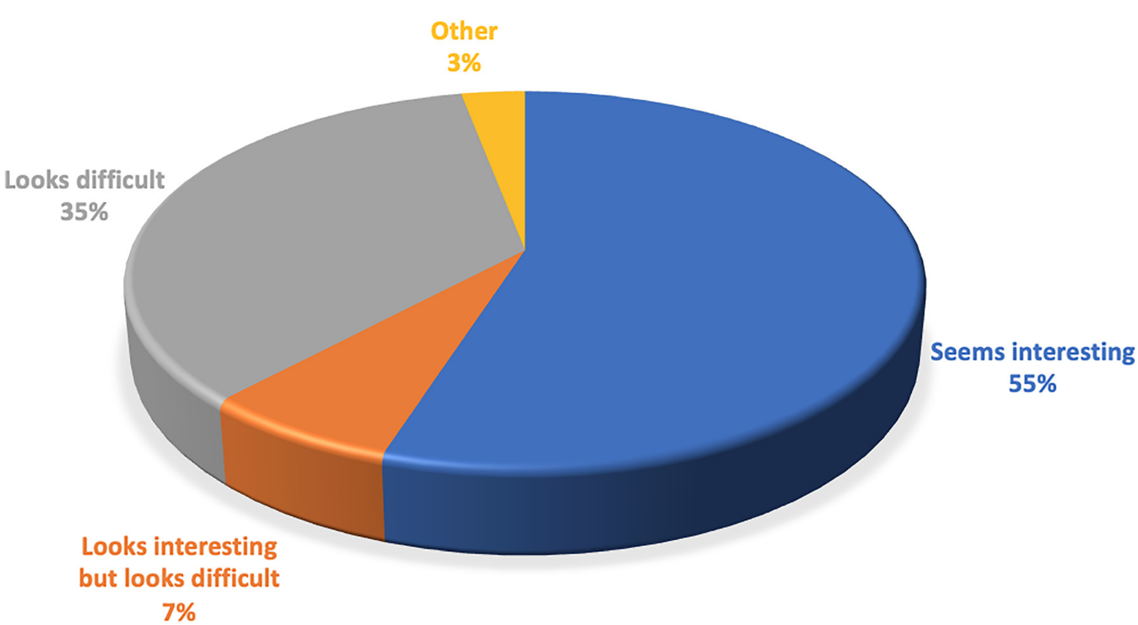

Figure 8: First impression of history of green and sustainable chemistry (GSC).

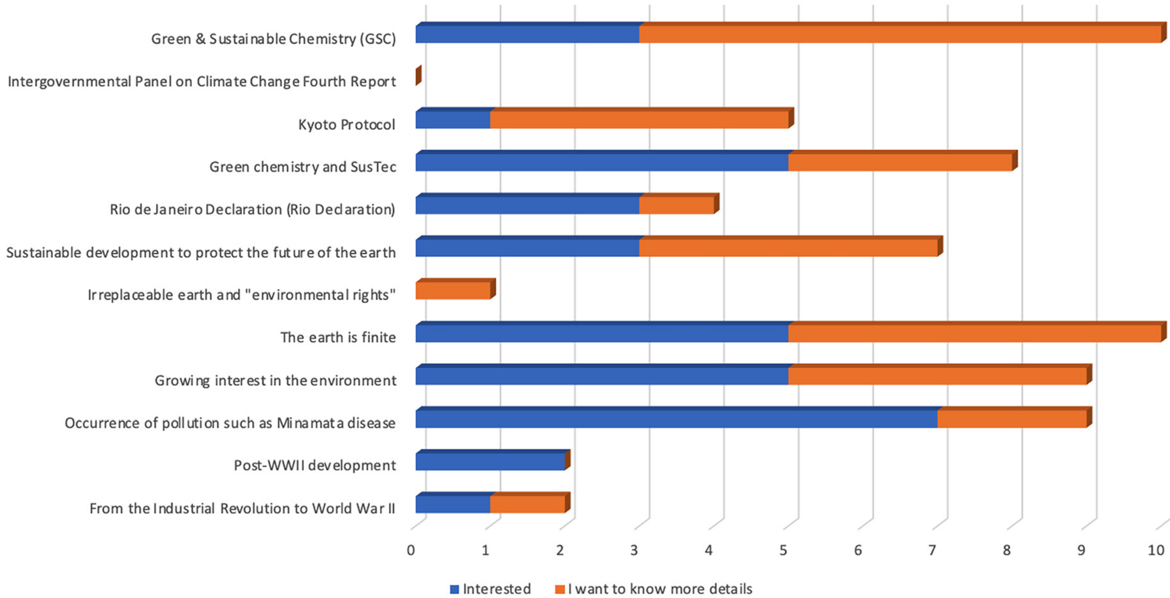

Figure 9: "I am interested" and "I want to know more".

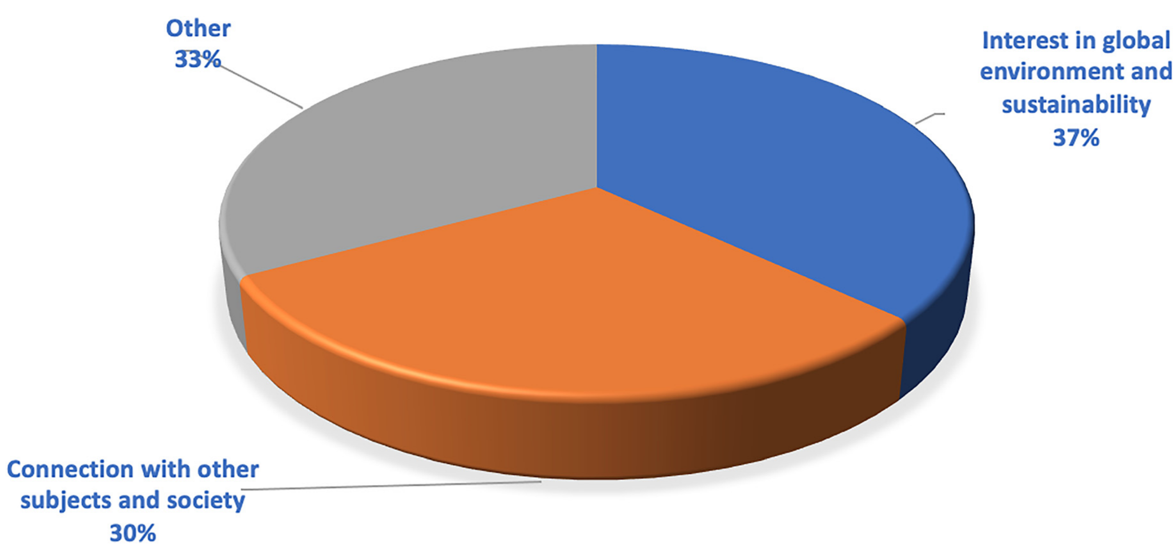

Figure 10: Reason for interest.

As expected, the survey results showed that many students were interested in familiar or real aspects. Specifically, approximately 70% of the students answered "interest in the global environment and sustainability itself" and "connection with other subjects and society" as "reasons for interest" in the "History of 02 GSC." The results reflect the purpose of the leaflet, which emphasizes the relationship between the content of "Chemistry Basics" and "Chemistry" in high school science textbooks and daily life, other subjects, society, and the global environment. It is focused on: (1) exploring familiar chemistry themes related to daily life; (2) making people aware of "connections" with other subjects, issues/societal impact, the global environment, and sustainability; and (3) science. We aspire to further produce and disseminate teaching materials that will foster interest and inquisitiveness in technology in general.

Future perspectives

In secondary chemistry education, it is important not only to arouse student interest in chemistry but also to give students an opportunity to think about the relationship between chemistry and society. In the future, we would like to undertake classes using the GSC teaching materials that we have prepared so far in secondary chemistry education, and continue fostering and spreading the GSC concept. In addition, there have been many reports on the ingenuity of microscale experiments in Japan. We would like to develop and evaluate a chemistry education curriculum that fosters the concept of GSC using these materials. Finally, JACI has been awarding high school students with the "GSC Junior Award" for outstanding research presentations on GSC since 2011. We would like to conduct a follow-up survey on the kind of research and occupation the award winners are involved in at universities, and perform a medium- to long-term evaluation of the promotion and awareness of GSC.

Conclusions

In 1999, GSC, which explicitly refers to sustainability, was defined in Japan as "human- and environment-friendly chemistry that supports the development of sustainable societies." In 2000, the government, industries, and academia collaborated to establish the GSCN. The GSCN, also known as the Working Group on Teaching Materials, partakes in educational activities and the development of teaching materials pertaining to GSC, the results of which are uploaded to the GSCN website (http://www.jaci.or.jp/english/gscn/page_05.html). In 2020, those results were also released in "The Nexus," the newsletter of the American Chemical Society Green Chemistry Institute.

Twenty years after GSC was defined, it is still not completely pervasive. In the future, it will be necessary to foster instructors capable of teaching GSC in secondary education. Nurturing human resources who are equipped with a scientific background and can engage with the government will be a focus for post-secondary education.

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