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Laboratory Experiment

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Reactivity of Household Oxygen Bleaches: A Stepwise Laboratory Exercise in High School Chemistry Course

Masayoshi Nakano, Haruka Ogasawara, Takeshi Wada, and Nobuyoshi Koga*

Department of Science Education, Graduate School of Education, Hiroshima University, 1-1-1 Kagamiyama, Higashi-Hiroshima 739-8524, Japan

Supporting Information

ABSTRACT: This paper reports on a learning program designed for high school chemistry classes that involves laboratory exercises using household oxygen bleaches. In this program, students are taught the chemistry of oxygen bleaches through a stepwise inquiry using laboratory exercises organized with different pedagogical intents. Through comparative investigations of chemical properties of liquid and solid oxygen bleaches, students are introduced to sophisticated chemical concepts behind household oxygen bleaches and the dependence of their oxidizing activities on certain reaction conditions. This learning program also provides suitable opportunities at each investigative step for the introduction of mechanisms of reactions that involves H_2O_2. The students effectively use the attained chemical knowledge and concepts for the reasoning of observed phenomena in each investigative step and construct the basis toward subsequent inquiry steps. This learning program is concluded with a discussion by the students on the effective use of the chemistry of oxygen bleaches and a demonstration of Fenton's reaction using liquid oxygen bleach as a possible solution for current environmental issues regarding contaminated water. An outline of the learning program is described based on practice trials within high schools and an undergraduate introductory chemistry class taught at our university.

KEYWORDS: *High School/Introductory Chemistry, Inorganic Chemistry, Laboratory Instruction, Hands-On Learning/Manipulatives, Consumer Chemistry, Oxidation/Reduction*

Household detergents and bleaches utilize various sophisticated chemical concepts that can be effectively applied to the learning content in high school chemistry courses.[1−8] These materials can be utilized at different learning stages in high school chemistry to introduce related chemical concepts in a step-by-step manner or to integrate acquired chemical knowledge into the students' daily lives. Additionally, the students' exposure to tiered chemical concepts for household detergents and bleaches proves that an educational storyline behind their systematic chemistry learning can be constructed through repeated exposure to these materials at different learning units. For example, a determination of the chemical compositions of sodium percarbonate (SPC) [sodium carbonate−hydrogen peroxide (2/3); $Na_2CO_3{\cdot}1.5H_2O_2$; CAS: 15630-89-4] and sodium sesquicarbonate (SSC) [$Na_2CO_3{\cdot}NaHCO_3{\cdot}2H_2O$; CAS: 533-96-0] used in solid oxygen bleach and as an alkaline agent in detergents, respectively, are suitable laboratory exercises that can expand high school students' chemical knowledge and ideas.[3,6,8]

Household oxidizing bleaches such as liquid and solid oxygen bleaches use different chemical concepts to control the reactivity of the oxidizing agents. For instance, liquid oxygen bleaches consist of a mixed aqueous solution of H_2O_2 and surfactants. The solution is adjusted to an acidic pH to prevent the spontaneous decomposition of H_2O_2 during storage. Prior to use, the solution is adjusted to a basic pH by mixing with detergents that have an alkaline agent such as SSC to activate the oxidizing agent. The solid oxygen bleach is typically composed of granulated SPC with a core−shell structure. The outer surface layer consists of a mixture of SPC and Na_2CO_3 and the inner core is composed of aggregates of the SPC crystalline particles.[3,8−11] This outer surface layer protects the internal SPC crystalline particles from any atmospheric moisture that promotes the detachment and decomposition of H_2O_2. The solid oxygen bleach dissolves into the water during use to produce a basic solution that activates the oxidant, $H_2O_2(aq)$. A teaching approach that compares different chemical concepts for liquid and solid oxygen bleaches can aid the high school students in establishing a correlation between the chemical activities of H_2O_2 with extraneous chemical conditions. This also creates an opportunity to introduce mechanisms that explain the bleaching action and decomposition of H_2O_2. However, some chemical concepts and theories for understanding the chemistry of oxygen bleaches are apparently beyond high school chemistry and university introductory chemistry levels. Therefore, well-organized stepwise approach is necessary for the success of the students' learning on the chemistry of oxygen bleaches. Such a learning program that uses stepwise inquiry is expected to provide opportunities for experiencing different cognitive skills in

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scientific inquiry and for establishing the basic chemical concepts related to the phenomena. Although the students' understanding attained by the learning program might be at a phenomenological level, the understanding of the chemistry of oxygen bleaches is necessary for all of the students to effectively use household bleaches in their daily lives and also to enrich the basis for studying the detailed concepts and theories of the redox reaction in future study.

This paper reports on a learning program in high school chemistry laboratories that uses a stepwise inquiry to introduce students to the chemistry of household bleaches. This was developed by arranging experiments using different household oxygen bleaches as part of students' exercises and instructor demonstrations. Trials for each component of the learning program were conducted to evaluate the practical relevance of the laboratory exercises in high school chemistry courses and in a freshman introductory chemistry course at our university. On the basis of the results of these preliminary educational trials, the learning program was further developed by effectively coordinating the students' exercises and the teachers' instructions with a chemical storyline on household oxygen bleaches. The learning program was designed as a 3 h laboratory course for 10 groups with 4 members each at high school chemistry classes or at university-level introductory chemistry classes. The final version of the learning program was trialed with one high school chemistry class (29 members) and two introductory chemistry classes at our university (total 56 members). The students' activities and achievements in each investigative step were evaluated on the basis of the answers given by each student on the students' handout. The students' discussions and experimental activities were also monitored throughout the duration of the program using video recording and analyzed in conjunction with the students' answers on the students' handout. The results were used for improving the flow of the learning program and student's experimental procedures for establishing the final version of the laboratory learning. For the final version of the learning program, the video recording was used to confirm the pedagogical success of each learning step. Approximately one month after the laboratory learning, multiple-choice tests on the basic concepts of the chemistry of oxygen bleaches were administrated to the students.

■ OUTLINE OF THE LEARNING PROGRAM

The developed learning program assumes that the students in the class have already been exposed to the learning units that address acid−base and redox reactions. The evolution of O_2 through the decomposition of H_2O_2(aq) has already been widely addressed in science courses at elementary and junior high schools. The students should also be familiar with the evolution of O_2 from solid oxygen bleach due to their encounters with these household chemicals in their daily lives. However, no students who participated in the educational practices in this study were aware of the differences between household liquid and solid oxygen bleaches or of the chemical concepts utilized to control the reactivity for bleaching.

Figure 1 shows a flowchart of the learning program, which shows a stepwise inquiry via a combination of structured and guided laboratory inquiries. The students will explore the chemical reactions of household oxygen bleaches through an introductory demonstration (Introduction in Figure 1), which is then followed by a discussion on the students' previous knowledge and experiences with these bleaches in their daily lives. Three laboratory exercises are designed to answer certain questions posited by the instructor (Steps 1 and 2 in Figure 1). One of these experiments involves the preparation of granular oxygen bleach with a method that was developed in this study, particularly for student laboratories (Step 1 in Figure 1). These exercises will allow students to observe different aspects that influence the reactions of oxygen bleaches. In each step, different chemical topics for the reactions of oxygen bleaches are introduced (Step 2 in Figure 1), which involves the compositional components of solid oxygen bleach, the bleaching mechanism, formation of hydroxyl radicals and their roles in the bleaching process, and variations in the observed reactivity of H_2O_2(aq) based on the basicity of the solution. Students will thus learn the chemical concepts of oxygen bleaches in the laboratory by explaining the chemical role of H_2O_2 as an oxidizing agent.

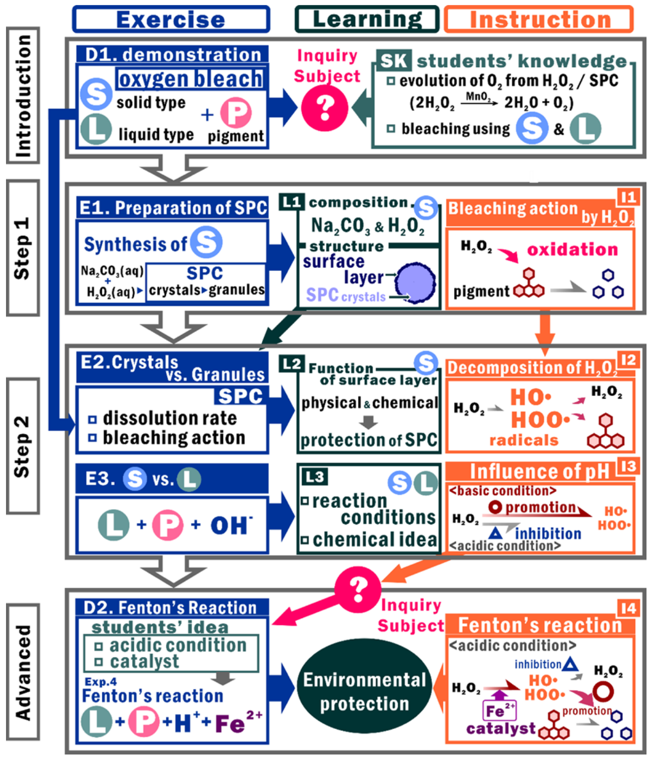

Figure 1. Flowchart of the learning program.

The chemical concepts of oxygen bleaches are further explored through in-class discussions with the instructor. The students are also prompted to propose a possible method for prolonging the activity of H_2O_2 by decreasing the decomposition rate of H_2O_2 (Advanced learning in Figure 1). As an example, the instructor will introduce the efficacy of Fenton's reaction[12−14] toward the oxidation of organic materials and provide an explanation for the mechanism behind this reaction.

Table 1 summarizes the learning objectives of each leaning stage of the program with respect to students' practice, thinking/discussion, and understanding. The entire student handout used in our educational practice in a high school chemistry course is supplied in the Supporting Information. The handouts for each student exercise were separately supplied to the students at each learning step.

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Table 1. Learning Objectives at Each Learning Stage

Stage	Practice	Thinking/Discussion	Understanding
Introduction	Observation/recognition of demonstrated chemical phenomena on the differences between solid and liquid oxygen bleaches	Prediction of the results of demonstration experiment	Recall of the related chemical concepts
	Confirmation of chemical contents of household oxygen bleaches from the descriptions on the bottles		Chemicals used for oxygen bleaches
Step 1	Preparations of SPC and it granulation	Presumption of chemical components in SPC	Components and construction of SPC granules
	Observation of morphologies of SPC crystals and granules	Presumption of the role of surface Na_2CO_3 layer	Phenomenological mechanism of the color degradation of organic dye by H_2O_2
	Testing of the activity of synthesized SPC		
Step 2−1	Comparison of rate of dissolution of SPC crystals and granules in water	Reasoning of the difference in the dissolution rate and bleaching activities of SPC crystals and granules	Role of the Na_2CO_3 surface layer of SPC granules
	Comparison of the bleaching efficacies of dissolved SPC crystals and granules	Analogical reasoning for the difference in lifetime of SPC crystals and granules	Phenomenological mechanism of H_2O_2 decomposition
			Formation of radicals by the decomposition of H_2O_2
			Reaction between organic dye and hydroxyl radicals
Step 2−2	pH test	Presumption of acidity/basicity of SPC solution and liquid oxygen bleach	Chemical role of Na_2CO_3 in SPC granules
	Verification experiment on the activation of bleaching action of liquid oxygen bleach	Presumption of the effect of pH on the bleaching action	Relation between the reactivity of H_2O_2 and pH of the solution
		Proposals of the method to activate the bleaching action of liquid oxygen bleach and setup of verification experiment	
Advanced	Observation/recognition of demonstrated chemical phenomena of the Fenton's reaction	Proposal of possible method to inhibit the decomposition of H_2O_2 by hydroxyl radicals	Combination of chemical concepts related to reactivity of H_2O_2 and redox reaction
		Proposal of possible method to activate H_2O_2 in acidic condition (use of catalyst)	Phenomenology of the Fenton's reaction

■ LABORATORY EXERCISES

Introductory Demonstration

This learning program is first introduced to students through a demonstration by the instructor (Figure 1, Introduction, D1), where the bleaching efficacies of solid and liquid oxygen bleaches are compared in dyed organic solutions (Rhodamine B). The majority of the students expected these two forms of oxygen bleaches to be equally effective (Figure 1, Introduction, SK). However, the results of the demonstration proved that only the solid oxygen bleach could actively oxidize the organic dye. At the beginning of the investigation, the students confirmed the contents for each of the oxygen bleaches by noting the descriptions on their respective labels for each bottle. The students observed that H_2O_2(aq) was the primary oxidizing component for liquid oxygen bleach. The students must first be introduced to the primary chemical component of solid oxygen bleach, SPC for proceeding their learning, because many of them do not know about the chemical substance.

Preparation of Granular Oxygen Bleach

The first laboratory exercise was designed to implant the knowledge of the compositional components of SPC to students (Figure 1, Step 1). The preparations of SPC crystalline particles and granules allow the students to recognize the compositional components (Figure 1, Step 1, E1), H_2O_2 and Na_2CO_3. If there is sufficient time and if the procedure is deemed to be suitable for the students, a previously reported laboratory exercise for determining the chemical composition of SPC[8] can also be used as an extended learning based on the preparation of SPC. The method for the preparation of SPC crystalline particles was first reevaluated in this study due to safety concerns. It was concluded that the mixing of saturated Na_2CO_3(aq) and 10% H_2O_2(aq) at room temperature was the most viable procedure for obtaining SPC crystalline particles with an acceptable purity of >90%. Figure 2 shows a typical experimental procedure for the synthesis of SPC crystalline particles and granules. A white precipitate of SPC crystalline particles was obtained after the addition of absolute ethanol to the mixed solution of saturated Na_2CO_3(aq) and 10% H_2O_2(aq) (Figure 2a). The axis length of these columnar crystals commonly measures between 20 and 30 μm, which has previously been reported in the literature.[8,10]

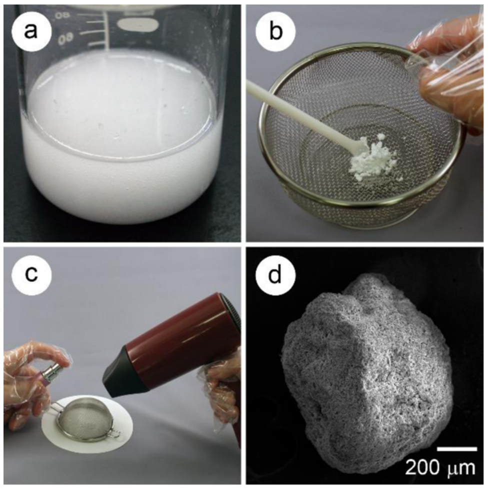

Figure 2. Procedure for preparing SPC granules: (a) precipitation of SPC crystalline particles, (b) sieving the precipitates with a kitchen strainer, (c) spray coating with Na_2CO_3, and (d) a SEM image of an as-prepared SPC granule.

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The SPC granules as in solid household oxygen bleach are prepared by hand using a granulation procedure that employs equipment that is typically available in laboratories and homes. After the SPC crystalline particles were separated from the solution through suction filtration, the solid was forced through the wire mesh of a kitchen strainer onto a Petri dish (Figure 2b). Sliding the Petri dish in a circular fashion creates SPC granules. Saturated Na_2CO_3(aq) was then repeatedly sprayed onto the granules, and the granules were immediately dried with hot air from an electric hair dryer (Figure 2c). The SPC granules prepared by the students were approximately spherical in shape with a diameter that measured several hundred micrometers (Figure 2d). The stepwise procedure for the preparation of SPC crystalline particles and granules is described in the Student Handout, and the detailed information for the development of the procedure is described under the Instructor Information provided in the Supporting Information.

The oxidative capacity of the prepared SPC granules was tested by students using the introductory demonstration procedure (Figure 1, Step 1, E1). The students, through preparing SPC crystalline particles and granules and the instructor's description of the adduct compounds, were now aware that H_2O_2 and Na_2CO_3 are the compositional components of SPC (Figure 1, Step 1, L1). The students also recognized that one of the components, H_2O_2, was primarily responsible for the bleaching action. Because the granulation procedure involves spray coating the granulated precipitates with saturated Na_2CO_3(aq), the students also deduced that the resulting SPC granules consist of a core−shell structure, where the outer Na_2CO_3(s) surface layer encapsulates the inner SPC crystalline particles. The students confirmed this core−shell structure by observing the prepared SPC granules with a magnifying glass (Figure 1, Step 1, E1, L1). The first laboratory exercise was concluded with the instructor's description of the schematic figures shown in the Student Handout. This gave an introduction to the mechanism of the degradation of colored organic dyes with H_2O_2 (Figure 1, Step 1, I1).[15−21]

Reactivity of Oxygen Bleaches: Crystalline Particles versus Granules

The students then applied their previous attained knowledge on the chemical composition and structure of the SPC granules toward the reactivities and reaction mechanisms of oxygen bleaches. The first topic involved a comparison of the bleaching reactivities of dissolved SPC crystalline particles and granules in water (Figure 1, Step 2). Although the students initially presumed that both solutions had comparable bleaching activities, they observed that only the solution of SPC granules exhibited an oxidation activity after a set of period of time (Figure 1, Step 2, E2). This is because SPC crystalline particles exhibit a higher dissolution rate, which subsequently leads to a higher rate of H_2O_2 decomposition. This result taught the students that the oxidation of the organic dyes and the decomposition of H_2O_2 were both competing reactions. This fact was also later reinforced by the instructor (Figure 1, Step 2, I2). Students also learned that the outer surface layer of SPC granules protected the internal SPC crystalline particles from atmospheric moisture (Figure 1, Step 2, L2), which allowed the particles to have a longer in-house storage. At this point, the instructor explained that the outer surface layer protected the internal SPC crystalline particles by acting a barrier to prevent the diffusion of water vapor into the granules. This is observed because the absorption of water vapor by Na_2CO_3(s) causes a hydration reaction that convers this chemical component to $Na_2CO_3 \cdot H_2O$(s).

At the end of the session, the instructor introduced the chemical concepts for the formation of hydroxyl radicals (Figure 1, Step 2, I2), which aids in the decomposition of H_2O_2.[22−26] The students also gained an understanding of the role of the generated hydroxyl radicals in the bleaching process, which allowed them to apply this gained knowledge toward the following exercise.

Reactivity of Oxygen Bleaches: Solid versus Liquid Oxygen Bleaches

The second topic asked the students to explain the possible cause for the difference in bleaching activities between the aqueous solutions of solid oxygen bleach and liquid oxygen bleach observed in the introductory demonstration (Figure 1, Step 2). Because of the students' previously attained knowledge on the compositional components of solid oxygen bleach, they knew that the solutions of solid oxygen bleach had a basic pH. Thus, a probable reason for the differences in bleaching activities could be attained to the basicity of the solutions. Students confirmed this explanation by measuring the pH values of the solutions, which led them to conclude that Na_2CO_3 in SPC played an important role in bleaching.

The students were then asked to propose a possible method for activating the liquid oxygen bleach. Discussion in each of the students' group led them to the conclusion that activation could be achieved with the addition of saturated Na_2CO_3(aq) to the liquid oxygen bleach (Figure 1, Step 2, L3). Each group then proposed a reasonable experimental procedure to validate their proposal. After the instructor ensured that each experimental proposal was both logical and safe, the students conducted their devised experiment and confirmed that the bleaching action of liquid oxygen bleach could only be activated in a basic solution (Figure 1, Step 2, E3).

The guided inquiry in this session introduced the students to the important chemical concept that different extraneous conditions could influence the bleaching reactivity. This gave the instructor an opportunity to describe the mechanism that was responsible for the changes in H_2O_2 bleaching activity depending on the basicity of the solution with reference to the electronic structure of the H_2O_2 molecule (Figure 1, Step 2, I3).[27] The students were also asked to devise a possible method for activating the liquid oxygen bleach for practical household use. A possible solution to this question could involve mixing the bleach with a detergent that contains an alkaline agent such as SSC, which was found in the label of household detergent bottles by the students. This also provides a sufficient explanation on why acidic conditions are commonly observed in liquid oxygen bleach.

Efficient Use of Oxygen Bleach: Fenton's Reaction

In the final session of the learning program, a more advanced question was posited to the students: "Is there a possible method for prolonging the bleaching activity on organic dyes by mitigating the effect of the hydroxyl radicals on the decomposition of H_2O_2?" (Figure 1, Advanced). On the basis of the previous knowledge acquired in this program, students proposed that the solution should be kept under acidic conditions. Some students also proposed that the solution should be adjusted to a neutral pH to prolong the bleaching activity and to increase the stability of H_2O_2. The use of

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catalysts to promote the formation of hydroxyl radicals was also proposed by some students.

After the students' discussion, the instructor demonstrated Fenton's reaction with the liquid household oxygen bleach by adding the catalyst, Fe^{2+}(aq), into an acidic solution with a pH value adjusted to 1−2 (Figure 1, Advanced, D2).[28−30] The color degradation of Rhodamine B promoted the instructor to provide the reaction mechanism for Fenton's reaction (Figure 1, Advanced, I4). The history of the reaction and its possible application toward environmental protection initiatives through several pilot tests and research should also be addressed.[12−14,31−36]

This learning program is concluded by emphasizing the sophisticated chemical concepts that are involved in household oxygen bleaches. There should also be an emphasis on the potential applications of oxygen bleach to our lives in the future.

■ HAZARDS

Students are required to wear safety goggles and protective gloves throughout the experiments. Aqueous solutions of H_2O_2, Na_2CO_3, SPC, and liquid oxygen bleach are all hazardous in the cases of skin contact, eye contact, or ingestion. Oxygen bleaches may cause irritation to the skin, eyes, and respiratory tract. They are also potentially harmful if they are swallowed or inhaled.

■ EVALUATION OF LEARNING PROGRAM

The students' activities during the learning program were analyzed using video recording and students' handout submitted after the laboratory exercise. The results for the educational practice in a high school chemistry class is as follows:

- Introduction: The students recalled their previous learnings in schools and experiences in their daily lives on the reaction of H_2O_2, bleaching, and redox reaction though group discussion. However, almost all of the students could not expect the difference in the bleaching efficacies of solid and liquid oxygen bleach. The results of the instructor's demonstration, which is different from students' expectation, was effectively used to motivate students to inquiry the reason. After confirming the components in household oxygen bleaches from the labels on the bottles, students easily identified H_2O_2 in the liquid oxygen bleach as the oxidizing component, but only a few of students found SPC in the solid oxygen bleach as the oxidizing agent. Thus, the instructor could smoothly transfer to the next learning step focused on the components of SPC.
- Step 1: SPC crystals and granules were prepared by students without any specified difficulties. From the experience of SPC preparation and morphological observations, students expected Na_2CO_3 and H_2O_2 as the components of SPC and drawn a figure of core−shell structure of SPC granules. The experimental test of the bleaching efficacy of the prepared SPC granules were carried out by students themselves without any supports.
- Step 2−1: Observations of the different dissolution rate of SPC crystals and granules and the evolution of gas provided sufficient information for discussing the reason for the different bleaching efficacies of the solutions of SPC crystals and granules in each students' group. Some students were aware of the competing reactions of H_2O_2 decomposition and oxidation of organic dye before introducing the phenomenological reaction mechanisms by the instructor. Recognition of the role of the Na_2CO_3 surface layer of SPC granules for protecting the internal SPC crystals from atmospheric moisture was not reached by many students' groups without introduction by the instructor.
- Step 2−2: A basic pH of the solution of SPC granules was easily expected by the students. After pH tests for the solutions of solid and liquid oxygen bleaches, students deducted that a basic pH is responsible for the activity of H_2O_2 as the oxidizing agent. They proposed addition of alkaline agent to the liquid oxygen bleach for activating bleaching action and selected saturated Na_2CO_3(aq) as the alkaline agent because of the previous use for preparing SPC. All of the students' groups proposed acceptable verification experiment for the activation of liquid oxygen bleach. The verification experiment was attractively received by the students, which is more than that expected. The observed phenomena were transferred to the household liquid oxygen bleach for laundry use. Students were aware of mixing of liquid oxygen bleach with household detergent for the use and predicted the involve of alkaline agent in the detergent. From the label of household detergent, students found out SSC.
- Advanced learning: During discussion for the efficient use of oxygen bleach in each group and in class, students used all the related chemical knowledge and concepts introduced in the learning program that involve phenomenological mechanism of H_2O_2 decomposition, change in the H_2O_2 activity depending on pH, and formation of hydroxyl radicals. An acidic or neutral condition was proposed by many students' groups to prevent decomposition of H_2O_2. They also proposed the use of catalyst for promoting formation of hydroxyl radicals in an acidic condition by listing MnO_2, Fe^{3+}(aq), and I^-(aq). They could conclude their discussion after the Fenton's reaction using household liquid oxygen bleach was demonstrated by the instructor.

Multichoice tests for assessing students' understanding of the phenomenology related to chemical actions of oxygen bleaches were administrated to the students after approximately one month from the laboratory learning. The tests involved 3−5 questions for each related knowledge and concepts categorized by decomposition and redox reaction of H_2O_2, function of SPC granules, reactively of H_2O_2 and pH, Fenton's reaction, and household bleaches. Figure 3 shows the average accuracy rate of the multichoice tests in each category of knowledge and concepts related to the phenomena studied in the learning program. The phenomenology of the reactions of H_2O_2 was well understood by the students as is seen by the high accuracy rates for the first three categories. Slight lower accuracy rate for decomposition and redox reaction of H_2O_2 is attributed to the difficulty of understanding of the mechanism of the redox reaction between H_2O_2 and organic dye. About the Fenton's reaction, students correctly answered the reaction conditions and the merits of the reaction. However, understanding of the mechanism of the Fenton's reaction was not reached at acceptable level. The high accuracy rate for household bleaches indicated that the students could correlated the chemical

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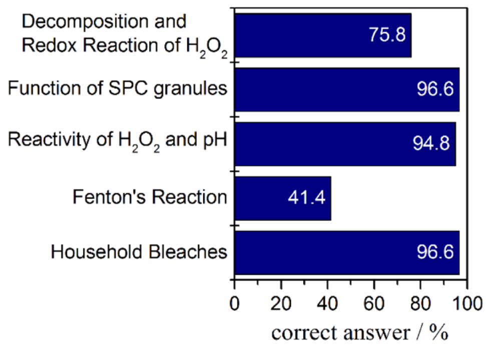

Figure 3. Average accuracy rates of multichoice tests in each category of knowledge and concepts related to the phenomena studied in the learning program (high school chemistry class, N = 29).

knowledge and concepts studied in the program and the daily use of household bleaches. Overall, the assessment results indicate that the objectives of the learning program were achieved especially on the phenomenological understanding of the chemistry of oxygen bleaches. The understanding was also correlated with the chemistry in students' daily lives. The analyses of the video recording and the multichoice tests indicate that the leaning program proposed in this study provides students various opportunities to use their chemical knowledge and concepts involving acid/base and redox reaction and to extend their understanding of the change in the reactivity of chemical reactions with reaction conditions as exemplified by the different reactions of H_2O_2.

■ CONCLUSIONS

Comparative experimental approaches to liquid and solid oxygen bleaches are effective for high school chemistry courses and university-level introductory chemistry courses. A learning program that utilized oxygen bleaches was designed using a stepwise inquiry with predictable conclusions, experimental planning and validation, and deductive reasoning based on previously attained knowledge. The mechanisms for the chemical reactions were also introduced in a stepwise manner by the instructor throughout the course of the learning program. The results showed that the students were sufficiently informed on the decomposition and redox reactions of H_2O_2 and the dependence of the bleaching activity on varying reaction conditions. They were also introduced to the sophisticated chemical concepts behind household oxygen bleaches and their potential applications within their daily lives.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.5b00742.

Student Handout and Instructor Information. (PDF)
Student Handout and Instructor Information. (DOCX)

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: nkoga@hiroshima-u.ac.jp.

Notes

The authors declare no competing financial interest.

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