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DESIGNING A SYSTEM OF SMALL-SCALE EXPERIMENTS APPLIED IN TEACHING "*SUBSTANCES AND THEIR CHANGES*" CONTENT IN SCIENCE SUBJECTS AT SECONDARY SCHOOLS

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Abstract. Applying small-scale experiments in teaching science to students has garnered a lot of interest from worldwide scientists. Compared to conventional experiments that are performed in regular laboratories, small-scale experiments have a variety of advantages including consuming a small number of chemicals and using small-size reusable apparatuses, thus saving money and contributing to protecting human health, safety, and the environment. In addition, applying small-scale experiments helps to develop students' science competence, critical thinking, and learning interests in experimental subjects. However, using small-scale experiments in teaching science in Vietnam has not been widespread yet, with not many studies focusing on this topic. Therefore, this study demonstrates basic ideas and strategies to design and apply small-scale experiments in teaching. Following the content and requirements of the General Education Program in 2018, a system of small-scale experiments used in the "*Substances and their changes*" topic in Science subjects is designed. A website demonstrating the practical steps to apply these experiments in teaching at secondary schools has been recently developed. It is hoped that the use of small-scale experiments will be developed widely as an effective approach to teaching science subjects in Vietnam in the upcoming years.

Keywords: small-scale experiments, "*Substances and their changes*" topic, Science subjects.

1. Introduction

In the educational program developed in 2018, Science is a subject that combines theory and experiment. Therefore, incorporating visual tools into teaching science in general and experiments, in particular, will help students explore, discover, and dominate knowledge in intuitive, vivid, and active ways.

Using experiments in teaching is an effective means of developing critical thinking in students. By observing and explaining experimental phenomena that occur during experiments, students can build up their ability to analyze and explore the actual nature of things and substances. As a result, the critical thinking ability of students is enhanced and students gradually become familiar with scientific research procedures. In addition, the experiment-related activities motivate students to be active and strengthen their teamwork and communication skills [1].

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"*Substances and their changes*" is one of the four main scientific topics in the Science subjects, playing an important role in the educational program that focuses on three primary contents: substances in the surrounding, the structure of substances, and their chemical changes [2].

Despite playing a crucial role in teaching and learning science, the use of experiments on the "*Substances and their changes*" topic in schools has become a major challenge in many parts of the world in general and developing countries in particular. Numerous experiments have been proposed in the educational program, but have been skipped at many levels including secondary schools, high schools, and universities, resulting in a remarkable shortage of practical activities or real-life experiences in learning. This fact is due to many reasons. Firstly, the high cost of experiment materials is unsuitable for the size of many schools, particularly in rural areas. The shortage of facilities and equipment to carry out experiments has been more severe during the Covid-19 pandemic when global trade and shipping face many difficulties. Secondly, most conventional experiments in school generally involve large-sized glass apparatuses and possibly hazardous chemicals that could harm the health of students, teachers, and laboratory staff. In addition, handling chemical leftovers or waste management is a common issue of experimental activities. Untreated chemical waste in large amounts can harm the environment. Therefore, experiments need designing to be carried out in a variety of school conditions, especially in limited spaces and resources; and to meet human health, safety, and environmental requirements [3, 4].

Using small-scale experiments (SSE) is one alternative approach to overcome the mentioned obstacles in teaching experiments in schools. SSE is a model of performing experiments with small-sized and portable apparatuses or laboratory instruments, which use low amounts of chemicals while retaining the scientific integrity and accuracy of the experiments. Due to the reduced chemical usage (up to 1000 times compared to conventional standard chemistry experiments [5]), as well as the smaller size and reusable laboratory equipment, using SSE will save money and be safer for human health and the environment [6]. In addition, the time for experiment preparing, performing, and cleaning up afterward can be greatly reduced. Therefore, the application of SSE would become more effective in the scope of teaching in schools [6, 7].

Small-scale experiments were implemented very early and developed in many areas all over the world. For example, SSE was first introduced to Africa in 1924 [8]. In 1990, the research project studying SSE was developed by "The Research and Development in Mathematics, Science and Technology Education (RADMASTE)" [7]. In 1996, the project "Global Microscience" in the research program about SSE was organized by UNESCO and IUPAC [7]. In recent years, the research on SSE has attracted more attention from scientists with many research centers and institutes established in many places such as Africa (RADMASTE in South Africa), the Americas (National Microscale Chemistry Center in the US, Centro Mexicano de Química en Microescala in Mexico, International Organization for Chemical Sciences in Development in Canada), Europe (Swedish Microscale Center in Sweden, Consortium of Local Education Authorities for the Provision of Science Services in UK) and Asia (University of Science in Malaysia, Victoria in Thailand).

Currently, SSE is included in syllabuses, textbooks, and manuals; and is taught in chemistry practices at both secondary and high school levels in some developed and developing countries. The effectiveness of using SSE at the high school and tertiary level in developing countries has been reported by several studies in India [9], Thailand [10], Malaysia [11], Slovenia [12], and some African countries (such as South Africa [13], Ghana [14], Ethiopia [15]). A noticeable feature of SSE is that the frequently used instruments and chemicals can be incorporated into a scientific kit that can be used for a variety of experiments and educational activities. Recently, scientific kits have been successfully developed and tested in many countries such as Brazil [16] and Malaysia [17]. Due to their advantages including small size, affordable price, safety, and

environmental friendliness, the SSE kits can offer teachers and students more flexibility in teaching and learning activities. The experiments and practical lessons can even be organized outside of the classroom with few laboratory tools. Therefore, using SSE is believed to be an effective alternative to altering or complementing conventional practical lessons in the upcoming years.

In Vietnam, the use of SSE in teaching and learning activities is still a relatively new research topic. In August 2019, the session to introduce the applications of SSE for high school teachers in Ho Chi Minh City was jointly organized by the Faculty of Chemistry of the University of Sciences - Vietnam National University Ho Chi Minh City and Chulalongkorn University (Thailand). Some authors such as Thai Hoai Minh and Dinh Thi Xuan Thao have conducted initial research on applying SSE in teaching some content in the Chemistry teaching program in high schools [18]. However, the amount of research on using SSE in teaching Science subjects in Vietnam is still rather limited, which requires more investigations in the future.

2. Content

2.1. Overview of Small-scale Experiments (SSE)

2.1.1. The concept and characteristics of Small-scale experiments (SSE)

There are many definitions of SSE, but in general, SSE refers to a method or approach of performing experiments on a smaller scale, which uses small amounts of chemicals and is frequently (but not always) carried out with tools/apparatuses of compact sizes. Therefore, SSE allows for teaching more flexibly, saving chemicals, and especially minimizing the chemical waste released into the environment. According to the report of The Global Microscience Experiments Project operated by UNESCO [7], SSE helps (i) to save money by significantly reducing consumed chemicals and disposed waste into the environment; (ii) to save time for preparing, performing experiments and cleaning; and (iii) to ensure a safe working environment for teachers and students.

Although there are differences in definitions, concepts of SSE all demonstrate the following primary characteristics: using *small amounts of chemicals, simple techniques, and laboratory apparatuses but still reflecting the accuracy of scientific experimentation*. Two basic features of Small-scale Experiments (SSE) include as following:

Firstly, chemicals consumed in SSE are in small but sufficient and adequate amounts. Compared to conventional experiments in regular laboratories, the amount of chemicals is reduced and minimized. For instance, each SSE commonly consumes only about 1 mL of solvents and 100 mg of solid chemicals [19]. Even a few drops of solutions can be sufficient for SSE, which greatly reduces the number of consumable chemicals, thereby saving costs and especially being safe for the health of teachers and students, as well as protecting the environment in the orientation of developing green chemistry.

Secondly, laboratory apparatuses can be made from polymers or recycled materials instead of conventional glassware. To fit the small number of consumed chemicals in the SSE, laboratory apparatuses and equipment in the SSE also need to be designed and standardized accordingly. Frequently, glass apparatuses are replaced by modern polymer or plastic materials. Moreover, it is feasible to develop many kinds of equipment and tools by recycling some items available in daily life while still ensuring the scientific integrity and accuracy of experiments.

2.1.2. Advantages of using small-scale experiments in teaching

** In terms of teaching organization*

Firstly, SSE contributes to the development of students' science competence by providing opportunities for students to directly observe phenomena and conduct experiments with their own hands.

The scientific nature of the experiments is preserved but practice methods are simplified with the number of chemicals reduced significantly. Therefore, students can apply their acquired knowledge to explain observed phenomena based on experimental data along with their theoretical understanding of chemistry and science.

Secondly, SSE enhances students' interest in Science in general and in Chemistry in particular. Students can actively engage in SSE rather than just learning theory or experiments through simulation approaches such as observing pictures or watching videos. Using SSE, therefore, helps students develop positive attitudes and passion for experimental subjects.

Thirdly, using SSE in teaching and learning Science and Chemistry subjects allows for saving costs. As previously discussed, the use of small amounts of chemicals as well as simple, easy-to-find, and easy-to-manufacture plastic apparatuses (instead of highly perishable glassware) can be very cost-effective for experimental activities.

** In terms of environmental protection and human health*

Reducing the consumption of chemicals as well as improving the reusability and durability of laboratory tools or apparatuses have been contributing to protecting the environment and human health. It is considered one of the green chemistry pathways. By considering the usage or reuse of lab equipment and reducing the number of chemicals used, students are also taught about environmental awareness and their responsibility to protect the environment. Using SSE also minimizes the chance of accidents during experiments such as fire, explosion, or human damage for students or teachers while working with glassware.

2.2. Designing a system of small-scale experiments in teaching the "*Substances and their changes*" topic of Science subjects in secondary schools

2.2.1. Design principles

To design teaching activities to apply SSE effectively, teachers must follow several key principles including achieving the teaching objectives, ensuring the scientific integrity and accuracy of experiments, ensuring safety, ensuring pedagogy and aesthetics/visual criteria, and ensuring environmental protection principles.

Achieving teaching objectives: It is a crucial principle when designing SSE in teaching Science subjects. Teachers must identify the specific requirements that need to be achieved in the lessons using experiments to study things/substances and phenomena in the natural world. From these requirements, small-scale experiments in these teaching activities are designed to be suitable for students to achieve the set goals.

Ensuring the scientific integrity and accuracy of experiments: Although the number of chemicals and size of equipment are adjusted, the SSE needs to be designed in a systematic and scientifically accurate manner. The list of equipment/tools and chemicals is comprehensive and detailed. The procedure of performing experiments is provided logically, guaranteeing the experiment's success. The phenomenon occurring in SSE should be consistent with the theoretical content of the lessons and with traditional or standard experiments.

Ensuring requirements for environmental protection: It is a guiding principle when designing SSE. When performing experiments with potentially hazardous chemicals, the proper precautions must be taken to limit a threat to the environment. In addition, recycling common items to create laboratory tools that can be used in SSE also contributes to environmental protection.

Besides, the principles of *ensuring safety, pedagogy, and aesthetics* when performing SSE should be followed in the same way as conducting conventional or standard scientific experiments.

2.2.2. Designing teaching activities using SSE

The process of designing and using SSE in teaching Science subjects usually consists of five steps as illustrated in Figure 1.

Step 1. Identify the teaching objectives and select the experiments

This step acts as a guide to the subsequent steps in the procedure of designing and using SSC in teaching Science. For teaching science in general and chemistry in particular in schools, it is necessary to base on the general objectives and content of the teaching to identify the specific goals and select the experiments to be designed. Teachers can rely on the requirements of students' quality and competence specified in the general education program to determine the goal of using SSE in each lesson. The goal set should be appropriate for students' ability to achieve through experimentation.

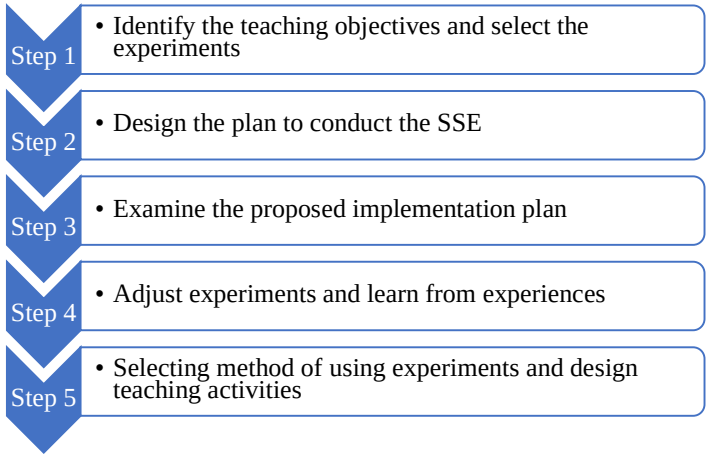

Figure 1. The five-step procedure of designing and using SSE in teaching science

Step 2. Design the plan to conduct the SSE

From the established goals, teachers search for references to choose experiments that need to be designed as SSE and get ideas about instruments or laboratory tools, chemicals as well as the way to perform experiments and organize teaching activities using SSE. The experimental plan can be planned based on traditional or standard experiments and then the instruments/tools, equipment, and a number of chemicals can be modified accordingly.

Step 3. Examine the proposed implementation plan

Based on the proposed ideas and plans for SSE, teachers prepare the appropriate laboratory equipment or tools and chemicals to experiment. Recently, we have developed detailed plans to conduct experiments in teaching *Substances and their changes* on the website https://sites.google.com/view/smallscalechemhnue. Some alternatives for traditional laboratory instruments/tools are demonstrated in Figure 2.

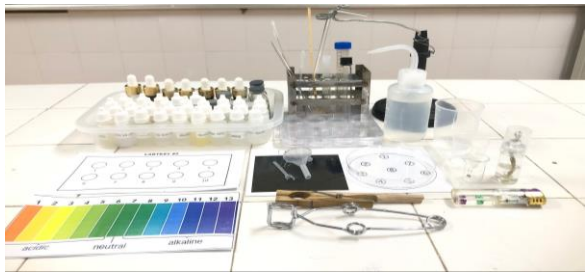

Figure 2. Pictures of some designed laboratory apparatuses used in SSE

Step 4. Adjust experiments and learn from experiences

Teachers need to review, evaluate, and make adjustments (if necessary) from the experimental results and examination of the designed SSE. For example, the number of used chemicals, types of equipment or tools, and experimental steps can be modified to ensure the design principles of SSE. Within the allowed time frame, teachers should perform experiments, verify results, and adjust experimental setups multiple times to obtain the most effective designed SSE.

Step 5. Select the method of using experiments and design teaching activities

After building a system of SSE, teachers choose the method of applying experiments and then design educational activities suitable for the specific goals and contents of the teaching program in Science subjects.

2.2.3. Designing a system of SSE in teaching *Substances and their changes* in Science subjects at secondary schools

Based on the principles and procedure mentioned above, we have designed a system of SSE that can be used in teaching *Substances and their changes* in Science subjects at secondary schools, which includes 21 experiments.

Table 1. The list of SSE applied in teaching "Substances and their changes" in Science subjects at secondary schools

Grade	Number	Name of experiments	Goals of experiments	QR code (video of experiments)
Grade 6	1	Solubility in the water of some substances (sugar, salt, cooking oil, and gasoline).	Study on the solubility of some properties of substances.	
	2	The transition of water from solid to liquid.	Performing simple experiments to track the state transitions of a substance.	
	3	The transition of water from liquid to gas.		
	4	Oxygen sustains combustion.	Prove that oxygen sustains combustion.	
	5	The volume composition of oxygen in the air.	Performing experiments to determine the volume composition of oxygen in the air.	

	6	Dissolving sugar in water to get a sugar solution. (Solubility of sugar in water) Solubility of cooking oil and gasoline in water.	Performing simple experiments to identify and distinguish solvents and solutions.	
Grade 8	1	Carbon dioxide reacts with limewater to form a precipitate.	Performing experiments on signs and phenomena of chemical reactions, distinguish between physical and chemical changes.	
	2	Burning Sulfur in the air and oxygen.		
	3	Experiments of hydrochloric acid (changing the color of indicators and reacting with metals).	Studying the chemical properties of acids.	
	4	Experiments of bases (changing the color of indicators, reacting with acids to form salts).	Studying the chemical properties of bases.	
	5	Experiments of salt reacting with metals, acids, bases, and salts.	Studying the chemical properties of salts.	
	6	Experiment with purple cabbage and indicator papers.	Performing some experiments to measure the pH (with indicator papers and natural indicators) of some foods (beverages, fruit juices...).	
Grade 9	1	Experiments of metals reacting with water, acids, and salts.	Studying the chemical properties of metals.	

	2	Experiment with butane combustion.	Performing butane combustion experiments and drawing chemical properties of alkane.	
	3	Experiments of ethylene: combustion reaction, bromine water decolorization reaction.	Performing experiments of ethylene, observing and explaining basic chemical properties of alkene.	
	4	Experiments of ethylic alcohol: combustion reaction and reaction with sodium.	Performing experiments of ethylene, observing and explaining basic chemical properties of ethylic alcohol.	
	5	Experiments of acetic acid: reaction with purple litmus papers, metal, metal oxide, base, salt, combustion reaction, esterification reaction).	Study on the chemical properties of acetic acid.	
	6	The experiment of silver mirror reaction of glucose.	Experimenting or observing the experiment of silver mirror reaction of glucose.	
	7	Experiments of starch: hydrolysis reaction and color reaction with iodine of starch.	Investigate hydrolysis reaction; and color reaction with iodine and conclude the chemical properties of starch.	
	8	Protein coagulation experiment.	Proved protein: coagulated under the effect of HCl, and temperature, easily decomposed when heated.	

These experiments are described comprehensively on the following website *https://sites.google.com/view/smallscalechemhnue*. The website includes a detailed description of laboratory equipment or tools and chemicals used in each experiment with videos demonstrating the experiment's progress.

2.3. An illustration of using SSE in teaching Science subjects at secondary schools

By studying with SSE, students' competence would be fully developed.

The following example illustrates one way to apply SSE in teaching the "*pH range*" lesson in the "*Acid-Base - pH - Oxide - Salt*" topic of Science grade 8. One requirement of this lesson is "Performing some experiments to measure the pH of some foods (drinks, fruit juice, etc.) by using indicator papers". Therefore, teachers can design activities for students to carry out experiments in groups to measure the pH (with indicator paper) of some fruit juice and beverages, following the instructions in the below worksheet. Students can perform experiments and complete the worksheet in 10 minutes.

WORKSHEET

Procedure

- Prepare a paper for the experiment named ***Labtest 1*** with positions numbered from 1-10.
- Put 6 pieces of indicator paper on positions from 1-6.
- Use a small transparent pipette to put a drop of lemon juice on the indicator paper at position 1.
- Repeat this step and put one drop of vinegar in position 2, Sprite drink in position 3, Lavie water in position 4, soapy water in position 5, and clear limewater in position 6.
- Compare the color of the indicator papers after adding one drop of the mentioned solutions to the standard pH color scale and record the pH value.

Discuss and complete the following table:

Positions number	Solutions	Substances causing color changes of indicator papers	pH of solutions	Type of solutions (acid, base, or neutral)
1	Lemon juice			
2	Vinegar			
3	Sprite drink			
4	Lavie water			
5	Soapy water			
6	Clear limewater			

A form of Labtest for SSE is shown in Figure 3.

After the experiment, the teacher can also encourage students to investigate and practice at home by creating a natural pH indicator and using a "labtest" to test the pH of at least 5 different foods or beverages. The teacher suggests some natural indicators such as juice of purple cabbage, beetroot, turmeric, butterfly pea flower, etc., then asks students to take pictures of the test results at home and report them. The following image shows the test results of students using purple cabbage juice as a pH indicator (Figure 4).

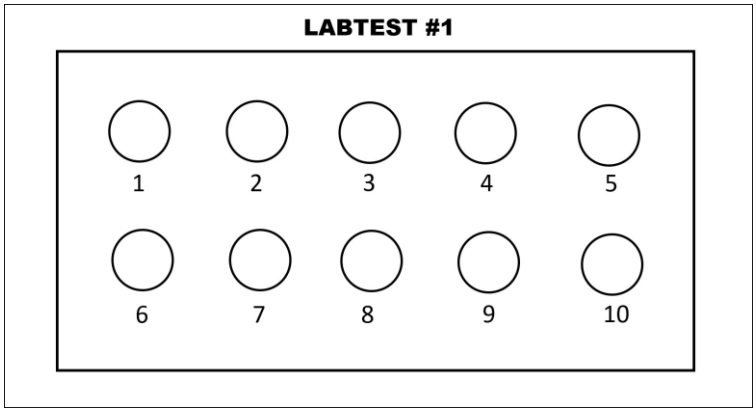

Figure 3. A Labtest used in small-scale experiments

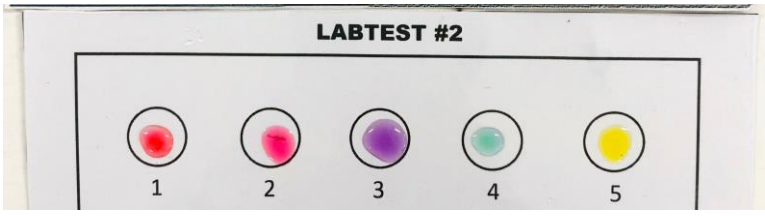

Figure 4. An example of using purple cabbage juice as a pH indicator

3. Conclusions

In conclusion, the application of Small-scale experiments in teaching the "*Substances and their changes*" topic in Science subjects would help to minimize consumed chemicals; reduce chemical wastes released to the environment; and recycle simple, easy-to-develop laboratory tools. Through a system of Small-scale experiments proposed and the website developed to demonstrate the use of these experiments in teaching Science, we hope that small-scale experiments will be applied widely shortly. Small-scale experiments can be designed as a simple, compact, and suitable kit to perform qualitative experiments with clear and easy-to-observe phenomena. Therefore, small-scale experiments will hold great promise to be an alternative solution that can replace completely the traditional experiments to support teachers in some schools where teaching equipment is insufficient. Especially, using small-scale experiments would contribute to educational programs for the environment and sustainable development.

REFERENCES

[1] Chabalengula, V.M., Mumba, F., Hunter, W. and Wilson, E., 2009. A model for assessing students' science process skills during science lab work. *Problems of Education in the 21st Century*, 11, pp. 28

[2] Ministry of Education and Training, 2018. *General education program in Chemistry*. Issued together with Document 32/2018/TT-BGDDT Hanoi.

[3] Listyarini, R.V., Pamenang, F.D.N., Harta, J., Wijayanti, L.W., Asy'ari, M. and Lee, W., 2019. The integration of green chemistry principles into small-scale chemistry practicum for senior high school students. *Journal Pendidikan IPA Indonesia*, 8(3), pp. 371-378.

[4] Zakaria, Z., Latip, J. and Tantayanon, S., 2012. Organic chemistry practices for undergraduates using a small lab kit. *Procedia-Social and Behavioral Sciences*, 59, pp. 508-514.

[5] Mamlok-Naaman, R. and Barnea, N., 2012. Laboratory activities in Israel. *Eurasia Journal of Mathematics, Science and Technology Education*, 8(1), pp. 49-57.

[6] Durbach, S. and Bradley, J.D., 1998. Hands-On Practical Chemistry for All: Why and How? *Journal of Chemical Education*, 75(11), pp. 1406-1409.

[7] UNESCO. 2012. Small is Beautiful, *African Journal of Chemical Education*, 2(1), pp. 23-31.

[8] Tesfamariam, G., Lykknes, A. and Kvittingen, L., 2014. Small-scale chemistry for a hands-on approach to chemistry practical work in secondary schools: Experiences from Ethiopia. *African Journal of Chemical Education*, 4(3), pp. 48-94.

[9] Kelkar, S.L. and Dhavale, D.D., 2000. Microscale experiments in chemistry: the need of the new millennium. *Resonance*, 5(10), pp. 24-31.

[10] Acharry, S. and Suwannathada, J., 2010. The development of microscale laboratory: Titration. *International Journal of Arts and Sciences*, 3(9), pp. 296-305.

[11] Zakaria, Z., Latip, J. and Tantayanon, S., 2012. Organic chemistry practices for undergraduates using a small lab kit. *Procedia-Social and Behavioral Sciences*, 59, pp. 508-514.

[12] Gros, N., 2012. Small-scale, low-cost analytical instruments: Extended opportunities for learning analytical chemistry. *New Perspective in Science Education*, pp.1-6.

[13] Bradley, J., 2000. The microscience project and its impact on pre-service and in-service teacher education. *Washington, DC: The World Bank http://web.worldbank.org/archive/ website00243B/ web/pdf/bradley.pdf*.

[14] Hanson, R., 2014. Using small-scale chemistry equipment for the study of some organic chemistry topics case study in an undergraduate class in Ghana. *Small*, 5(18).

[15] Hanson, R. and Acquah, S., 2014. Enhancing concept understanding through the use of microchemistry equipment and collaborative activities. *Journal of Education and Practice*, 5(12), pp. 120-130.

[16] Toma, H.E., 2021. Microscale Educational Kits for Learning Chemistry at Home. *Journal of Chemical Education*, 98(12), pp. 3841-3851.

[17] Rayner-Canham, G., 1994. Microscale methods in general chemistry. *Education in Chemistry*, 31(3), pp. 68-70.

[18] Thai, H. M., Dinh, T.X.T., 2021. Design learning activities using microscale experiments in teaching Chemistry at high school. *HNUE Journal of Science. Educational Sciences*, 66, pp. 3-12.

[19] Singh, M.M., Pike, R.M. and Szafran, Z., 2000. The philosophy of green chemistry is applied to the microscale inorganic chemistry laboratory. *Educación Química*, 11(1), pp. 172-173.