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Laboratory module design for Biology Students: A Systematic review

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ABSTRACT

Module design for students' laboratory activities plays an important role in the effective implementation of scientific investigation in the laboratory. The purpose of this review is to examine the types, topics, competencies, and approaches to develop laboratory module for biology students. The review of the literature was conducted systematically. Eighteen research articles were selected from 41 articles published within 2009 and 2019. The systematic review followed 5 steps. The research articles were searched using Google Scholar's online database and then traced back from the relevant international and national journals. The articles collected were selected by two reviewers who rated the quality. The results of the analysis showed that the laboratory modules are designed using the following basis: online, research, quantitative skills, inquiry, and traditional. The biology topics focused are Genetics, Ecology, Phylogenetics, Biochemistry, Molecular Biology, Evolution, Biotechnology, and Tissue Culture. The methods used for laboratory module development by Indonesian researchers are 4D, ADDIE, R & D, Dick & Carey, and Borg & Gall, while international researchers generally do not specify the name of the method used. Generally, the need analysis which focuses on the novelty of the developed concept is conducted in the beginning. It continues with module designing, validation, implementation, and response survey from the students as the module users.

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Introduction

Module is a learning instrument containing materials, methods, definitions, terminologies, and evaluation procedures that is designed interestingly to achieve expected competencies. Laboratory module is one of the supporting modules for research- oriented activities which replaces or complement the traditional "cookbook" practicum modules in various disciplines (Siritunga et al., 2011).

Laboratory modules in higher education are commonly provided by lecturers and contain a sort of experiment procedures that students simply follow. For courses that demand laboratory activities, generally in the early semester, Biology students use laboratory modules consisting of some experiments which already have results (Peteroy-Kelly, 2010). The low number of research-oriented laboratory modules that contain scientifically tested research techniques and procedures and the

lack of students' research experience during their study can affect the quality of students' scientific skills in the laboratory (Siritunga et al., 2011).

An alternative that can be taken to boost students' research skills and quality of experiment activities in the laboratory is to formulate the qualified and research-based module. The module that is developed from a research on particular material can help students construct interactive individual experience, understand their involvement during the research process, and apply knowledge in formulating scientific questions that lead to research activities (Goff et al., 2017; Howard & Miskowski, 2005). The laboratory modules are generally designed to include some material components and student activities which can be adopted by cognate study programs in higher education. The designed laboratory modules are expected to facilitate students in developing research mindset through a process of scientific reasoning along with improving the students' conceptual understanding. In addition, the use of modules is expected to be able to nurture students' abilities for their career.

A great number of designs and materials for laboratory modules have been used in universities. The selection of laboratory module design will certainly affect the development of students' skills and knowledge. The importance of module design in the implementation of laboratory activities, especially in biology, has encouraged the researchers to examine the diversity of laboratory module designs that have been used by biology students. This article will identify and analyze research on biology modules that have been used and published in international and national journals. The purpose of writing the article is to find the types of module design, topics, the competencies being empowered, and the approaches used in formulating the biology laboratory modules.

The research problems constructed in the article are: (1) What are the types of biology laboratory module designs that have been studied? (2) What are the biology topics or themes of laboratory modules covered? (3) What are the effects of using different kinds of laboratory module designs on students' competencies? (4) What are the approaches for developing biology laboratory modules that are often used by Indonesian and international researchers?

Method

This study followed the steps of systematic review approach adopted from (Khan, Kunz, Kleijnen, & Antes, 2003) which consists of 5 steps: 1) Developing a framework for formulating review questions, 2) Identifying relevant research, 3) Assessing the quality of research being reviewed, 4) Writing the results of the study, and 5) Analyzing and interpreting the results of the study.

The first step was determining four questions that would be investigated structurally: 1) Types of biology modules that have been studied, 2) Biology laboratory module themes, 3) Competencies are focused in the modules, and 4) Approaches for designing the modules.

The second step was determining the keywords search, the inclusion and exclusion criteria that would be used as the basis for searching the research articles. For the inclusion criteria, the phrase "biology laboratory modules", and the word "undergraduate" were used. The exclusion criteria limited the search on quantitative research that were published in the last ten years (2009-2019). The first search was conducted using Google scholar with the keywords "module, laboratory, biology, and undergraduate". Twenty articles in the selected relevant international journals were found and 8 articles were selected. In the second search, the keywords "biology module" and "undergraduate" were used and 5 articles were selected from 12 articles in the relevant international journals. The third search was carried out in the national journals. The selection of articles in the national journals focused on searching research-based modules in Indonesia. The keywords used were "research-based biology student modules" and 5 articles were selected from 9 articles found.

The eligibility of the eighteen articles selected were checked by two experts who assessed the quality of the research based on the research design criteria and publisher (the third step). The assessment showed that the 18 articles were eligible to be reviewed. From those articles, 13 articles were taken from international journals, four from national journals and one from international proceedings. The fourth step

was presenting the data, and analyzing the results.

Analysis were focused on the types of module design, biology topics, competencies designated, and the module development approaches. The fifth step was interpreting and reviewing the eighteen articles

Results and Discussion

Data that presented in the table are journal identity, and information of research on laboratory modules that have been used by Biology undergraduate students. The articles that were reviewed are presented in Table 1 and Table 2.

1. Types of laboratory module design

The success of laboratory activities is determined by the design of the laboratory modules used. It is found that the designs of biology laboratory modules that were identified in the reviewed articles consists of five types: online-based with quantitative skills approach, research-based, inquiry-based, quantitative skills-based and traditionally-based.

1.1 Online or web-based modules

Mathbench module is an online-based module used by biology students at Maryland University. The module contains texts, graphics, and interactive elements. The module component contains interactive programs that enable students to explore mathematical concepts in biology which focus on molecular biology (Thompson, Nelson, Marbach-Ad, Keller, & Fagan, 2010).

1.2 Research-based modules

It is the most common type of module design. Modules developed based on research results contain a combination of theory and research activities which promote students understand the concrete application of the concepts being studied and help them achieve the expected competencies (Fajarwati, Kiswandianta, & Pujiati, 2018).

Table 1. List of articles on laboratory modules developed for Biology students by international researchers

Year	Author (s) ; (Title); Publisher	Types of module	Materials	Competencies
2009	Kären C. Nelson, Gili Marbach-Ad, Katie Schneider, Katerina V. Thompson, Patricia A. Shields, and William F. Fagan (MathBench Biology Modules Web-Based Math for All Biology Undergraduates) Journal of College Science Teaching	Online or web-based interactive module (quantitative approach)	Genetics	The ability to calculate probabilities, use graphs, and use mathematical concepts in biology.
2010	Raina Robeva,* Robin Davies,† Terrell Hodge,‡ and Alexander Enyedi (Mathematical Biology Modules Based on Modern Molecular Biology and Modern Discrete Mathematics) CBE—Life Sciences Education	Skill-based module (quantitative)	Molecular biology and phylogenetics	Increasing interest in integrating modern mathematics and modern biology, increasing awareness of the importance of biomathematics in life, and encouraging collaboration and development across disciplines
2010	Katerina V. Thompson,* Ka¨ren C. Nelson,† Gili Marbach-Ad,* Michael Keller,*and William F. Fagan† (Online Interactive Teaching Modules Enhance Quantitative Proficiency of Introductory Biology Students) CBE—Life Sciences Education	Online-based interactive module (quantitative approach)	Normal Distribution, population and Scientific Methods	Quantitative biology skills and concept reinforcement
2012	Sara E. Brownell, Matthew J. Kloser, Tadashi Fukami, and Rich Shavelson (Undergraduate Biology Lab Courses: Comparing the Impact of Traditionally Based “Cookbook” and Authentic Research-Based Courses on Student Lab Experiences) Journal of College Science Teaching	Traditional Module and research-based module	Ecology	Formulating hypotheses, analyzing data, and communicating results in verbal and written form

2012	Adrienne Alaie, Virginia Teller, Wei-Gang Qiu (A Bioinformatics Module for use in an Introductory Biology Laboratory) National Association of Biology Teachers	Research-based module (bioinformatics)	Gen Bank and BLAST program	Student performance
2013	James M. Burnette and Susan R. Wessler (Transposing from the Laboratory to the Classroom to Generate Authentic Research Experiences for Undergraduates) The Genetics Society of America (Education)	Research-based module	GENOME (transgenic plant, PCR analysis)	Research skills & research concept
2014	Krissi M. Hewitt, Lori J. Kayes, David Hubert and Adam Chouinard (Investigating Issues in the Laboratory: The Behavior of Red Swamp Crayfish as an Invasive Species) National Association of Biology Teachers	Research-based module (problems)	Invasion biology, animal behavior, and behavioral ecology.	students' perceptions of their learning experience
2014	Rosanna L. Robinson & James E. McDonald (Developing Skills in Second Year Biological Science Undergraduates) Bioscience Education	Skill-based module	Biosciences	Project design skills, literacy skills, critical and creative thinking skills
2016	Kathleen Hoffman, Sarah Leupen, Kathy Dowell, Kerrie Kephart, and Jeff Leips (Development and Assessment of Modules to Integrate Quantitative Skills in Introductory Biology Courses) CBE—Life Sciences Education	Skill-based module (quantitative)	Ecology and Evolution	Quantitative reasoning and skill
2017	Carolyn F. Weber; Microgreen Farming and Nutrition (A Discovery-Based Laboratory Module to Cultivate Biological and Information Literacy in Undergraduates) National Association of Biology Teachers.	Research-based module	biotechnology	quantitative skills and information literacy in the context of biology.
2018	Jay M, Bhatt, and Anil Kumar Challa (First Year Course-Based Undergraduate Research Experience (CURE) Using the CRISPR/Cas9 Genome Engineering Technology in Zebrafish) American Society for Microbiology	Research-based module	Molecular Biology	Skills and understanding of laboratory work principles
2019	Marta Hammerstad† Åsmund K. Røhr, Hans-Petter Hersleth (A Research-Inspired Biochemistry Laboratory Module - Combining Expression, Purification, Crystallization, Structure-Solving, and Characterization of a Flavodoxin-like Protein) Biochemistry and Molecular Biology Education	Research-based module	Biochemistry and Biological structure	Skills and knowledge
2019	Lawrence S. Blumer and Christopher W. Beck (Laboratory Courses with Guided-Inquiry Modules Improve Scientific Reasoning and Experimental Design Skills for the Least-Prepared Undergraduate Students) CBE—Life Sciences Education	Guided inquiry-based module	Insect Ecology	scientific reasoning and experimental design

One of the research-based modules that can be developed is bioinformatics module. Biology students need to be equipped with basic skills in computational and quantitative biology. Becoming familiar with bioinformatics will be a strength for students when they apply for a job because biologists are expected to be able to use information in the field of bioinformatics (Alaie, Teller, & Qiu, 2012). The application of research-based modules requires biology students to be ready to meet biological issues in the real world and to make connection between science and society (Hewitt, Kayes, Hubert, & Chouinard, 2014).

Table 2. List of articles on laboratory modules developed for Biology students by Indonesian researchers

Year	Author; (Title); Publisher	Types of laboratory module	Materials	Development Method
2014	Umi Fitriyati, Nandang Mufti, Umie Lestari (Pengembangan Modul Berbasis Riset Pada Matakuliah Bioteknologi /The Development of Research-based Module on Biotechnology Course) Jurnal Pendidikan Sains	Research-based	Biotechnology - Animal tissue culture techniques and antiproliferative test of ZnO particles against breast cancer cells	Thiagarajan (4D)
2016	Wasiatus Sa'diyah, Endang Suarsini, Ibrohim (Pengembangan Modul Bioteknologi Lingkungan Berbasis Penelitian Matakuliah Bioteknologi Untuk Mahasiswa S1 Universitas Negeri Malang / The Development of Research-based Module on Environmental Biotechnology for Biotechnology Undergraduate Students of Universitas Negeri Malang) Jurnal Pendidikan	Research-based	Environmental biotechnology in reducing heavy metal pollution	Borg and Gall
2016	Rizka Elan Fadilah, Mohamad Amin, Umie Lestari (Pengembangan Buku Ajar Evolusi Berbasis Penelitian Untuk Mahasiswa S1 Pendidikan Biologi Universitas Jember/ The Development of Evolution Research-based Module for Biology Education Undergraduate Students of Universitas Jember) Jurnal Pendidikan	Research-based	The use of molecular data analysis in evolution	Dick and Carey
2018	Nanda Hilda Khikmawati1, Mohamad Amin, Endang Suarsini (Buku Ajar Berbasis Penelitian In Silico pada Matakuliah Teknik Analisis Biologi Molekuler untuk Mahasiswa Strata 1 Biologi / In Silico Research-based Module of Molecular Biology Analysis Techniques Course for Biology Undergraduate Students) Jurnal Pendidikan	Research-based	Molecular Biology	ADDIE
2018	Nurul Hidayah Nasution , Fauziyah Harahap , Tumiur Gultom (The Development of Tissue Culture Textbook on Callus Induction of Mangosteen (Garcinia mangostana L.) Based on Research) Prosiding Atlantis Press	Research-based	Tissue Culture	Thiagarajan (4D)

1.3 Inquiry-based modules

Each student has different initial preparations prior to conducting activities in the laboratory. Therefore, the guided inquiry activities in the module aim to maximize the development of students' skills (Blumer & Beck, 2019).

1.4 Quantitative skills-based modules

There is a discrepancy between the expected skills that should be acquired by graduates and the real outcome. Therefore, it is important to develop skills-based modules. The types of skill required by Biology graduates are identified to develop a module for students. This skills-based module is expected to be able to teach students various skills needed in the real world to increase students' confidence (Robinson & McDonald, 2014).

Biology students generally have quantitative problem-solving skills. Thus, a module that facilitates the development of quantitative skills is needed (Hoffman, Leupen, Dowell, Kephart, & Leips, 2016; Robeva, Davies, Hodge, & Enyedi, 2010; Thompson et al., 2010).

1.5 Traditionally-based modules

Laboratory modules that are traditionally designed are generally like "cookbooks" and are often used as an

indicator of how well students can follow procedures with little regard for conceptual and procedural understanding of inquiry (Brownell, Kloser, Fukami, & Shavelson, 2012).

2. Module topics

The biology topics found in the review are Genetics, Ecology, Phylogenetics, Biochemistry, Molecular Biology, Evolution, Biotechnology, and Tissue Culture. The materials that require mathematical skills such as molecular biology, ecology, evolution, and phylogenetic use modules that are designed based on quantitative skills. On the other hand, the materials that require the use of informatics technology such as gen bank use bioinformatics module design to support laboratory activities (Alaie et al., 2012). Genetics topics in cross probabilities require an interactive animation learning so that web-based module is used (Thompson et al., 2010). Ecology consists of a variety of natural phenomena that can be used as learning materials so that it is used as one of the topics for problem-based modules (Hewitt et al., 2014) and inquiry-based modules (Blumer & Beck, 2019).

In general, research topics that produce good data can be used as learning materials in the relevant fields. Thus, it is possible to use research results as materials for creating modules. Based on the review, research-based materials for Biology students in Indonesia that have been identified by the researchers include: Biotechnology (Fitriyati, Mufti, & Lestari, 2015; Wasiatus, Suarsini, & Ibrohim, 2016), Molecular Biology (Fadilah, Amin, & Lestari, 2016; Khikmawati, Amin, & Suarsini, 2018), Tissue Culture (Nasution, Harahap, & Gultom, 2018), and the topics for research-based modules in the international journals include: ecology (Blumer & Beck, 2019; Brownell et al., 2012), biotechnology (Weber, 2017), molecular biology (Bhatt & Challa, 2018), dan biochemistry (Hammerstad, Røhr, & Hersleth, 2019).

3. Students competencies trained through modules

Student interest in laboratory activity is able to encourage active participation in order to achieve the competency goals that have been set during learning. Overall, the competencies expected to acquire by Biology students from the innovation of laboratory module design include: understanding and reinforcing concepts/ knowledge, scientific reasoning, quantitative skills, science process skills (formulating hypotheses, designing project, analyzing data, and communicating results in verbal and written form), thinking skills (literacy skills, critical and creative thinking skills), laboratory skills (performance, research skills, research concepts, students' perceptions of their learning experience).

Online or web-based modules that combine biological concepts with mathematical concepts have proven that students have an interest in the material being studied. The use of online-based modules is considered fun for students because they can check whether their understanding of a concept is wrong or right instead of just reading a physical textbook. In addition, the use of web-based modules is expected to improve students' abilities in calculating probabilities, using graphs, and mathematical concepts in biology (Thompson et al., 2010).

The bioinformatics module helps students store information they are learning so that they are able to apply the knowledge well later, even one week after using the module. The quantitative skills-based modules can improve skills in data interpretation, drawing conclusions, and numeracy (Hoffman et al., 2016).

The research-based laboratory module trains students to design experiments, including determining variables that can lead to designing a project to find a methodology that is widely used. Students' interest in research-based modules is caused by activities that provide direct experience in discovering new facts from their own research. Research-based module is a form of innovation in improving the quality of teaching materials because the available materials in the textbooks are not sufficiently contextual and applicative (Rohmani, Amin, & Lestari, 2017). Modules that are developed based on the results of research are able to create meaningful learning as the materials presented are contextual, deeper, and more interesting. Not only theories or concepts but also scientifically proven facts are presented (Wahyuni, Kiswardianta, & Yuhanna, 2018).

Similar to other innovative modules, the research problem-based laboratory modules are also able to increase the interest of biology students to actively take part in laboratory research activities. The content of the module can also challenge students' intelligence for a wider mindset (Hewitt et al., 2014).

4. Module development approach

Researchers in Indonesia generally develop modules using approaches that tend to be the same, such as 4D, ADDIE, Dick & Carey, and Borg & Gall. In contrast, based on the review on international research publications related to module development, the approach or development model used is not clearly stated. Each development approach has different characteristics in the stages. The differences of the development stages are presented in Table 3 (international researchers) and Table 4 (Indonesian researchers).

The module development model presented in Table 4 generally has the same goal, producing an empirically tested module. The core stages of the four models begin with identifying problems, continue with designing the required module, testing and repairing the module, and end with implementing the module. Development research requires various types of data, data sources, and data analysis methods that vary depending on the needs of researchers.

Table 3. Findings of research approaches used by international researchers in developing undergraduate biology laboratory modules

Types of biology laboratory module	Research methods used	Findings	Strengths	Researchers' recommendation
Online-based (quantitative approach)	Analyzing the need of mastering mathematical concepts in biology→ determining concept→ designing module → implementing module→ quantitative skills assessment from pretest-posttest and survey response of the module	55%: text and interactive online-based modules complement each other well, 39%: prefer module 6%: prefer textbook because web-based module is considered complicated	Interactive, more fun with a variety of colorful images, and not boring.	Increasing the level of interactivity, such as: interactive feedback when students make mistakes, student flexibility in operating random choices in the data base, and increasing the number of respondents with a broader, more heterogeneous scale.
Quantitative skills-based	Analyzing the need of understanding the integration of mathematical and biology concepts → Selecting various concepts that can be developed in module → designing module (still in the development stage)	Some integration of mathematical and biology concepts that can be developed in module: Mathematical model in gene regulation and lac operon Comparison between algebra-based and calculus-based models on lac operon Regulation in Biochemistry Role of mathematics in explaining how evolution happens Linear algebraic approach for metabolite Role of Geometry in reconstruction of phylogenetic tree Use of codon and genome DNA sequence analysis	Increasing interest in integrating modern mathematics and biology, increasing awareness of the importance of biomathematics in life, encouraging collaboration and development across disciplines	Module testing should be conducted if the draft module has been completed and research-based applications that can be used for mathematics and biology curriculum should be provided

Research-based	Analyzing the importance of novelty of the materials that need to be developed in the laboratory module→ determining pure research methods→ doing pure research and discovering findings→ designing module → implementing module → conduct survey response from students	Better than traditional module in improving students' skills, self-confidence, and understanding of concepts in biology	Students can do guided inquiry with open questions Students can analyze data and draw conclusions which are self-proven Students can undertake elements of scientific research independently Stimulating student interest in conducting biology research and encouraging participation in future research Developing critical thinking skills in biology research which can be recommended to other researchers Students can experience success and failure in doing laboratory research Students will experience success and challenges for collaborative research Students can communicate the results in a discipline manner using various media.	Research-based module development needs to be conducted periodically and continuously as an effort to update information.
Guided inquiry-based	Comparing students' readiness in using the available inquiry-based module	In general, there is no significant difference between the use of modules on students' scientific reasoning skills and experimental design skills although students' learning readiness is different	Providing modern biology research experience at undergraduate level with inquiry-based module, preparing students effectively to do future work independently	Conducting further research to see the significance of intervention on different students' readiness separately
Traditionally-based	The study was conducted to compare the control class which was given a traditional module with the experiment class which used a research-based module. Mixed methods were used: student survey, classroom observation, and interview	The modules contain complete materials and procedures that must be followed so that students do not seem to develop confidence in doing laboratory work.	The traditionally-based module is used for particular objectives such as: Knowing how well students follow research instructions Presenting a general overview of theory or specific model Introducing research methodology to conduct research structurally and properly. Training students to write scientifically using general framework	Other types of modules can be used, such as research-based module which can better increase student interest, scientific attitude, confidence in conducting laboratory research

On the other hand, the international researchers generally develop modules by analyzing the need of module which tends to focus on the novelty of concepts that is necessary to be developed. The next stages are designing modules, implementing modules, and conducting a periodic and extensive survey from students as the module users.

The most common module design found in the review is research-based module. Review of some literature shows that research-based modules have improved the quality of research activities and the competence of Biology students in Indonesia. The strengths of research-based modules are (1) providing accurate, up-to-date and sustainable information and data, (2) providing and creating independent student learning conditions (Sanjaya, Kiswardianta, & Pujiati, 2017), (3) module content is better because it is made based on research and able to provide students more opportunity to increase participation (Kartikasari, Sulistyarsi, & Pujiati, 2017), (4) learning more through direct experience, (5) obtaining skills, (6) students can independently assess the results of the work that has been done, and (7) increasing students' independence and confidence in learning (Fitriyati et al., 2015).

Table 3 shows that different types of laboratory module designs that have been developed have their own strengths depending on the concept presented. For example, the concept in the field of bioinformatics has the following learning objectives: (1) train students to have biological computing and bioinformatics skills (2) motivate students to develop an interest in answering biology questions using bioinformatics approach, and (3) enable students to appreciate the use of bioinformatics in the field of modern biology (Madlung, 2018). The use of bioinformatics content in the module can assist researchers in analyzing data to solve research problems (Barone, Williams, & Micklos, 2017; Madlung, 2018). Another example is inquiry-based modules that show effectiveness in improving scientific reasoning skills and experimental design skills of students who have low initial ability (Blumer & Beck, 2019).

Table 4. Review of the literature regarding different approaches used for module development by Indonesian researchers

Characteristics	4D	ADDIE	Borg & Gall	Dick & Carey
Number of stages	4	5	9	10
Stages	*Define*	*Analyze*	*Research and information collecting*	*Identify Instructional Goal*
	Design	*Design*	*Planning*	*Conduct Instructional Analysis*
	Develop	*Development*	*Develop preminary form of product*	*Analyze Learners and Contexts*
	Disseminate	*Implementation*	*Preliminary field testing*	*Write Performance Objectives*
		Evaluate	*Main product revision*	*Develop Assessment Instruments*
			Main field testing	*Develop Instructional Strategy*
			Operational product revision	*Develop and Select Instructional Materials*
			Operational Field Testing	*Design and Conduct formative evaluation of instruction*
			Final Product Revision	*Reverse Instruction*
				Design and conduct summative evaluation
Sources	(Thiagarajan, Sivasailam, Semmel, Semmel, & Melvyn I., 1974)	(Branch, 2009)	(Gall, Gall, & Borg, 2003)	(Dick, Carey, & Carey, 2015)

The use of the right type of module will also be able to improve students' Science Process Skills (SPS). This will benefit students in solving problems, both in the

laboratory and in everyday life. The effort to improve students' SPS can be started by improving the quality of SPS through the development of teaching materials, such as modules that will later be presented by teachers to facilitate students in doing experiment or exploration activities (Sukarno, Permanasari, & Hamidah, 2013).

The review results show that it is important to study and develop the design of laboratory modules used for experiment activities and that the traditional modules or existing modules need improvement. Therefore, the results of this study can be used as a reference about Biology student laboratory module designs that have been developed by researchers to provide insights for other researchers.

Conclusion

There are five types of laboratory module designs that were identified by the researchers. Overall, various innovations in module development for biology students that have been carried out show a better impact on biology students' laboratory skills. The research results on the implementation of modules for biology students can be used as a reference for other researchers to improve other innovative modules. Students' interest in the development of laboratory modules with varied materials shows that the development of laboratory modules for students needs to be continually reviewed to obtain new ideas in developing modules for other materials that are not yet available and complementing the modules with assessment instrument to measure laboratory skills.

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