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A Story-Based Virtual Laboratory Practicum in an Undergraduate Genetics Course to Improve Concept Understanding and Visual Literacy

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Abstract. Genetic concepts, particularly DNA technology, often lead to misconceptions among students. Integrating a virtual laboratory (VL) into coursework presents an innovative approach to enhancing concept understanding and visual literacy through interactive, story-based simulations that bridge theory and practice. This study aimed to analyze the students' concept understanding and visual literacy improvement by applying a VL to teach DNA Test Simulation (Paternity Test) using a contextual narrative method. The research was conducted in the Science Education undergraduate program with a purposive total sampling of students enrolled in Genetics (First Semester 2024/2025), utilizing an open-source web-based VL platform. Pretest and posttest assessments measured students' concept understanding and visual literacy before and after VL integration. The findings reveal a significant improvement, with concept understanding rising from an average pretest score of 42.6 to posttest 69.9 (N-Gain 0.46) and visual literacy increasing from 53.8 to 71.8 (N-Gain 0.37). Furthermore, 97% of students were satisfied with the VL-based learning method. This research contributes to knowledge and science development by demonstrating that VL can improve concept learning and visual literacy in genetics education. It offers an accessible and scalable solution for teaching complex DNA technology concepts, reducing reliance on costly wet laboratory experiments while maintaining scientific rigor. Beyond academia, the study supports broader educational equity, making advanced molecular biology concepts more available to diverse learners and fostering scientific literacy in society.

Keywords: concept understanding; story-based practicum; undergraduate student; virtual laboratory; visual literacy

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INTRODUCTION

Laboratory experiments play a vital role in science learning, allowing students to enhance their knowledge, develop critical thinking skills, and connect theory with practice (Hofstein, 2017). Laboratory activities also play an essential role in improving concept memorization in the Genetics course (Mas' ud et al., 2022). In Genetics, these activities improve concept retention and cover essential topics like DNA, gene expression, and molecular techniques, which are increasingly relevant due to biotechnology advancements. However, the abstract nature of genetic concepts often leads to misconceptions caused by passive learning and difficulties in understanding specific terminology (Rusmana et al., 2021). To address these challenges, lecturers can guide students through systematic teaching, utilizing optimized resources and instruments (Agyei, 2022). In addition, some students struggle with visuospatial ability, making abstract genetic concepts difficult to grasp, even with classroom explanations and hands-on laboratory practice. To enhance understanding, lecturers use various visualization tools, such as diagrams, animations, and virtual laboratories (VL), which are particularly helpful in illustrating molecular and cellular biosciences

(Verma et al., 2025). Since genetic materials like DNA and chromosomes are invisible to the naked eye, traditional lectures alone may not be sufficient. Regarding this issue, implementing the VL practicum is promising to facilitate students' imagination of the concepts. It is also essential for lecturers to teach students the visualization skills to interpret VL, to ensure they can have visual literacy skills (Fibriana et al., 2017).

Moreover, the complexity of genetics education requires research, laboratory methods, and instructional strategies to help students build proficiency. However, high-tech equipment and chemicals essential for experiments like DNA isolation, DNA purification, polymerase chain reaction (PCR), DNA cutting and ligating, and gel electrophoresis are often unavailable due to limited facilities, leaving students reliant on theory-based learning (Hofstein, 2017). In this case, VL offers an alternative by simulating genetic experiments at the molecular level (Mas' ud et al., 2022), providing an interactive experience that enhances understanding despite not fully replacing real laboratory work (Abramov et al., 2017). In fact, VL environments have been utilized at many levels of education, scientific workplaces, and job training (Zhang et al., 2024). Moreover, VL gives more advantages, including flexibility, safety, and economic availability, since practicum does not need laboratory equipment and materials, and it does not handle hazardous materials. Also, the post-pandemic new normal era introduced us to online teaching and virtual experiences such as VL (Vergara et al., 2022).

Some classroom research related to science or biology majors has been incorporating VL in the genetics course or other topics. Mas'ud et al. (2022) reported that while VL and traditional laboratories contribute positively to learning, students prefer hands-on experiences in real laboratories. Similarly, Zhou (2020) found that online genetics courses incorporating simulation activities can facilitate learning, and the study suggests a hybrid approach could enhance teaching outcomes, where VL supplements real laboratories. However, these studies focus primarily on student preferences and general VL effectiveness rather than their role in improving specific cognitive and visual literacy skills in genetics education. In addition to learning effectiveness, VL has been examined regarding student motivation and preparedness. Scherp & Meier (2016) found that students perceived VL positively and considered it beneficial for laboratory readiness. However, Dyrberg et al. (2017) noted that while VL increases confidence in operating laboratory equipment, it does not necessarily enhance motivation compared to real laboratories. These studies highlight VL's role in familiarizing students with laboratory techniques. VL is also acknowledged as a valuable complement to theoretical education, as reported by Oser & Fraser (2015). Their studies indicate that VL protocols can support theoretical learning and serve as supplementary methods. Additionally, Savitri et al. 2023) provided evidence that virtual experiments in DNA isolation and hybridoma techniques improve students' critical thinking, reinforcing VL's educational benefits. There is still a need to explore how VL can specifically enhance concept understanding and visual literacy in genetics-related molecular techniques. Also, how VL enhances understanding of molecular-level techniques such as DNA isolation, PCR, DNA cutting, and gel electrophoresis, which are fundamental to genetics education, must be investigated.

Therefore, this study applied VL in genetics coursework with a topic-specific focus on paternity testing using molecular techniques. By integrating an open-source web-based VL platform, it demonstrates how VL enhances concept and visual learning while promoting educational equity. While VL is comparable to traditional learning methods, research on its role in improving concept understanding and visual literacy remains limited. Based on this background, the following research questions were proposed as the focus of this study: 1. Could implementing a virtual laboratory (VL) in molecular biology practicum as part of the Genetics concept improve students' concept understanding and visual literacy? 2. What is students' satisfaction with learning methods that probably impacted the concept understanding and visual literacy?

The research questions were answered by designing an implementation of a story-based virtual laboratory to teach Genetics subject in the topic of Practicum: DNA Test Simulation (Paternity Test) related to molecular biology concepts. This study offers significant contributions to genetics education by enhancing students' concept understanding and visual literacy by integrating virtual laboratory (VL). By bridging traditional instruction with digital tools, this study provides a forward-looking approach to genetics education, advancing pedagogical strategies and scientific accessibility.

METHODS

Participants

The study was conducted in the Science Education Undergraduate Study Program at the Faculty of Mathematics and Natural Sciences, Universitas Negeri Semarang, Indonesia. The data were collected from undergraduate students enrolled in the Genetics course (Course code: 20P00171). A total sampling method of 130 students in 4 classes from the third-year level was used. The course was designed to help students comprehend the Genetics concept related to DNA isolation, polymerase chain reaction (PCR) technique, DNA cutting, and gel electrophoresis.

Course Design

The Genetics course (3 credits) included 16 meetings in 1 semester, with the story-based experiment using the virtual laboratory conducted in the 15th meeting. Each credit equals 50 min of classroom learning, 60 min of structured assignment, and 60 min of emancipated learning. Throughout the course, visual literacy and concept understanding were not limited to the 15th meeting. Still, they were progressively instilled from the first session through foundational discussions, interactive visuals, and structured exercises, ensuring a comprehensive learning experience. The course design is presented in Table 1, whereas the course steps during the 15th meeting are shown in Table 2.

Table 1. Genetics course design for one semester

Meeting	Topic	Meeting	Topic
1	Course contract, Introduction to Genetics	9	Chromosome, Gene, Genome, and DNA
2	Mendelian Genetics	10	Gene Expression
3	Beyond Mendelian Genetics	11	Gene Mutation
4	Gene Interactions (Epistasis)	12	Sex Determination
5	Gene Linkage and Crossing Over	13	Population Genetics
6	Practicum: Variation in Animals, Plants, and Humans	14	Practicum: Sex-Linked and Sex-Influenced Genes
7	Practicum: Multiple Alleles	15	Practicum: DNA Test Simulation (Paternity Test)
8	Midterm Examination	16	Final Examination

Table 2. Genetics course steps during the 15th meeting for a learning period of 150 minutes

Steps	Objectives	Description	Time (min)
1	To measure the students' initial ability of concept understanding and visual literacy (pretest)	Opening Story-based experiments using the principles of DNA isolation and purification, polymerase chain reaction (PCR) technique, DNA cutting, and gel electrophoresis capture images and concepts	20
2	To provide students with the materials related to principles of isolation and purification of DNA, the polymerase chain reaction (PCR) technique, DNA cutting, and gel electrophoresis	DNA isolation and purification, polymerase chain reaction (PCR) technique, DNA cutting, and gel electrophoresis Story explanation, a disclaimer about the criminal case	40
3	To provide students with virtual hands-on experiments using the accessible sources of a virtual laboratory	Story-based experiment using the principles of DNA isolation and purification, polymerase chain reaction (PCR) technique, DNA cutting, and gel electrophoresis, virtual laboratory	40
4	To construct the concept and master the visual literacy, students discuss their work results with their classmates in a group	DNA isolation and purification, polymerase chain reaction (PCR) technique, DNA cutting, gel electrophoresis, and their application in the case study	30
5	To assess their concept mastery and visual literacy (posttest)	Story-based experiments using the principles of DNA isolation and purification, polymerase chain reaction (PCR) technique, DNA cutting, gel electrophoresis, and concepts Closing	20

Research Design

A quasi-experiment with a one-group pretest-posttest design (Figure 1) was employed. All students learned Genetics concepts incorporated with a virtual laboratory (VL) in the 15th meeting (practicum of paternity test simulation). Before the experiment, the students were given a pretest and then continued with treatment. Next, a posttest was conducted, and the results were compared with the pretest results. The difference between the pretest and posttest scores was obtained and analyzed.

O_1	X	O_2

Figure 1. One-group pretest-posttest design

This study compared the dependent variable between before and after treatment. The dependent variable in this research is the results of concept understanding and visual literacy of students in molecular biology in the Genetics course. In contrast, the independent variable in this research is the application of a virtual laboratory.

Story-based Practicum Using Virtual Laboratory

Students worked in small groups (4-5 members) using a practicum worksheet and an open-source web-based virtual laboratory (VL) developed by the University of Utah (https://learn.genetics.utah.edu/content/labs/). They first reviewed the theoretical framework before exploring problems inspired by a modified real-world case involving DNA testing with modification (https://shorturl.at/s8rUZ). Given the sensitive nature of the story, students were informed in advance and given the option to leave if they felt uncomfortable. After ensuring consent, the lecturer guided the students through the case and practicum using the virtual laboratory. The story written in the worksheet is as follows:

A mother who married a husband has given birth to a daughter. However, the mother doubts who her child's biological father is. The mother was a victim of sexual harassment, and after the incident, she became pregnant. The perpetrator had been arrested and tried. The mother wants to prove who the biological father of the child is. The daughter has the right to know who her biological father is because it is related to the need to determine the legitimate heir. How do you test the child's DNA to determine her biological father? The DNA that will be used as the sample is the DNA of the mother (Mother), child (Child), husband (Suspected Father A), and perpetrator (Suspected Father B). Simulate the steps in a virtual laboratory with your lecturer and analyze the result!

Problem Statement:

How do you test for DNA in the case of paternity?

How do you simulate the steps/methods for testing DNA paternity (paternity test) with a virtual lab?

Research Instrument and Validation

Data on students' initial ability to understand concepts and visual literacy were measured by pretest, while learning results were measured using a posttest. The general observation was performed during the learning process. The assessment of concept understanding and visual literacy in this study was conducted using 25 pretest and posttest questions designed to measure students' cognitive and interpretative abilities systematically. The concept understanding indicators were structured around three key dimensions, whereas the 15 VL-specific questions were incorporated to evaluate the visual literacy indicators. All questions were designed to be concise, following the concept of understanding indicators, i.e., recognizing new information, constructing explanations, and connecting scientific phenomena (Widiyatmoko & Shimizu, 2018). In contrast, the VL questions measured concept knowledge (C), reasoning skills (R), and mode of representation (M) (Fibriana et al., 2017). The pretest and posttest were used to measure students' initial and final abilities in concept understanding and visual literacy. The improvements in concept knowledge and visual literacy were quantified through statistical comparison of pretest and posttest scores, demonstrating the effectiveness of VL in enhancing comprehension and analytical skills. The research instruments used in this study are presented in Table 3.

Table 3. The research instrument of this study

Indicator	Instrument	Validation and analysis	Analysis
Concept understanding	Pretest and posttest questions	Validity and reliability of statistical testing	Quantitative
		Expert validation	Quantitative and feedback analysis
Visual literacy	Pretest and posttest questions	Validity and reliability of statistical testing	Quantitative
		Expert validation	Quantitative and feedback analysis
Students' satisfaction	Questionnaire	Expert validation	Quantitative and feedback analysis

Data Analysis

Data obtained consisted of cognitive scores related to the study results from the pretest and posttest, which were analyzed using descriptive and analytic statistics. The data normality was measured by the Kolmogorov-Smirnov test, and the Levene test measured the homogeneity. The average test scores were calculated using a statistical mean formula. Further, a paired t-test and an ANOVA F-test were conducted to determine the hypothesis on the effect of the virtual laboratory (VL) on concept understanding and visual literacy. N-Gain analysis was also performed. After learning, a satisfaction analysis was conducted to measure their satisfaction with the learning experience. There were 9 questions, and each item was rated according to three grades: satisfactory, general, and unsatisfactory.

RESULTS AND DISCUSSION

This study used a One-Shot Case Study type of research, with the research subjects being students participating in the genetics course in the First Semester of the academic year 2023/2024. This study used a virtual laboratory (VL) to measure the increase in students' concept understanding related to DNA isolation, PCR techniques, DNA cutting techniques, gel electrophoresis techniques, and result analysis, as well as to measure visual literacy skills. The indicators measured in this study are shown in Table 4. In addition, this study also uses a response questionnaire to determine students' responses regarding the use of VL in Genetics. The Genetics course in the 15th meeting was designed as a story-based experiment using a virtual laboratory (VL), which played an essential role in reinforcing students' concept understanding and visual literacy in this research. The lecturer set this session carefully and structured it into five key phases, guiding students through a virtual simulation of molecular techniques such as DNA isolation, purification, PCR, DNA cutting, and gel electrophoresis within a contextualized case study from a story. Lecturers with pedagogical competence always find a way to manage learning with varied approaches, models, and methods (Parmin et al., 2024).

The opening phase was conducted to assess students' initial concept understanding and visual literacy through a pretest. As students engaged with molecular biology principles within the context of a criminal case narrative given by the lecturer, some students struggled to recall foundational knowledge, particularly related to DNA structure, isolation and purification steps, and PCR mechanisms. Moreover, the observable phenomena in this step included students revisiting course materials, engaging in discussions to reconstruct previously learned concepts, and identifying gaps in their prior understanding. The lecturer engaged well in this step to help students brainstorm and understand the story. The interaction between the lecturer and students is an important factor in learning (Alforque et al., 2024).

Next, during the materials introduction phase, students were introduced to the theoretical framework of DNA isolation and purification, PCR techniques, DNA cutting, and gel electrophoresis. Students were guided that each biological sample requires an appropriate method to obtain high-quality DNA (Fathurahman et al., 2025), and in this case, the sample is from humans. Including a real-world narrative contextualized within forensic science helped students connect abstract molecular processes with practical applications. Some students exhibited cognitive conflict, questioning how DNA analysis could definitively determine relationships or solve forensic cases, leading to active discussions and knowledge validation.

Table 4. Concept understanding and visual literacy indicators measured in this study

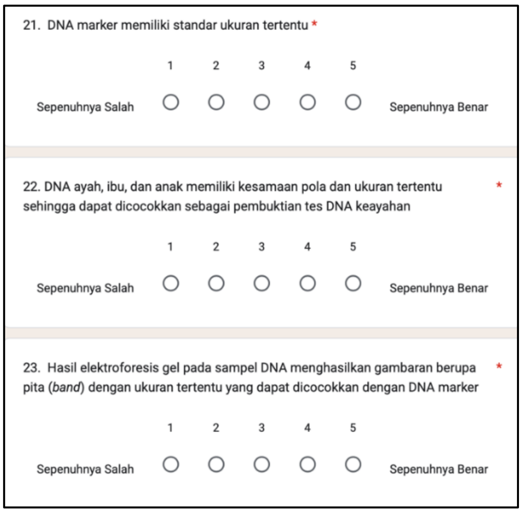
Aspects	Indicators	Descriptions
Concept understanding	Recognizing new information	Students were evaluated on their ability to identify and comprehend novel concepts in genetics and molecular biology, particularly related to DNA isolation, PCR, DNA cutting, and gel electrophoresis.
	Constructing explanations	The test assessed how well students could develop coherent explanations for genetic phenomena, demonstrating their ability to articulate scientific principles based on VL experiences.
	Connecting scientific phenomena	This indicator measured students' ability to relate molecular processes to broader biological concepts, ensuring they could apply their knowledge contextually.
Visual Literacy	Concept knowledge (C)	Direct comprehension of genetics concepts presented in the virtual laboratory.
	Reasoning skills (R)	The ability to logically interpret data, form hypotheses, and analyze molecular techniques.
	Mode of representation (M)	Students' capacity to decode and interpret visual information, such as genomic diagrams, electrophoresis results, and DNA sequence patterns.

The VL hands-on experiment was conducted, where students interacted with their computer to simulate the molecular techniques in an interactive simulation. This phase revealed differences in students' ability to interpret genomic representations, particularly in reading electrophoresis gel results. Some students struggled with fragment size interpretation and migration patterns, leading to deeper inquiry, peer discussions, and iterative visual analysis. They finally understood that the results of interpolating molecular band sizes in base pair units (bp) are essential data in molecular analysis (Wangiyana et al., 2024). Others exhibited enhanced confidence in executing digital simulations, demonstrating improved scientific reasoning. After the hands-on experiment, the discussion phase encouraged students to reflect on their findings. In collaborative groups, students actively constructed their understanding, critically evaluated data, and applied their knowledge to the case study scenario. Based on the observation, the students could relate their understanding to a hot recent topic in Indonesian infotainment, a paternity scandal in one of the Indonesian celebrities. This learning is instilled well in their cognitive ability, giving meaningful learning (Bryce & Blown, 2024). Observable challenges included difficulties linking theoretical explanations with experimental outcomes in some students, reinforcing the need for guidance in reasoning-based learning.

Finally, after VL engagement, the posttest phase measured students' concept mastery and visual literacy. Based on the observation and results of the posttest, many students demonstrated improved comprehension, confidently articulating molecular processes, including DNA extraction, PCR process, DNA cutting using restriction enzymes, DNA ligating using ligase, gel electrophoresis process, and analyzing the DNA band results. Using a VL to simulate DNA paternity tests has significantly improved students' understanding of genetics concepts and visual literacy skills. Notably, students with weaker initial understanding showed significant improvements, validating the effectiveness of VL integration in concept reinforcement.

The data obtained were visual literacy data, concept understanding, and student response questionnaires, which were then analyzed quantitatively. The example of pretest and posttest questions used in this research is shown in Figure 2. After obtaining the pretest and posttest research data, the Kolmogorov-Smirnov test was used to test the normality of data in terms of both concept understanding and visual literacy skills. The pretest and posttest data of concept understanding, i.e., pretest data 0.094 and posttest data 0.087, are normally distributed with a maximum D test < Critical value. Meanwhile, the visual literacy skill normality test results show the pretest and posttest data at 0.124 and 0.087, respectively. The pretest data were not normally distributed because D_{max} > Critical value, whereas the posttest data were normally distributed because D_{max} < Critical value.

The result of the t-test analysis on the pretest and posttest data used a group average score. It was determined by comparing t_{count} of 18.576 with t_{table} of 1.978, where $t_{count} > t_{table}$ 1.978, showing that H_0 is rejected and H_1 is accepted. It can be interpreted as a significant difference between concept understanding before and after learning with VL. Therefore, VL has a significant influence on concept understanding. The ANOVA F-test analysis on the pretest and posttest data obtained each F_{count} of 129.749 and F_{table} 3.878. This F-test compares the variance of each group where $F_{count} > F_{table}$ 3.878 (H_0 is rejected, H_1 is accepted). Based on this result, there is a significant difference between concept understanding before and after learning. The t-test analysis on the pretest and posttest data obtained t_{count} 13.265 > t_{table} 1.978 (H_0 rejected, H_1 accepted). It can be interpreted as a significant difference between visual literacy skills before and after learning. Based on statistical test results, the virtual laboratory significantly influenced students' visual literacy skills. The F-test analysis on the pretest and posttest data obtained F_{count} 114.952 > F_{table} 3.878 (H_0 rejected, H_1 accepted). Therefore, it is statistically concluded that a significant difference was found between before and after learning with VL. Moreover, the N-Gain analysis was also performed to measure the improved concept understanding and visual literacy level, where 0.46 and 0.37 (moderate) were achieved, respectively.


21. DNA marker memiliki standar ukuran tertentu *

1 2 3 4 5

Sepenuhnya Salah ○ ○ ○ ○ ○ Sepenuhnya Benar

22. DNA ayah, ibu, dan anak memiliki kesamaan pola dan ukuran tertentu sehingga dapat dicocokkan sebagai pembuktian tes DNA keayahan *

1 2 3 4 5

Sepenuhnya Salah ○ ○ ○ ○ ○ Sepenuhnya Benar

23. Hasil elektroforesis gel pada sampel DNA menghasilkan gambaran berupa pita (*band*) dengan ukuran tertentu yang dapat dicocokkan dengan DNA marker *

1 2 3 4 5

Sepenuhnya Salah ○ ○ ○ ○ ○ Sepenuhnya Benar

(A)

(B)

English translation:

21. DNA markers have specific size standards

Completely False (1) (2) (3) (4) (5) Completely True

22. DNA of the father, mother, and child has specific similar patterns and sizes, so that it can be matched as proof of a DNA paternity test

Completely False (1) (2) (3) (4) (5) Completely True

23. The results of gel electrophoresis on DNA samples produce an image in the form of a band with a specific size that can be matched with DNA markers

Completely False (1) (2) (3) (4) (5) Completely True

English translation

1. The following is a picture of the preparation of human cheek epithelial cells as a source of DNA. The correct statement related to the picture is…

- Cell collection technique by cutting, epithelial cells contain many cell nuclei, and epithelial cells are efficiently lysed because their membranes are thin

- Cell collection technique by cotton swab smear, epithelial cells are easy to obtain, and epithelial cells are efficiently lysed because their membranes are thin

- Cell collection technique by cotton swab smear, epithelial cells contain many cell nuclei, epithelial cells are efficiently lysed because their membranes are thin

Figure 2. Example questions to measure concept understanding and visual literacy

Table 5. Questionnaire items for students' perception related to concept understanding, reasoning skills, and mode of representation (C-R-M) indicators

Questionnaire item no	Description	Indicators
1	VL significantly improves concept understanding	C
2	VL helps to explain scientific phenomena	C
3	VL significantly improves concept memorization	C
4	VL helps to analyze detailed techniques and laboratory experiment protocols	R
5	VL is preferred over reading textbooks to help with analysis	R
6	VL helps with critical thinking, such as evaluation and synthesis skills	R
7	VL helps to get the related information quickly	M
8	VL represents the real fundamental techniques and protocols	M
9	VL represents abstract concepts in genetics and molecular biology	M

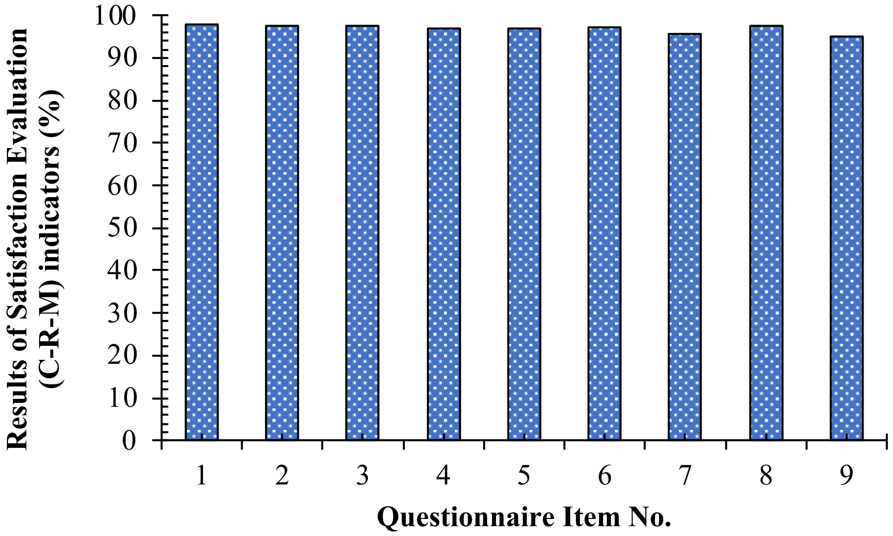


Figure 3. Students' satisfaction with the learning process using story-based practicum and virtual laboratory

The students' satisfaction with the VL application in learning the concept was measured after the learning process. They filled out the response questionnaire after completing the posttest. The student response questionnaire consists of 9 statements related to the learning process that had been carried out. The statements included concept understanding, reasoning skills, and mode of representation (C-R-M), as shown in Table 5. The satisfaction evaluation of each item was rated according to three grades: satisfactory, general, and unsatisfactory.

The analysis of this questionnaire obtained an average of 97% (satisfactory). The following are the details of the response questionnaire in Figure 3. The results from comparing pretest and posttest scores and N-Gain indicated a substantial enhancement in students' comprehension and skills after the learning experience. The significant improvement in posttest scores suggests that VL effectively facilitated a deeper understanding of genetic concepts from the elaboration of meetings 1 to 15. Additionally, students expressed high satisfaction (97%) with the story-based method, highlighting its engaging and immersive learning impact. This structured session provided critical insights into the effectiveness of VL in genetics education, demonstrating its ability to reduce misconceptions, enhance visualization skills, and bridge theoretical learning with applied molecular techniques. By engaging with interactive simulations in VL, students could visualize and understand genetic data, which likely contributed to their enhanced comprehension. Incorporating real-world scenarios and digital simulations created an interactive, inquiry-driven environment, fostering scientific literacy, analytical reasoning, and deeper engagement (Sholeha et al., 2024). This aligns with previous research indicating that VL can bridge the gap between theoretical knowledge and practical application (Mas' ud et al., 2022).

Most students involved said that the concept of genetics related to the molecular biology concept tends to be challenging to study. Research reported that the factors affecting low scientific literacy included textual teaching material, students' misconceptions, non-contextual learning, and low ability in reading comprehension (Hartono et al., 2023). Moreover, it needs high imagination ability, critical thinking, analysis, and synthesis skills to understand the sub-materials of DNA isolation, PCR techniques, DNA cutting techniques, gel electrophoresis techniques, and result analysis. VL provided the visualization and explanation related to the materials. The story-based practicum helped them to arrange and experience the laboratory protocols. Understanding key concepts in genetics and molecular biology, such as DNA isolation, DNA cutting and ligating, PCR techniques, and gel electrophoresis, can be effectively achieved through VL. VL can simulate extracting DNA from cells, allowing students to understand the steps involved without needing physical samples. VL can also demonstrate DNA cutting and ligation, showing how enzymes interact with DNA and how the fragments are joined. Moreover, VL can guide students through setting up a PCR reaction, understanding the role of primer nucleotides, how to operate the thermal cycler, and what happens inside the machine (Carroll et al., 2025; May et al., 2023). VL helps students simulate preparing and running an agarose gel electrophoresis, applying the electric field, and analyzing the results. Thus, VL provides several advantages, including cost-effectiveness, safety, accessibility, engagement, and helping the students grasp the principles and concepts to achieve learning outcomes (Alvarez, 2021).

On the other hand, the concept of visual literacy was introduced by Debes in 1969 and has since evolved through extensive research. In this research, VL allowed students to use complex visual data, such as DNA sequences and paternity test results. The pictures and animations provided in VL were used as a cooperative learning strategy to teach DNA isolation, DNA cutting and ligating, PCR techniques, and agarose gel electrophoresis with DNA band interpretation steps. Visual literacy, the ability to interpret and make meaning from information presented as an image, is crucial in Genetics. The improvement in visual literacy observed in this study is consistent with findings from other studies that highlight the benefits of visual aids in science education. While the absence of a control class limits the ability to attribute improvements solely to the VL intervention, the significant gains observed in this study are promising. Additionally, all students agreed they were satisfied with the story-based practicum using VL to learn the materials. This qualitative data, including student satisfaction feedback, could provide further insights into the specific aspects of the VL that were most beneficial. Visual literacy encompasses vision-related skills humans develop through seeing and integrating other sensory experiences. These skills are crucial for normal learning processes, enabling individuals to distinguish and interpret various visual elements in their natural or artificial environment. Individuals, such as scientists, can communicate effectively by creatively applying these skills and conveying knowledge through images. Visualization is related to scientific thinking, as scientists rely on various visual tools to make discoveries and communicate findings (Listiawati et al., 2022; Putri et al., 2021). Different types of visual representations in science serve distinct purposes. For instance, realistic diagrams highlight key features of objects, while schematic diagrams illustrate relationships and processes. Other scientific visualizations, such as photographs and simulations, help imagine unseen phenomena like molecular structures (Strazdina, 2021). Researchers emphasize that visual literacy development is a lifelong process involving increasingly sophisticated ways to create and analyze images. Students should observe textbook images and be guided to visualize concepts to foster visual literacy. Visual literacy skills can be taught similarly to textual literacy, enabling individuals to recognize, interpret, and use different visual forms effectively (Matusiak et al., 2019; May et al., 2023; Özsoy & Saribas, 2021).

CONCLUSION

In conclusion, using a virtual laboratory (VL) to simulate DNA paternity tests has significantly improved students' understanding of genetics and visual literacy skills. The pretest-posttest design revealed significant improvement, with average scores increasing from 42.6 to 69.9 (N-Gain 0.46) for concept understanding and 53.8 to 71.8 (N-Gain 0.37) for visual literacy, and 97% of students were satisfied with the VL-based learning method. The interactive nature of the VL allowed students to visualize genetic data, bridging the gap between theoretical knowledge and practical application and highlighting its effectiveness in enhancing learning outcomes. The findings suggest that a VL is a valuable tool in genetics education. Future research should include control groups and gather qualitative data to validate these results further and identify the most beneficial aspects. Educators are encouraged to integrate VL into their curriculum to provide a more comprehensive and engaging learning experience.

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CONFLICT OF INTEREST

All authors have no conflicts of interest to disclose.

ETHICAL CLEARANCE

All participants in this research had signed the consent to participate form before conducting the research. The ethics committee of FMIPA UNNES approved all methods used.

AUTHOR CONTRIBUTION

FF – Data curation, data analysis, research design, writing; ZA – supervising, funding acquisition, reviewing; MAN – data curation; HF – co-teaching, data curation; FA – administration, data analysis; KSN, NSN – research assistant, observer; AU – supervising, reviewing.

USE OF ARTIFICIAL INTELLIGENCE (AI)-ASSISTED TECHNOLOGY

The authors declare that no artificial intelligence (AI) tools were used in the generation, analysis, or writing of this manuscript.

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