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ORIGINAL

How Does Pre-Lab Virtual Laboratory Affect Students' Self-Efficacy and Understanding Mendel's Law?

¿Cómo afecta el laboratorio virtual previo al laboratorio a la autoeficacia y la comprensión de la ley de Mendel por parte de los estudiantes?

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ABSTRACT

Introduction: genetics learning presents challenges, requiring a strong understanding of theoretical concepts and practical skills. Mendel's Laws are key concepts that are difficult to grasp without practical experience.
Objective: this study investigated how virtual laboratories influence students' learning readiness, self-efficacy, and conceptual understanding of Mendel's Laws using *D. melanogaster* as a model.
Method: the study used a quantitative, quasi-experimental design with pre-test and post-test control groups. One hundred twenty-two undergraduate biology education students participated. The study employed three instruments: a pre-lab readiness test, a self-efficacy questionnaire, and a Mendelian concept comprehension test. The experimental group (n = 57) received Project-Based Learning (PBL) combined with virtual lab simulations, while the control group (n = 65) received conventional PBL.
Results: analysis revealed that the experimental group scored significantly higher than the control group on all measures (p < 0,05). The virtual laboratory improved students' conceptual and procedural readiness, boosted their confidence in experiments, and reinforced their understanding of Mendel's segregation and independent assortment principles.
Conclusions: the virtual laboratory enhanced genetics learning, especially in preparing students for accurate experimental tasks. The results suggest that virtual simulations are valuable in genetics education, offering practical insights for educators to adopt in laboratory courses.

Keywords: Genetics Education; Virtual Laboratory; Mendel's Law; Self-Efficacy; Pre-Lab Preparation; *D.* Melanogaster; Project-Based Learning (PBL).

RESUMEN

Introducción: el aprendizaje de la genética presenta desafíos, requiriendo una comprensión sólida de los conceptos teóricos y las habilidades prácticas. Las Leyes de Mendel son conceptos clave que son difíciles de entender sin experiencia práctica.
Objetivo: este estudio investigó cómo los laboratorios virtuales influyen en la preparación para el aprendizaje de los estudiantes, su autoeficacia y su comprensión conceptual de las Leyes de Mendel utilizando D. melanogaster como modelo.
Método: el estudio utilizó un diseño cuantitativo cuasi-experimental con grupos de control pre-prueba y post-prueba. Ciento veintidós estudiantes de educación en biología participaron en el estudio. Se emplearon

tres instrumentos: una prueba de preparación pre-laboratorio, un cuestionario de autoeficacia y una prueba de comprensión de los conceptos mendelianos. El grupo experimental (n = 57) recibió Aprendizaje Basado en Proyectos (PBL) combinado con simulaciones de laboratorio virtual, mientras que el grupo de control (n = 65) recibió PBL convencional.
Resultados: el análisis reveló que el grupo experimental obtuvo puntuaciones significativamente más altas que el grupo de control en todas las medidas (p < 0,05). El laboratorio virtual mejoró la preparación conceptual y procedural de los estudiantes, aumentó su confianza en los experimentos y reforzó su comprensión de los principios de segregación y distribución independiente de Mendel.
Conclusiones: el laboratorio virtual mejoró el aprendizaje de la genética, especialmente en la preparación de los estudiantes para tareas experimentales precisas. Los resultados sugieren que las simulaciones virtuales son valiosas en la educación genética, ofreciendo perspectivas prácticas para que los educadores las adopten en los cursos de laboratorio.

Palabras clave: Educación en Genética; Laboratorio Virtual; Ley de Mendel; Autoeficacia; Preparación Pre-Laboratorio; D. Melanogaster; Aprendizaje Basado en Proyectos (PBL).

INTRODUCTION

Genetics represents a branch of biology that is highly complex in both theoretical and practical aspects.[1,2] Students memorize abstract foundational concepts and understand intricate biological mechanisms that govern inheritance.[3,4] Additionally, they analyze experimental data, interpret laboratory outcomes accurately, and apply this knowledge to real-world contexts.[5,6] When students learn modern genetic data analysis, they must also master relevant tools and software, which increases their cognitive load.[7] Because of these challenges, many first-year university students find introductory genetics one of the most difficult courses.

To address these challenges, educators must strengthen students' comprehension of Mendel's Laws.[8,9] These laws describe the principles of segregation and independent assortment and form the conceptual foundation for understanding genetic inheritance.[10] They support the development of more advanced theories, including molecular and quantitative genetics.[11] Students who grasp Mendel's Laws solidly can also apply biotechnology techniques such as genetic engineering and transgenic organism development—applications that continue to grow in importance across research and industry.[12,13] However, many educators struggle to translate these abstract principles into meaningful student learning.

At the State University of Malang, educators implement Mendel's Laws using a Project-Based Learning (PBL) model to foster student engagement.[14] This method encourages learners to take active roles in solving genetic contextual problems, such as analyzing family inheritance patterns or identifying genetic factors behind specific diseases.[15,16] Through authentic, student-led investigations, learners actively engage in meaningful experiences that connect theory with practice.[17,18] This process strengthens critical and analytical thinking skills for scientific inquiry.[19,20] Yet, additional barriers often arise when PBL relies heavily on laboratory practice.

One practical application of the PBL model in genetics education involves laboratory work using D. melanogaster (fruit flies) as a model organism.[21,22] Researchers widely use D. melanogaster in genetic studies because of its short life cycle, easy breeding, and easily observable phenotypic traits, such as eye colour and wing shape.[23,24] By conducting monohybrid and dihybrid crosses, students directly apply Mendelian principles and analyze phenotypic ratios among offspring.[25] This hands-on approach reinforces theoretical learning and enhances students' understanding of inheritance patterns through real-time experimentation.[26] Despite these advantages, D. melanogaster experiments often overwhelm novice learners.

Although this method offers substantial pedagogical value, it presents several technical and logistical challenges.[27] Lab experiments with D. melanogaster require well-equipped facilities, long observation periods, and specialized technical skills, such as crossbreeding techniques between individuals.[28] These requirements create significant barriers, especially for first-year university students who lack laboratory experience and are still adjusting to experiment-based learning.[29] Consequently, many students struggle with the practical demands of such coursework.[30] At this stage, self-efficacy—the belief in one's ability to succeed in academic tasks—becomes a decisive factor.

In this context, self-efficacy plays a pivotal role.[31] Students with high self-efficacy approach experimental challenges confidently, overcome technical difficulties effectively, and connect theory with practice more easily.[32] Conversely, those with low self-efficacy often experience heightened anxiety, indecision, and difficulty managing cognitive load.[33] These challenges undermine their performance and reduce the effectiveness of the learning process.[34] Therefore, educators must design interventions that strengthen students' self-efficacy to support successful genetics learning.

In recent years, virtual learning technologies, particularly virtual reality (VR), have gained significant educational momentum.[35] Analysts predict substantial growth in the global VR in education market over the next several years.[36] Research indicates that VR can significantly enhance learning effectiveness, improve retention, and foster better student engagement. VR facilitates deeper cognitive, behavioral, and emotional involvement, especially when educators are adequately trained to integrate it into their teaching methods.[37] Real-world applications, such as Mindflight7 in Australia and corporate training programs by companies like UPS, Walmart, and Volvo, demonstrate how VR can transform abstract concepts into immersive, hands-on experiences, helping students navigate complex challenges and manage cognitive overload.[38]

To help students overcome these difficulties, educators must adopt innovative strategies that reduce cognitive strain and build confidence.[39,40] One promising approach involves interactive pre-lab virtual simulations that allow students to prepare digitally before conducting real experiments.[41,42] Through these simulations, learners explore experimental procedures, recognize the tools and materials, and internalize the lab workflow.[43,44] This preparation scaffolds students' readiness and helps them succeed in their physical lab experiences.[45,46]

Virtual labs give students a safe, low-risk environment to explore experimental designs, minimize the fear of failure, and encourage trial and error.[47] When they engage with simulations, students strengthen their mental readiness, develop more effective learning strategies, and deepen their understanding of genetic concepts.[48,49] As such, pre-lab virtual laboratories hold significant promise for improving the quality of genetics education, particularly within project-based, high-cognitive-demand environments.[50]

However, empirical research on the effectiveness of virtual labs in genetics education remains limited.[51] Most existing studies examine learning outcomes broadly rather than explicitly addressing self-efficacy.[52,53,54,55] In addition, prior research has focused mainly on simpler science topics—such as Newtonian mechanics or acid-base reactions—rather than conceptually demanding areas like Mendel's Laws and genetic crosses.[56,57,58] Although D. melanogaster experiments play a central role in teaching Mendelian inheritance, researchers have not yet explored how virtual labs can integrate with these experiments.[59,60]

This neglect leaves an important question unanswered: Can virtual labs meaningfully improve students' self-efficacy in mastering complex genetics content? Addressing this gap is critical because students transitioning to higher education must establish foundational scientific competencies and confidence.[61,62,63] Identifying how virtual labs can scaffold this transition offers theoretical contributions to the study of self-efficacy and practical strategies for inclusive genetics education.[64]

Based on these considerations, this study addresses a central research question: Can a pre-lab virtual laboratory enhance first-year students' self-efficacy and strengthen their understanding of Mendel's Laws when conducting D. melanogaster experiments? In line with prior findings, this study hypothesizes that students who engage in pre-lab virtual laboratories will demonstrate higher self-efficacy and better understand Mendel's Laws than those who do not.

In light of these gaps, this study characterizes the role of pre-lab virtual laboratory in shaping students' self-efficacy in genetics learning. Using *D. melanogaster* as a model organism determines their effectiveness in strengthening students' understanding of Mendel's Laws. The findings provide theoretical contributions to advancing science education and offer practical guidance for integrating innovative educational technologies in higher education contexts.

METHOD

Research Type

This study employs a quantitative research paradigm using a quasi-experimental design, characterised by a pre-test and a post-test with a control group. The design enables a systematic investigation of causal relationships by applying different treatments to comparable groups. Specifically, the experimental group received the Project-Based Learning (PBL) model integrated with a virtual laboratory, while the control group followed conventional PBL without technological enhancement. This approach ensures the internal validity of the findings and supports robust statistical análisis.

Research Design

This study employed a quasi-experimental design with a pre-test and post-test control group structure. The treatment involved using a virtual laboratory as a pre-lab support tool during the first four weeks of instruction. After this preparatory phase, the control and experimental groups participated in Mendel-based practicum activities, followed by a post-test evaluation. The design enabled the researchers to assess the effects of the virtual lab on student self-efficacy and concept mastery. It also ensured that any performance improvements could be confidently linked to using the digital intervention.

Instrument Validation and Reliability

We established validity and reliability before implementation to ensure the quality of the instruments. Two experts in genetics education and instructional design reviewed all items in the pre-lab test, self-efficacy questionnaire, and concept knowledge test for relevance, clarity, and alignment with course objectives. Their evaluation confirmed that all items were appropriate, with CVI values ranging from 0,86 to 0,90 (table 1).

We tested the reliability with a pilot group of 25 students from a previous cohort. The self-efficacy questionnaire demonstrated high internal consistency (Cronbach's α = 0,82), while the concept knowledge test showed satisfactory reliability (KR-20 = 0,76 for multiple-choice items; Cohen's κ = 0,81 for essay items). These results confirmed that the instruments were valid and reliable for the main stud

Table 1. Validity and Reliability of Instruments for Pre-Lab Test, Self-Efficacy Questionnaire, and Concept Knowledge Test

Instrument	Validity Method	Result	Reliability Method	Result	Category
Pre-lab test	Expert judgment	CVI = 0,86	Cronbach's α	0,79	Reliable
Self-efficacy questionnaire	Expert judgment	CVI = 0,90	Cronbach's α	0,82	Reliable
Concept knowledge test	Expert judgment	CVI = 0,88	KR-20 (MC), κ (essay)	0,76; 0,81	Reliable

Course and Practicum Structure

The Genetics course at the State University of Malang is designed to integrate theoretical knowledge and practical application into a comprehensive learning experience. The practicum runs for 16 weeks and utilises D. melanogaster as the model organism. The course adopts a Project-Based Learning (PBL) model in which students are divided into eight groups, each assigned a different practicum topic. Under the supervision of a laboratory assistant, each group conducts experiments, documents their activities in a practicum journal, and presents their findings for assessment. This structure promotes collaborative learning, strengthens conceptual understanding, and encourages student responsibility.

Table 2. Mendel's Law Topic Practicum Agenda

Week	Agenda	Activities Information
1	Introduction to practicum activities	Explanation of general practicum activities by practicum assistants
2	Division of D. melanogaster culture and identification of D. melanogaster strains	Each group received a different strain for the Mendel's Law topic practicum with the following details: 1. Group 1 = N x e (Mendel Law I) 2. Group 2 = e x cl (Mendel Law II) 3. Group 3 = N x vg (Mendel Law I) 4. Group 4 = e x vg (Mendel II) 5. Group 5 = N x b (Mendel I) 6. Group 6 = N x ecl (Mendel II) 7. Group 7 = N x eym (Mendel I) 8. Group 4 = N x evg (Mendel II)
3	Explanation and verification of the correctness of practicum procedures by laboratory assistants	The practicum procedure is written on a predetermined handout
4	Preparation of practicum proposal	
5	Practicum implementation	
6	Practicum implementation	
7	Practicum implementation	
8	Practicum progress	Checking data acquisition and the correctness of data interpretation
9	Practicum implementation	
10	Practicum implementation	
11	Practicum implementation	
12	Practicum implementation	
13	Practicum implementation	
14	Presentation of practicum results	
15	Practicum report collection	
16	Mendel's Law topic test	

This study centres on practicum activities related to Mendel's First and Second Laws. The practicum follows a structured weekly agenda (table 2), beginning with an introductory session and progressing through culture distribution, experimental implementation, and final evaluations. During the practicum, students receive D. melanogaster cultures, identify strain types, perform genetic crosses, and observe trait inheritance across two generations. All activities follow the procedures outlined in the practicum handouts and are guided and validated by laboratory assistants to ensure the accuracy and integrity of student data.

Participants

The participants in this study were undergraduate students from the Biology Education Study Program at State University of Malang enrolled in the Genetics course during the 2024/2025 academic year. We divided 122 students into two groups: a control group of 65 students who followed the conventional PBL model and an experimental group of 57 students who participated in PBL combined with a virtual lab. The university had already enrolled students in parallel classes, and administrative scheduling prevented us from reassigning them randomly. Therefore, we selected the groups through an intact class group design. We designated one class (n = 65) as the control group and the other (n = 57) as the experimental group. We conducted an initial equivalence test based on the students' Grade Point Averages (GPA) and found no significant difference between the two groups. This procedure ensured group comparability and allowed us to attribute outcome differences to the instructional treatment rather than prior academic performance.

Virtual Laboratory Description

The virtual laboratory was an interactive simulation platform to prepare students for genetics practicum activities. From weeks one to four, students in the experimental group accessed the platform and completed preparatory modules aligned with the practicum content. The platform featured five structured components that mirrored actual laboratory processes: defined competencies, theoretical materials on Mendel's Laws and *D. melanogaster* morphology, simulated procedures, conceptual evaluations, and supporting references. These components, illustrated in figure 1 and detailed further in figure 2, guided students through each stage of learning—from understanding Theory to simulating critical lab tasks.

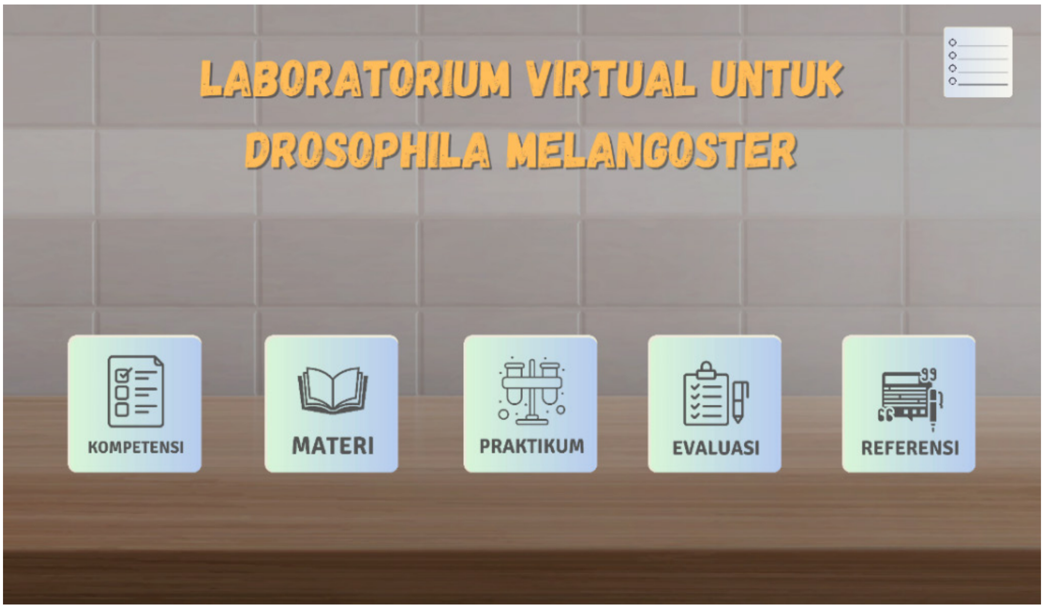

Figure 1. The feature set in the virtual laboratory. From left to right: competency, material, practicum, evaluation, references

Through these modules, students practised identifying phenotypes, conducting genetic crosses, preparing culture media, and calculating offspring ratios in a low-risk digital environment. This simulation experience helped reduce anxiety, improve procedural accuracy, and reinforce their understanding of Mendelian principles. As a result, students approached the real practicum with greater confidence, technical readiness, and conceptual clarity.

The design of the virtual laboratory was grounded in constructivist learning theory and the cognitive theory of multimedia learning, both of which emphasize active engagement, multimodal representation, and contextualized tasks as key to deeper understanding. Within the framework of Project-Based Learning, the virtual laboratory provided a scaffold that enabled students to explore, test, and reflect on Mendelian principles in a safe and low-risk environment before engaging in real laboratory work.

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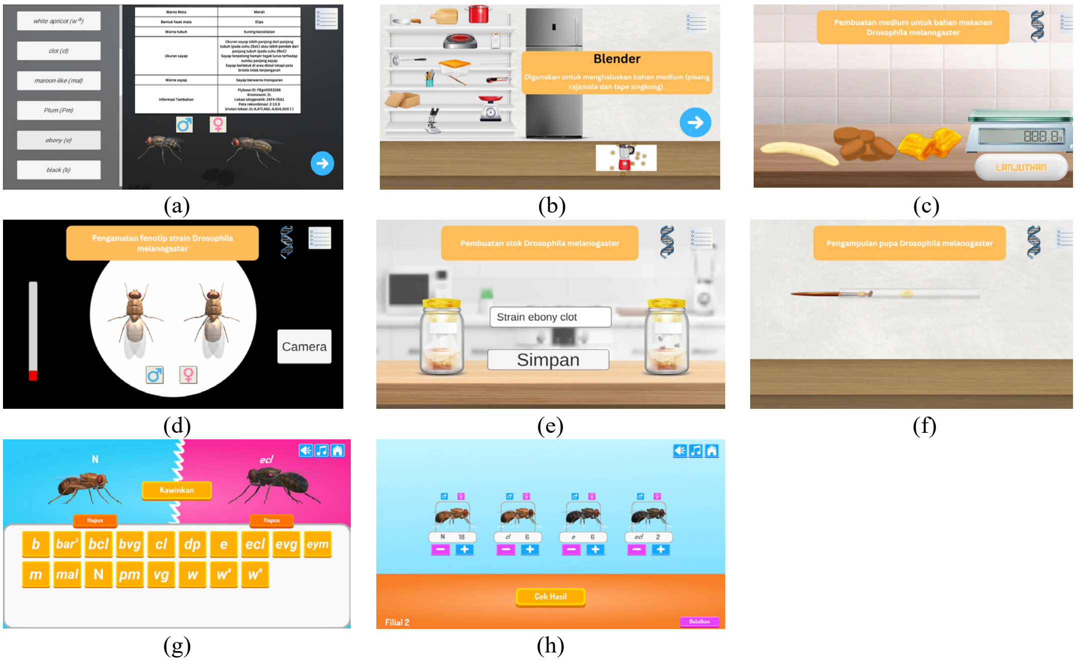

Figure 2. The menu series in the practicum simulation consists of several activities, namely (a) D. melanogaster atlas, (b) justification of practicum tools and materials, (c) making culture medium, (d) observation of D. melanogaster phenotypes, (e) making D. melanogaster stocks, (f) pupal ampoules, (g) D. melanogaster mating, (h) calculation of D. melanogaster offspring

To ensure the accuracy and usability of the platform, we conducted a content validation process involving three experts in genetics education and instructional technology. The experts reviewed the virtual laboratory to ensure alignment with practicum objectives, content accuracy, clarity of procedures, and user interface design. As summarized in table 3, the mean scores for all aspects ranged from 4,00 to 4,50 on a 5-point scale, indicating that the modules were valid and appropriate for implementation. Based on their feedback, we refined several modules by simplifying instructions, adjusting task sequencing, and improving interface readability.

Table 3. Content Validation Results for the Virtual Laboratory Modules

Aspect Evaluated	Expert 1	Expert 2	Expert 3	Mean Score	Category
Alignment with practicum goals	4	5	5	4,67	Valid
Content accuracy	5	5	5	5,00	Valid
Clarity of procedures	4	5	5	4,67	Valid
User interface design	5	5	4	4,67	Valid
Overall	-	-	-	4,75	Valid

In addition, we conducted a pilot test with 25 undergraduate students from a previous cohort to assess usability and clarity before full implementation. The results in table 4 showed mean scores ranging from 4,3 to 4,6 across aspects such as navigation, clarity, usefulness, and technical reliability, with an overall mean of 4,45. These findings indicated that students could navigate the platform without technical difficulties, complete the modules as intended, and perceived the virtual laboratory as highly useful for preparing practicum activities.

Table 4. Usability and Clarity Assessment Results from Pilot Test of the Virtual Laboratory

Usability Aspect	Mean Score	Category
Ease of navigation	4,5	Very Good
Clarity of instructions	4,3	Good
Usefulness for practicum prep	4,6	Very Good
Technical reliability	4,4	Good
Overall	4,45	Very Good

Together, these validation and pilot test results ensured the virtual laboratory was pedagogically sound and practically feasible for integration into the Genetics course.

Research Instruments

Pre-lab Test

Before the practicum began, all participants took a pre-lab test to assess their baseline understanding of lab procedures and Mendelian genetics. The instrument included one item to validate general laboratory knowledge and six essay questions that measured three domains: (1) understanding of laboratory procedures and safety, (2) conceptual knowledge of Mendel's First and Second Laws, and (3) analytical skills in solving fundamental genetic cross problems. Students answered each essay question by providing explanations or calculations, and we scored their responses using a 1–20 scale rubric that considered accuracy, completeness, and clarity of reasoning. Three experts in genetics education evaluated the items for content validity, yielding a CVI value of 0,86. At the same time, a pilot test with 25 students from a previous cohort confirmed reliability with Cronbach's $\alpha = 0,79$. The researchers applied an independent t-test to compare the scores between the two groups, confirming that both groups had comparable levels of prior knowledge. Establishing this equivalence in baseline knowledge helped ensure the internal validity of the experimental design.

Self-Efficacy Questionnaire

A self-efficacy questionnaire was administered twice, at the beginning (pre-test) and in the fourth week (post-test), to measure students' confidence in performing genetic experiments. The instrument contained eight statements rated on a 5-point Likert scale, assessing students' perceived competence in understanding procedures, conducting experiments, and analyzing data.[65] The post-test scores were analyzed using ANCOVA, with the pre-test scores as the covariate and group membership (control or experimental) as the independent variable. This analysis provided insight into whether the virtual lab experience enhanced students' confidence in completing practicum tasks.

Concept Knowledge Test

Students completed a concept knowledge test before and after the intervention to assess conceptual mastery. The test comprised two multiple-choice and two essay questions on segregation and genotype classification. The researchers used ANCOVA for data analysis, treating the pre-test scores as covariates. This method enabled a more straightforward interpretation of the treatment's effect on conceptual understanding by adjusting for any initial differences in student knowledge.

Data Analysis

We conducted quantitative analyses using parametric statistical methods. We used an independent t-test to examine differences in the pre-lab test, confirming baseline equivalence between groups. We analyzed both the concept knowledge test and the self-efficacy questionnaire using ANCOVA. For each outcome, we treated the post-test score as the dependent variable, the pre-test as the covariate, and group membership as the independent variable. We set the significance level at 5 % for all statistical tests. This approach ensured robust interpretation of results and strengthened the reliability of the study's conclusions.

Ethic aspects.

We obtained research permission from the State University of Malang, letter 20.6.137/UN32.20/LT/2023. We obtained informed consent from all participants. We treated the data as confidential and used it exclusively for research purposes, ensuring that no participant could be identified from the data.

RESULTS

Student Readiness Before Practicum (Pre-lab Test Results)

The pre-lab scores' normality test indicated that the experimental and control group data were normally distributed (tables 5 and 6). An independent t-test showed a statistically significant difference between the groups ($p < 0,05$; table 7), with the experimental group achieving a higher average score. Levene's test for equality of variances ($F = 1,072$; $p = 0,303$) showed that the data met the assumption of homogeneity of variances.

Table 5. Test of Normality[b]

	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	**df**	**Sig.**	**Statistic**	**df**	**Sig.**
Pre-lab test	0,104	65	0,079	0,951	65	0,012

Note: a. Lilliefors Significance Correction b. Group = PBL

Table 6. Test of Normality[b]						
	Kolmogorov-Smirnov[a]			**Shapiro-Wilk**		
	Statistic	**df**	**Sig.**	**Statistic**	**df**	**Sig.**
Pre-lab test	0,115	57	0,059	0,942	57	0,008
Note: a. Lilliefors Significance Correction b. Group = PBL + Virtual Laboratory						

Table 7. Independent Samples Test									
Variable	**Levene's Test for Equality of Variances**		**t-test for Equality of Means**						
Self-efficacy	**F**	**Sig.**	**t**	**df**	**Sig. (2-tailed)**	**Mean Difference**	**Std. Error Difference**	**95 % Confidence Interval of the Difference**	
								Lower	**Upper**
Equal variances assumed	1,072	0,303	-7,148	120	0,000	-14,11741	1,97494	-18,02765	-10,20716
Equal variances not assumed.			-7,081	111,601	0,000	-14,11741	1,99376	-18,06795	-10,16687

Self-efficacy Level of Students Before Starting Practicum on Mendel's Law Topic

The results of the self-efficacy questionnaire showed that the data in both groups were normally distributed (tables 8 and 9), and the independent t-test revealed a statistically significant difference ($p < 0,05$; table 10). Students in the experimental group reported higher levels of self-efficacy in areas such as understanding laboratory procedures, executing practicum tasks, and addressing experimental challenges, as illustrated in figure 3.

Table 8. Test of Normality[a]						
	Kolmogorov-Smirnov[a]			**Shapiro-Wilk**		
	Statistic	**df**	**Sig.**	**Statistic**	**df**	**Sig.**
Self-efficacy	0,065	122	0,200	0,989	122	0,401

Table 9. Homogeneity Test			
F	**df1**	**df2**	**Sig.**
3,554	1	120	0,062

Dependent Variable: Post-test Self-efficacy

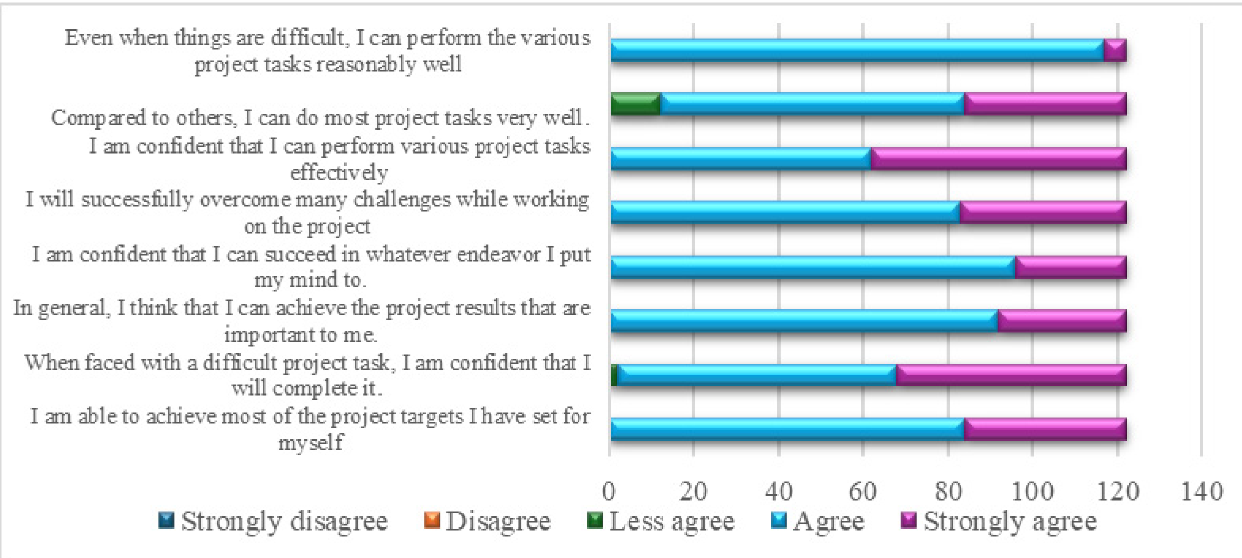

Figure 3. Self-efficacy level of experimental group students

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Table 10. ANCOVA Test					
Source	**Type III Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**
Corrected Model	738,642[a]	2	396,321	73,023	0,000
Intercept	1597,096	1	1597,096	315,780	0,000
XSE	444,583	1	444,583	87,903	0,000
Group	291,936	1	291,936	57,722	0,000
Error	601,858	199	5,058		
Total	146551,000	122			
Corrected Total	1340,500	121			
Note: a. R Squared = 0,876 (Adjusted R Squared = 0,874)					

Mendel's Law Topic Concept Knowledge Test

To evaluate the effect of the virtual laboratory on student tests for residual normality and homogeneity, we tested the data for residual normality and homogeneity, which confirmed that the data met the assumptions for ANCOVA analysis (tables 11 and 12). ANCOVA results (table 13) revealed a significant difference in post-test scores between the groups (p < 0,05).

Table 11. Test of Normality[b]						
	Kolmogorov-Smirnov[a]			**Shapiro-Wilk**		
	Statistic	**df**	**Sig.**	**Statistic**	**df**	**Sig.**
Residual for YCK	0,076	122	0,083	0,987	122	0,305
Note: a. Lilliefors Significance Correction						

Table 12. Homogeneity Test			
F	**df1**	**df2**	**Sig.**
0,252	1	120	0,617

Dependent Variable: Post-test Concept of Mendel's Law

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

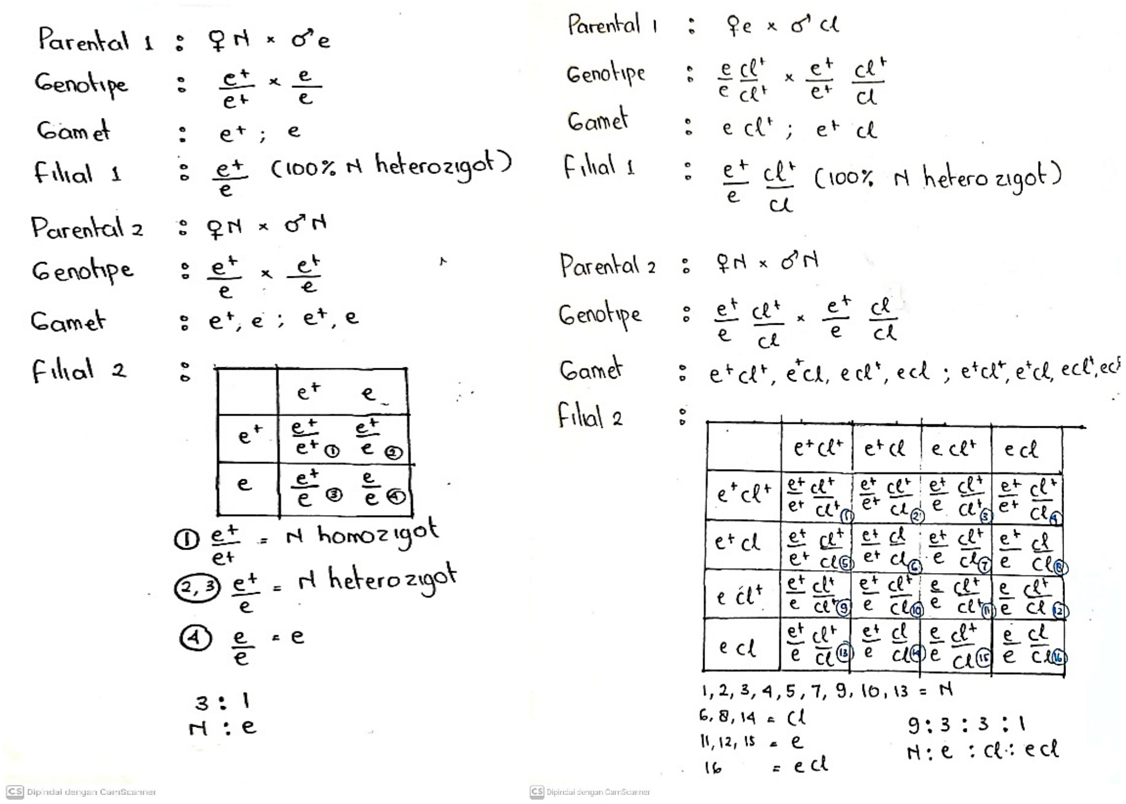
Table 13. ANCOVA Test					
Source	**Type III Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**
Corrected Model	18067,586[a]	2	9033,793	422,012	0,000
Intercept	10085,953	1	10085,953	471,163	0,000
XSE	12526,663	1	13526,662	631,895	0,000
Group	2034,331	1	2034,331	95,033	0,000
Error	2547,373	199	21,406		
Total	531525,000	122			
Corrected Total	20614,959	121			
Note: a. R Squared = 0,876 (Adjusted R Squared = 0,874)					

DISCUSSION

One of the persistent challenges in genetics education is that students often enter laboratory sessions with limited preparedness, leading to anxiety, confusion, and inefficient use of time. This study demonstrates that integrating a virtual laboratory addresses these challenges by providing students with early, low-risk exposure to experimental procedures. By rehearsing technical steps and clarifying objectives in a simulated environment, students developed stronger mental models that prepared them for the demands of physical laboratory work.[66,67] This preparation reduced initial uncertainty, facilitated smoother transitions to hands-on practice, and strengthened theoretical readiness and procedural fluency, crucial for meaningful genetic experimentation.[68,69,70]

Beyond addressing practical challenges, the improvements observed in this study can be interpreted through Bandura's self-efficacy theory. The opportunity to repeatedly practice laboratory tasks in a safe digital environment provided mastery experiences, the most influential source of self-efficacy.(71,72) Students reported increased confidence, reduced anxiety, and enhanced competence before engaging in real laboratory work. The simulation also offered low-stakes opportunities for trial and error, allowing learners to explore procedures freely without fear of failure.(73) These experiences reinforced their belief in their capacity to succeed in scientific tasks.(74,75) As a result, students in the experimental group demonstrated greater confidence in completing tasks, meeting project goals, and overcoming laboratory challenges than their peers in the control group.(76,77,78) In this sense, the virtual laboratory functioned as an instructional scaffold that empowered students by cultivating the psychological readiness necessary for scientific experimentation.(79)

Complementing these psychological benefits, the cognitive advantages of the intervention can also be explained using cognitive load theory. Virtual laboratories reduce extraneous cognitive load by providing step-by-step visual scaffolding and immediate feedback, which enables students to focus their mental resources on germane processing of abstract concepts.(80,81) The reduction of extraneous cognitive load was particularly evident in students' mastery of Mendel's Laws. The ANCOVA results revealed significant differences in post-test scores between the experimental and control groups, indicating that the virtual laboratory enhanced students' understanding of the Law of Segregation and the Law of Independent Assortment (table 13). Through simulation, students reconstructed monohybrid and dihybrid crosses, observed phenotypic ratios, and analysed inheritance patterns in real time.(82) For instance, when simulating a clot-eye × ebony-body cross, students visualised the segregation of dominant and recessive alleles, while in dihybrid crosses, they observed the classic 9:3:3:1 phenotypic ratio and linked it to the independent assortment of alleles at different loci (figure 4).(83,84) These experiences transformed abstract theoretical constructs into action patterns, strengthening students' reasoning skills and ability to connect experimental results with underlying genetic principles.(85)



(a) (b)

Figure 4. The results of the reconstruction of crosses made by students. (a) Mendel's Law of Segregation (Law I) states that two alleles for each gene separate during gamete formation. (b) The Law of Independent Assortment/Mendel's Law II states that alleles for different genes are separated independently

Building on these psychological and cognitive outcomes, this study shows that integrating virtual laboratories into genetics instruction yields positive outcomes across learning readiness, self-efficacy, and conceptual mastery.(86,87) The virtual environment provided students with flexible, exploratory experiences that prepared them for the demands of experimental work.(88,89) By engaging with simulations beforehand, students developed foundational knowledge and procedural familiarity, which improved their performance in real lab settings.(90,91,92) Moreover, integrating virtual labs complements the Project-Based Learning (PBL) framework, allowing students to investigate real-world scientific problems through guided inquiry and experimentation.(93) The virtual lab acted as a pre-lab foundation, making the transition to hands-on tasks smoother and more effective.[94] As a result, students gained deeper conceptual understanding and developed practical competency, two pillars of meaningful science education.[95,96]

In relation to prior scholarship, these findings align with and extend previous research on the role of digital simulations in science education.[97] Earlier studies often emphasized motivational and engagement-related benefits but provided limited evidence of conceptual gains. In contrast, the present study demonstrates measurable improvements in self-efficacy and conceptual mastery, suggesting that the benefits of virtual laboratories extend beyond the affective domain. At the same time, these results corroborate previous findings that reported reduced student anxiety and improved readiness when simulations were used as preparatory tools.[98,99] By showing that virtual laboratories contribute simultaneously to affective and cognitive outcomes, this study adds to the ongoing scholarly debate. It supports the argument that virtual laboratories should be treated as integral components of science instruction rather than optional supplements.[100]

Taken together, these outcomes carry essential theoretical implications. This study contributes to Bandura's framework by illustrating how digital mastery experiences embedded within formal instruction can substitute for scarce opportunities in physical laboratories and still produce significant gains in self-efficacy.[101] It also reinforces cognitive load theory by demonstrating how well-designed simulations can reduce extraneous demands and support the germane processing of complex scientific ideas.[102,103] In this way, the study positions virtual laboratories as technological innovations and pedagogically grounded tools that reshape how scientific competence is cultivated.

From a practical perspective, the results provide actionable guidance for educators. Virtual laboratories should be considered integral pre-lab stages connecting theoretical learning with practical application. By embedding virtual labs into project-based learning frameworks, educators can create blended environments that maximize the efficiency of limited laboratory resources, reduce student anxiety, and enhance the overall quality of scientific inquiry.[104] This approach is especially valuable in educational contexts where restricted laboratory access or safety concerns limit student practice opportunities, as digital preparation can ensure that time spent in physical laboratories is more efficient and productive.[105,106]

Despite these contributions, the study has several limitations that must be acknowledged. The sample was restricted to a single institution, which constrains the generalizability of the findings. The short intervention period limits conclusions regarding long-term impacts on knowledge retention and sustained self-efficacy. The study relied primarily on quantitative measures, which restricted the ability to capture the depth of students' subjective experiences. Another limitation lies in the omission of collaborative dimensions, since project-based learning contexts often emphasize teamwork and co-construction of knowledge, aspects not addressed in this study.

Future research should therefore broaden the scope by including larger and more diverse samples across institutions and disciplines and employing longitudinal designs to assess retention and transfer of learning. Mixed-method approaches are recommended to capture measurable outcomes and students' lived experiences in virtual environments. Further investigation is needed to explore how virtual laboratories can facilitate collaborative learning, teamwork, and creativity. Moreover, comparative studies with emerging digital tools, such as augmented or mixed reality platforms, could provide valuable insights into the relative effectiveness of different technological approaches in enhancing science education.

CONCLUSIONS

Virtual laboratories represent a practical pedagogical innovation that directly addresses the objectives of genetics education. They are foundational pre-lab stages that strengthen readiness, foster self-efficacy, and deepen conceptual understanding. More broadly, they mark a paradigm shift in science instruction, moving from optional supplements toward integral components of higher education curricula.

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CONFLICT OF INTEREST

No potential conflict of interest was reported by the author(s).

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