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Virtual Laboratory Based on Ingenhousz Experiment Modeling: Enhancing Conceptual Understanding and Scientific Literacy

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ABSTRACT

Purpose – This study aims to evaluate the effectiveness of the Ingenhousz Experiment Virtual Laboratory, integrated with the GENIUS syntax, within a Blended Learning framework to accelerate students' conceptual understanding and science literacy in photosynthesis.

Methodology – A quasi-experimental research with a Replicated Experimental Design was employed. The study involved 136 eleventh-grade science students at SMA Negeri 3 Makassar, divided into three experimental replication classes and one control class. Conceptual understanding was measured using a 20-item multiple-choice test, while science literacy was assessed through a 5-item essay test. Data were analyzed using descriptive statistics, N-Gain calculations, ANCOVA, and Least Significant Difference (LSD) post-hoc tests.

Findings – Initial assessments indicated equivalent suboptimal cognitive baselines across all groups. Post-intervention, all replication classes demonstrated a profound cognitive escalation, achieving a "High" N-Gain category (0.77–0.89), whereas the control group remained in the "Moderate" category. ANCOVA confirmed a highly significant treatment effect ($p = 0.000$). LSD tests revealed no significant variance among the three replication classes, but all significantly outperformed the control group, confirming the intervention's consistency and reliability.

Contribution – This study provides a replicable pedagogical framework, demonstrating that synergizing structured inquiry syntax with interactive virtual simulations successfully transforms students into active scientific researchers and effectively overcomes the limitations of conventional teaching.

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INTRODUCTION

The development of digital technology in the contemporary educational landscape has driven a shift in instructional paradigms towards an adaptive virtual learning environment (Ahmed & Hasegawa, 2021; Garzón, 2021; Wahab et al., 2026; Yanti et al., 2022). The education system in Indonesia still faces significant challenges in developing higher-order cognitive skills to keep pace with global dynamics (Adnan, Saenab, et al., 2025; Astuti & Najuba, 2024; Berenjian et al., 2026; Yustina et al., 2020). Referring to the 2020 PISA assessment data, Indonesia's average scientific literacy score stood at 396, far below the OECD average of 498, placing Indonesia 62nd out of 81 participating countries (Adnan, Saenab, et al., 2025; Johar & Shanwal, 2023; Mahmud et al., 2025; Oktobianti et al., 2026). Education plays a vital role in empowering students to navigate the complexities of the modern era by fostering scientific literacy and in-depth conceptual understanding (Khatimah et al., 2026; Mahmud et al., 2025; Putri et al., 2026).

The mastery of basic science should ideally go hand in hand with digital literacy and agility, enabling students to navigate technical information objectively and without misconceptions (Adnan et al., 2012). However, the reality in the field reveals a significant discrepancy. Based on preliminary observations and analyses of learning resource needs conducted at SMA Negeri 3 Makassar, students' current levels of scientific literacy and conceptual understanding remain relatively underdeveloped (Arsal et al., 2017; Hasruddin & Rezeqi, 2012; Muis & Bahri, 2018). The learning process is predominantly teacher-centered, with insufficient space for inquiry and exploration (Johar & Shanwal, 2023). Furthermore, the limitations of physical laboratory facilities and the minimal time allocation mean that essential practicals, such as the Ingenhousz Experiment, are rarely implemented optimally. Consequently, students lose direct experience in manipulating scientific variables, leading to metacognitive stagnation and the tendency to accept information instantly without inquiry when faced with applied science problems (Adnan, Saenab, et al., 2025; Adnan & Bahri, 2016; Ismayani et al., 2023; Vančugovienė et al., 2024).

Addressing these empirical problems requires pedagogical innovations grounded in constructivist learning theory, which posits that learners actively construct knowledge through direct experience and structured inquiry rather than passive reception (Adnan & Bahri, 2016; Yustina et al., 2020). The integration of Information and Communication Technology (ICT)-based constructivist pedagogical models provides a viable means of facilitating this process (Andika et al., 2025; Wahab et al., 2026). The use of the Blended Learning framework, supported by a Learning Management System (LMS), has proven effective in overcoming the limitations of conventional classrooms in fostering scientific collaboration (Andika et al., 2026; Muis & Bahri, 2018). The engineering of such hybrid learning environments not only provides computational access but also systematically reconstructs students' intrinsic motivation and cognitive outcomes by positioning learners as active subjects within a well-planned syntax (Johar & Shanwal, 2023; Khatimah et al., 2026; Kusmawan, 2022).

The topic of photosynthesis is a foundational subject in biology that consistently demands an understanding of cross-variable bioprocesses with physiological precision (Jančaříková & Jančařík, 2022; Taiz & Zeiger, 2003). To accommodate this, pedagogical engineering innovations that integrate digital technology with the syntax of structured inquiry learning have become necessary (Clarinda et al., 2022; Herunata et al., 2022). The formulated comprehensive solution is the implementation of a Blended Learning approach utilizing the GENIUS syntax (Generate Curiosity, Explore Conceptually, Navigate Investigation, Integrate Understanding, Utilize Knowledge, Share & Reflect), integrally connected to the Ingenhousz Experiment Virtual Laboratory (Adnan, Ristiana, et al., 2025; Sherrer, 2020).

The variables are deeply interconnected within the learning ecosystem. The Virtual Laboratory serves as an interactive medium that enables precise manipulation of independent plant physiological variables, such as light intensity, water temperature, and carbon dioxide concentration, without physical constraints (Al-Nakhle, 2022; Zaturrahmi et al., 2020). Meanwhile, the GENIUS syntax serves as pedagogical scaffolding, guiding students systematically through the inquiry process. By autonomously manipulating these digital variables and navigating the investigation phase, students can visualize abstract bioprocesses, which directly constructs their deep Conceptual Understanding (Jufri et al., 2026; Wahab et al., 2026). Furthermore, as the platform automatically records data and converts it into real-time analytical graphs, students are trained to evaluate empirical evidence and draw logical conclusions, thereby persistently sharpening their *Scientific Literacy* (Clarinda et al., 2022; Ismail et al., 2016).

While successive empirical validations have revealed the benefits of integrating web-based virtual laboratories (Ambusaidi et al., 2018) and inquiry models (Adnan & Bahri, 2016; Gunawan et al., 2018) in escalating learners' metacognition, a prominent research gap remains. Advanced empirical explorations that specifically integrate the Ingenhousz Virtual Laboratory into the GENIUS Blended Learning syntax corridor to evaluate the dual outcomes of conceptual understanding and scientific literacy among high school students are exceptionally rare in the literature (Herunata et al., 2022; Hikmah et al., 2026; Kusmawan, 2022).

Building on this crucial academic gap, the novelty of this study lies in its specific synergistic framework, which provides a replicable pedagogical standard that connects structured constructivist syntax with interactive biological simulations to address concrete classroom limitations. Therefore, this study is conducted to evaluate the effectiveness of implementing the Ingenhousz Experiment Virtual Laboratory with the GENIUS syntax to accelerate conceptual understanding and scientific literacy, testing the premise that students' active immersion in systematically manipulating simulated variables will persistently catalyze higher-order cognitive outcomes (Hikmah et al., 2026; Kubayan et al., 2025; Putra et al., 2025).

METHODOLOGY

Research Design

This study is a quantitative research that employed a quasi-experimental design utilizing a Replicated Experimental Design technique. In this study, four intact classes were involved as research subjects. Three classes served as replication groups, all of which received a single, identical treatment (X), specifically a Blended Learning approach using the GENIUS syntax fully integrated with the Ingenhousz Experiment Virtual Laboratory modeling. The implementation of this single treatment across three distinct groups serves as a form of replication to examine the stability, consistency, and generalizability of the media's effectiveness. Meanwhile, one class acted as the control group following conventional learning (X_0). Each group was administered a pre-test and a post-test using the same cognitive measurement instruments. A general overview of the research design is presented in Table 1.

Table 1. Research Design Table

Class	Pretest	Experiment	Postest
Replication I	O_1	X	O_2
Replication II	O_3	X	O_4
Replication III	O_5	X	O_6
Control	O_7	X_0	O_8

X: Blended Learning dengan sintaks GENIUS yang terintegrasi dengan Laboratorium Virtual Eksperimen Ingenhousz (Replikasi paralel identik); XO: Pembelajaran konvensional; O_1, O_3, O_5, O_7: Skor pre-test; O_2, O_4, O_6, O_8: Skor post-test.

Participant

The study population comprised eleventh-grade science students at SMA Negeri 3 Makassar. The sample was selected using a cluster random sampling technique, in which whole classes were randomly assigned to study groups to maintain a natural classroom setting. After randomization, four classes were selected as the study sample, comprising three experimental replication classes and one control class. Each class, both in the experimental and control groups, consisted of 34 students, yielding a total of 136 participants. These relatively homogeneous participant characteristics were considered important for minimizing variability and ensuring comparability between the experimental and control groups.

Data Collection

Data collection techniques in this study consisted of written tests administered during two distinct phases. The pre-test was administered before the instructional treatment to determine the students' baseline equivalence. Following the implementation of the learning intervention, the post-test was administered using the same instrument. Students were given 90 minutes to complete the test. The administration of these tests aimed to accurately evaluate the cognitive enhancement and literacy acceleration attributed to the learning media.

Instrument

This study utilized two expert-validated instruments to collect data. Conceptual understanding was measured using a 20-item multiple-choice test (five options) focusing on photosynthesis concepts and experimental variable manipulation. Meanwhile, science literacy was assessed through a 5-item essay test that evaluated students' ability to analyze physiological data, interpret virtual lab graphs, assess experimental designs, and build evidence-based arguments.

Data Analysis

Once the research data have been collected, they will be analyzed using both descriptive and inferential statistical methods. Descriptive statistics were employed to outline the mean, standard deviation, and N-Gain scores. Inferential analysis will be conducted to test the research hypotheses. Prior to hypothesis testing, normality and homogeneity tests will be carried out. If the data satisfy the assumptions of normality and homogeneity, hypothesis testing will proceed using parametric analysis (ANCOVA). To identify specific differences in students' conceptual understanding and science literacy among the learning groups, a post hoc analysis will be conducted using the Least Significant Difference (LSD) test.

FINDINGS

The results of this study are presented through several stages of comprehensive analysis. These include descriptive statistical analysis, significance tests for improvement in effectiveness using N-Gain scores, prerequisite tests (normality and homogeneity of variances), and hypothesis testing using Analysis of Covariance (ANCOVA), followed by the Least Significant Difference (LSD) test to map the significance of differences between groups precisely. Descriptive analysis is presented first to provide a factual overview of the distribution and improvement of students' conceptual understanding skills in each group before and after the intervention.

Conceptual Understanding

Descriptive analysis was conducted to thoroughly review the profile of students' conceptual understanding skills. The extracted statistical parameters include the mean, standard deviation, maximum value, minimum value, range, variance, and effectiveness score (N-Gain). A summary of the descriptive analysis results is presented in detail in Table 2.

From Table 2, the average pre-test score for the control group was 45.00, while the scores for Replication 1, Replication 2, and Replication 3 were 34.56, 30.94, and 35.29, respectively. This indicates that before the intervention, students across all groups had an equivalent, relatively low level of foundational understanding of photosynthesis concepts. However, after the learning process, a sharp contrast in achievement emerged. The control group recorded an average post-test score of 77.38, whereas the three replication classes exceeded this average with scores of 88.21 (Replication 1), 85.88 (Replication 2), and 85.85 (Replication 3).

The effectiveness of this treatment is absolutely confirmed through the N-Gain score calculations. The three replication classes receiving the parallel replication treatment consistently achieved the "High" improvement category, with N-Gain scores of 0.81, 0.79, and 0.77, respectively. Conversely, the improvement in the control group was confined to the "Moderate" category with an N-Gain score of 0.57. This empirical data provides robust evidence that the Blended Learning approach, with the GENIUS syntax integrated into the Virtual Laboratory, is highly effective in developing conceptual understanding.

Table 2. Results of Descriptive Analysis of Conceptual Understanding for Each Treatment

Class	Type of test	N	Average	Deviation Standart	N-Max	N-Min	Range	Variance
Replication 1	Pre-test	34	34.56	6.907	48.00	20.00	28.00	47.709
	Post-test	34	88.21	5.330	100.00	78.00	22.00	28.411
	N-Gain	34	0.8178	0.0825	1.00	0.66	0.34	0.0068
Replication 2	Pre-test	34	30.94	6.281	47.00	20.00	27.00	39.451
	Post-test	34	85.88	3.867	95.00	79.00	16.00	14.955
	N-Gain	34	0.7937	0.0585	0.93	0.70	0.23	0.0034
Replication 3	Pre-test	34	35.29	8.565	53.00	20.00	33.00	73.365
	Post-test	34	85.85	4.678	95.00	77.00	18.00	21.887
	N-Gain	34	0.7766	0.0821	0.93	0.63	0.30	0.0067
Control	Pre-test	34	45.00	8.124	59.00	26.00	33.00	66.000
	Post-test	34	77.38	4.533	86.00	66.00	20.00	20.546
	N-Gain	34	0.5796	0.1038	0.79	0.33	0.46	0.0108

This effectiveness stems from the engineering of the Virtual Laboratory learning environment, which can deconstruct the complexity of photosynthesis bioprocesses into logical, interactive scientific experiences. During the Navigate Investigation phase in the GENIUS syntax, students are given full autonomy to act as subjects of inquiry. They manipulate independent digital variables, such as adjusting the lamp distance to alter light intensity, regulating ambient temperature, and controlling CO2 concentration, to directly analyze their effects by observing the appearance of oxygen bubbles in the Ingenhousz Experiment model. This experimental approach compels students to think critically, evaluate evidence, and synthesize cross-variable conceptual understanding, thereby minimizing misconceptions that often arise in purely theoretical learning.

The subsequent testing phase focused on the normality prerequisite test to validate data suitability before executing the parametric inferential test (ANCOVA). Fulfilling this statistical assumption is a fundamental methodological requirement to ensure that the variance within both the experimental replication cohorts and the control group follows a symmetrical distribution. Verifying this distribution prevents biased estimations and guarantees the mathematical robustness of the covariance analysis when isolating the intervention's true effect. To confirm that the sample data accurately represents a normally distributed population, an evaluation against an alpha threshold of 0.05 was established. The normality test for this conceptual understanding data was conducted using the Kolmogorov-Smirnov test, with the results presented in Table 3.

Table 3. Normality Test of Conceptual Understanding Research Data

Type of learning	Kolmogorov-Smirnov		
	Statistic	df	Sig.
Pretest Replication 1	0.103	34	0.200*
Posttest Replication 1	0.104	34	0.200*
Pretest Replication 2	0.079	34	0.200*
Posttest Replication 2	0.120	34	0.200*
Pretest Replication 3	0.076	34	0.200*
Posttest Replication 3	0.125	34	0.200*
Pretest Control	0.098	34	0.200*
Posttest Control	0.108	34	0.200*

Description: df: Degree of freedom; Sig.: Significance; * (lower bound of true significance).

The normality test ensures that the variance in students' conceptual understanding scores follows a normal distribution. Based on Table 3, all testing groups for both the pre-test and post-test data across all classes obtained a significance value (Sig.) of 0.200. Given that all these significance probabilities exceed the alpha threshold of 0.05 ($p > 0.05$), it can be concluded that the research data are normally distributed, thereby fully meeting the crucial prerequisite to proceed with the homogeneity and ANCOVA tests.

After confirming the data's normality, the subsequent prerequisite analysis was the homogeneity test. The homogeneity of variance test aims to ensure that the sample groups compared in this study originate from populations with equal (homogeneous) variances. This test was conducted using Levene's Test of Equality of Variances, with the results summarized in Table 4.

Table 4. Homogeneity Test of Research Data on Conceptual Understanding

		Levene Statistic	df1	df2	Sig.
Conceptual Understanding Pre-test	Based on Mean	1.246	3	132	0.296
Conceptual Understanding Post-test	Based on Mean	0.522	3	132	0.668

Description: df1: Degree of freedom of the numerator; df2: Degree of freedom of the denominator; Sig: Significance

Based on Table 4, Levene's homogeneity test results indicate significance probabilities (Sig.) of 0.296 for the pre-test data and 0.668 for the post-test data. Since both significance values are strictly greater than the 0.05 alpha level, the null hypothesis (H0) is accepted. This proves that the variance in students' conceptual understanding skills among the research groups is homogeneous, both before and after the treatment was administered.

The fulfillment of both parametric prerequisite tests, namely, normality of the data distribution and homogeneity of variances across groups, provides a valid foundation for conducting inferential tests to answer the research questions. To statistically test the treatment's effectiveness, an Analysis of Covariance (ANCOVA) was conducted. This test was selected because it can control for the influence of the covariate, specifically students' initial ability scores (pre-test), ensuring that the measured differences in post-test results are attributable solely to the administered treatment's effectiveness. The ANCOVA test was subsequently conducted to determine whether there is a significant difference in students' conceptual understanding skills after controlling for their initial abilities. The results of this analysis are crucial in identifying the extent to which the integrated Virtual Laboratory treatment contributes to student learning. By mathematically isolating the variance attributed exclusively to the digital instructional media, this model systematically eliminates potential confounding factors stemming from prior cognitive disparities. A calculated probability value below the standard alpha threshold provides the rigorous empirical justification needed to reject the null hypothesis decisively. This statistical validation definitively confirms the pedagogical robustness of the experimental intervention compared to traditional classroom environments. A summary of the ANCOVA hypothesis test results is presented in Table 5.

Table 5. ANCOVA Test of Conceptual Understanding (Tests of Between-Subjects Effects)

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	2325.974a	4	581.494	27.031	0.000
Intercept	39837.992	1	39837.992	1851.854	0.000
NilaiPre (Covariate)	13.246	1	13.246	0.616	0.434
KelasPost (Group)	1554.495	3	518.165	24.087	0.000
Error	2818.136	131	21.512		
Total	972335.000	136			
Corrected Total	5144.110	135			

Description: aR Squared = .452 (Adjusted R Squared = .435); Dependent Variable: Posttest Conceptual Understanding

In Table 5, the ANCOVA test results for the inter-class treatment variation source (KelasPost/Group) show a calculated F-value of 24.087 with a significance level of 0.000 ($p < 0.05$). This empirical fact directly rejects the null hypothesis, indicating a highly significant difference in the improvement of conceptual understanding between students learning through the Blended Learning approach using the GENIUS syntax integrated with the Ingenhousz Experiment Virtual Laboratory modeling, and those following conventional learning. This significance substantiates the effectiveness level of the developed virtual learning media.

To more precisely analyze the specific locations of differences in effectiveness among the groups, the testing proceeded with the post hoc Least Significant Difference (LSD) test. This pairwise comparison test is essential for verifying the intervention's robustness across the three replication classes that serve as parallel replications. The results of the LSD post-hoc test are summarized in Table 6.

These results reveal that students participating in the Virtual Laboratory integrated with the GENIUS syntax achieved significantly higher conceptual understanding scores than those in the conventional learning group. Based on the LSD post-hoc test (Table 6), the Control class recorded the lowest average score of 77.38. The replication classes demonstrated significantly superior performance, with Replication 1 achieving the highest conceptual understanding score (mean = 88.21), followed by Replication 2 (mean = 85.88) and Replication 3 (mean = 85.85).

Table 6. LSD (Least Significant Difference) Test of Conceptual Understanding

Class	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
Control	77.38[a]	0.777	75.80	78.96
Replication 3	85.85[b]	0.802	84.22	87.49
Replication 2	85.88[b]	0.663	84.53	87.23
Replication 1	88.21[b]	0.914	86.35	90.07

Description: The superscript letters (a,b) indicate significant differences based on the LSD test ($p < 0.05$). Means sharing the same letter are not significantly different from each other.

The distinct superscript notations clearly illustrate the robustness of the Blended Learning intervention. All replication classes (Replication 1, 2, and 3) consistently demonstrated significantly higher conceptual understanding compared to the Control class, forming a completely separate and superior performing subset (subset b) against the control group (subset a). Furthermore, the absence of statistically significant differences among the three replication classes demonstrates that the effectiveness of the virtual laboratory is not an isolated anomaly in a single classroom, but rather a highly consistent and reliable intervention across multiple trials. This robust replication confirms that the Virtual Laboratory successfully reconstructed the students' cognitive frameworks, prevented rote memorization, and enabled them to comprehend abstract bioprocesses more deeply than conventional learning. Such profound conceptual mastery is achieved because the interactive simulation provides immediate, data-driven feedback during variable manipulation, effectively scaffolding the assimilation of complex physiological mechanisms. Consequently, this statistical uniformity across parallel groups firmly establishes the GENIUS-integrated virtual environment as a highly scalable pedagogical standard for overcoming intrinsic barriers to learning in science education.

Science Literacy

The subsequent analysis focused on the second dependent variable, namely the students' science literacy skills. As with the previous variable, a descriptive analysis was conducted initially to provide a comprehensive overview of the science literacy skills profile for each group before and after the treatment. The evaluated metrics included the mean, standard deviation, maximum score, minimum score, range, variance, and the improvement or effectiveness score (N-Gain). A summary of the descriptive analysis results for science literacy is presented in Table 7. This descriptive analysis provides an initial baseline for identifying differences in science literacy achievement among the groups, and the results presented in Table 7 serve as the foundation for further inferential analysis to test the effectiveness of the Virtual Laboratory integrated with the GENIUS syntax.

Table 7, the mean science literacy pre-test score for the control group was 47.38. Meanwhile, Replication 1, Replication 2, and Replication 3 obtained scores of 48.53, 48.47, and 35.29, respectively. These figures confirm that prior to the intervention, the students’ science literacy competencies across all groups were at a relatively equivalent, albeit suboptimal, level. Following the treatment, the control group achieved a mean post-test score of 74.65, whereas the three replication classes demonstrated a remarkable surge in achievement, yielding averages of 94.62 (Replication 1), 92.76 (Replication 2), and 85.76 (Replication 3).

Table 7. Results of Descriptive Analysis of Science Literacy for Each Treatment

Class	Type of test	N	Average	Deviation Standart	N-Max	N-Min	Range	Variance
Replication 1	Pre-test	34	34.56	6.907	48.00	20.00	28.00	47.709
	Post-test	34	88.21	5.330	100.00	78.00	22.00	28.411
	N-Gain	34	0.8178	0.0825	1.00	0.66	0.34	0.0068
Replication 2	Pre-test	34	30.94	6.281	47.00	20.00	27.00	39.451
	Post-test	34	85.88	3.867	95.00	79.00	16.00	14.955
	N-Gain	34	0.7937	0.0585	0.93	0.70	0.23	0.0034
Replication 3	Pre-test	34	35.29	8.565	53.00	20.00	33.00	73.365
	Post-test	34	85.85	4.678	95.00	77.00	18.00	21.887
	N-Gain	34	0.7766	0.0821	0.93	0.63	0.30	0.0067
Control	Pre-test	34	45.00	8.124	59.00	26.00	33.00	66.000
	Post-test	34	77.38	4.533	86.00	66.00	20.00	20.546
	N-Gain	34	0.5796	0.1038	0.79	0.33	0.46	0.0108

This superiority is further corroborated by the effectiveness metric analysis (N-Gain). Students instructed via the Ingenhousz modeling-based Virtual Laboratory in the three replication classes (parallel replications) achieved a “High” level of effectiveness, with N-Gain scores of 0.89, 0.86, and 0.78, respectively. This attainment stands in stark contrast to the control group, which solely recorded an N-Gain of 0.51 (classified as “Moderate”). This substantial mean disparity serves as an empirical indicator that integrating the Blended Learning approach with the GENIUS syntax is highly robust in elevating students’ science literacy. The magnitude of this cognitive escalation is directly attributable to the simulation’s interactive architecture, which visually translates abstract bioprocesses into manipulable digital elements. By systematically modifying experimental variables within the structured GENIUS framework, learners engage in authentic scientific inquiry rather than passively receiving knowledge. This immersive digital environment compels students to continuously evaluate empirical evidence, interpret real-time data, and construct logical scientific arguments based on the Ingenhousz model. Consequently, such rigorous analytical practice consistently sharpens the fundamental pillars of science literacy, thereby explaining the substantial effectiveness gap relative to traditional instructional methods.

Table 8. Normality Test of Science Literacy Research Data

Type of learning	Kolmogorov-Smirnov[a]		
	Statistic	df	Sig.
Pre-test Replication 1	0.048	34	0.200*
Post-test Replication 1	0.135	34	0.124
Pre-test Replication 2	0.050	34	0.200*
Post-test Replication 2	0.084	34	0.200*
Pre-test Replication 3	0.076	34	0.200*
Post-test Replication 3	0.117	34	0.200*
Pre-test Control	0.071	34	0.200*
Post-test Control	0.062	34	0.200*

Description: df: Degree of freedom; Sig.: Significance; * This is a lower bound of the true significance

The sharp escalation in science literacy stems from the cognitive demands embedded within the virtual replication environment. Rather than memorizing factual information, students are trained to apply scientific knowledge to investigate complex biological processes systematically. Interaction with the Ingenhousz Virtual Laboratory modeling facilitates students’ observation of fluctuations in photosynthesis rate indicator data as they manipulate independent variables. The processes of autonomously recording data, comparing evidence, and formulating scientific explanations serve as the primary catalysts for developing their science literacy competencies to an optimal level. Ultimately, these systematic exploratory activities sharpen critical thinking and data-driven argumentation, which are the fundamental pillars of the science literacy domain. Innovative learning models that actively involve students in scientific investigation and problem-solving are essential for developing these critical 21st-century skills. Consequently, this technological integration transforms students' roles from mere passive consumers of information to active, independent scientific investigators, fulfilling the core objectives of modern education.

The normality test was conducted to ensure that the data met the requirements for parametric inferential analysis. All significance values (Sig.) presented in Table 8 demonstrate figures greater than 0.05 (with significance ranging between 0.124 and 0.200). Based on these values, the null hypothesis is accepted, indicating that the distribution of science literacy scores in both the replication and control classes meets the assumption of normality. This statistical compliance guarantees that the datasets are free from severe skewness, thereby preventing biased analytical outcomes. Consequently, it provides a robust methodological foundation for proceeding with further parametric evaluations.

Subsequently, to ascertain that the research samples originated from populations with equal variability, a homogeneity of variance test was conducted using Levene's analysis (Levene's Test). The test results indicate a significance value of 0.980 for the pre-test data and 0.181 for the post-test data. Given that both values are consistently well above the 0.05 threshold, the variances among the research groups are equal (homogeneous), thereby satisfying all assumptions for parametric analysis. This uniform variability confirms that the sample cohorts possess highly comparable dispersion characteristics throughout the experimental phases. Consequently, the statistical model can accurately evaluate the treatment's true effect without being compromised by heterogeneous data spreads. The findings from this homogeneity test on the science literacy data are displayed in Table 9.

Table 9. Homogeneity Test of Research Data on Science Literacy

		Levene Statistic	df1	df2	Sig.
Science Literacy Pre-test	Based on Mean	0.062	3	132	0.980
Science Literacy Post-test	Based on Mean	1.649	3	132	0.181

Description: df1: Degree of freedom of the numerator; df2: Degree of freedom of the denominator; Sig: Significance

Having passed the normality and homogeneity prerequisite tests, the subsequent stage involved hypothesis testing for the science literacy variable using Analysis of Covariance (ANCOVA). This test was applied to determine the significant effect of the treatment on students' science literacy while controlling for the covariate, namely, students' initial ability (pre-test) scores. By mathematically integrating these baseline scores as a covariate, the analytical model effectively isolates the variance directly attributable to the GENIUS-integrated virtual laboratory. This rigorous statistical adjustment ensures that the measured cognitive escalation is genuinely attributable to the applied instructional treatment rather than to pre-existing literacy disparities. The ANCOVA test results for science literacy are presented in Table 10.

Table 10. ANCOVA Test of Science Literacy (Tests of Between-Subjects Effects)

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	8822.380a	4	2205.595	134.873	0.000
Intercept	28183.753	1	28183.753	1723.447	0.000
NilaiPre (Covariate)	479.769	1	479.769	29.338	0.000
KelasPost (Group)	8106.533	3	2702.178	165.239	0.000
Error	2142.260	131	16.353		
Total	1039131.000	136			
Corrected Total	10964.640	135			

Description: a R Squared = .805 (Adjusted R Squared = .799); Dependent Variable: Posttest Science Literacy

Based on Table 10, the ANCOVA test results for the inter-class treatment factor (Group) yield a calculated F-value of 165.239 with a significance of 0.000 ($p < 0.05$). This significance value, well below the standard 0.05 alpha threshold, indicates that the Blended Learning treatment using the GENIUS syntax integrated with the

Ingenhousz Virtual Laboratory has a highly significant effect on enhancing students' science literacy. This exceptionally large calculated F-value demonstrates that the applied learning model provides a dominant contribution to the variation in students' final scores. Furthermore, because the ANCOVA model rigorously controls for students' initial abilities as a covariate, this statistical result decisively confirms that the observed cognitive escalation is attributable to the applied instructional treatment rather than to any pre-existing literacy disparities.

While the covariance analysis successfully validates the overarching main effect of the intervention, it does not identify the specific nature of the variance among the tested cohorts. Therefore, to more precisely map the locations of differences in science literacy effectiveness among the groups, the Least Significant Difference (LSD) post hoc test was subsequently conducted. This pairwise comparison test assesses whether the three experimental classes (with parallel replications) exhibit equal instructional robustness in improving students' science literacy relative to the conventional control class. Executing this analytical step is a crucial methodological requirement to ensure that the intervention's success is uniformly distributed across multiple classroom dynamics rather than being merely an isolated anomaly. By systematically evaluating the mean differences between all possible pairs of cohorts, the LSD analysis provides a highly granular view of instructional consistency. This rigorous statistical verification confirms that the observed cognitive escalation is inherently driven by the GENIUS-integrated virtual learning ecosystem itself, thereby establishing its ultimate reliability across diverse sample groups. A summary of the detailed LSD test results, which explicitly delineates these precise pairwise comparisons, is presented in Table 11.

Table 11. LSD (Least Significant Difference) Test of Science Literacy

Class	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
Control	74.65a	0.794	73.03	76.26
Replication 3	85.76b	0.875	83.99	87.54
Replication 2	92.76c	0.792	91.15	94.38
Replication 1	94.62c	0.560	93.48	95.76

Description: The superscript letters (a, b, c) indicate significant differences based on the LSD test ($p < 0.05$). Means sharing the same letter are not significantly different from each other.

A similarly highly significant impact is also evident in the students' science literacy skills data. The LSD test results presented in Table 11 indicate that the conventional learning approach yielded the lowest achievement, with an average score of merely 74.65 (subset a). Conversely, all three replication classes that used the Ingenhousz Virtual Laboratory demonstrated a significant increase in science literacy. Replication 1, Replication 2, and Replication 3 achieved remarkably equivalent high effectiveness, collectively forming a distinct and superior subset (subset b) with average scores of 94.62, 92.76, and 85.76, respectively. The shared superscript letter across the replication classes indicates that there is no significant difference between them.

This substantial disparity confirms that the GENIUS syntax within the Virtual Laboratory environment is highly effective as an instructional instrument for science literacy. The uniform outperformance of all three replication classes over the control group robustly proves that the intervention's success is highly consistent and not coincidental. The digital investigation process, wherein students autonomously manipulate independent variables such as light intensity and CO_2 concentration to observe the resulting oxygen bubbles, fundamentally transforms them into active scientific investigators. This structured digital exploration and hands-on practice provide a broader cognitive space for students to identify scientific issues, systematically analyze data, and draw evidence-based conclusions, thereby achieving science literacy competencies that far exceed those attained in teacher-centered conventional classrooms.

Based on the frequency and percentage distributions presented in Table 12, there is a stark contrast in final cognitive achievement between the experimental and control groups. In terms of conceptual understanding, the entire student population across the three replication classes successfully reached the "Very High" and "High" categories, with Replication 1 dominating the "Very High" tier at 67.65%. Conversely, a significant portion of the control group (38.24%) stagnated in the "Moderate" category. A parallel yet more pronounced trend is observed in science literacy outcomes. The intervention classes demonstrated exceptional performance, particularly Replication 1, where 100% of the students achieved the "Very High" category. In direct contrast, none of the students in the control group reached the "Very High" level for science literacy, with the majority (55.88%) remaining in the "Moderate" category. This distribution definitively illustrates that the GENIUS-integrated Virtual Laboratory effectively shifts the student population towards the highest cognitive and literacy tiers compared to conventional instructional methods.

Table 12. Frequency and Percentage Distribution of Conceptual Understanding and Science Literacy

Variable	Category	Interval	Replication 1		Replication 2		Replication 3		Control	
			F	%	F	%	F	%	F	%
Conceptual Understanding	Very High	86 - 100	23	67.65	18	52.94	17	50.00	1	2.94
	High	76 - 85	11	32.35	16	47.06	17	50.00	20	58.82
	Moderate	60 - 75	0	0.00	0	0.00	0	0.00	13	38.24
	Low	55 - 59	0	0.00	0	0.00	0	0.00	0	0.00
	Very Low	54	0	0.00	0	0.00	0	0.00	0	0.00
Science Literacy	Very High	86 - 100	34	100.00	32	94.12	18	52.94	0	0.00
	High	76 - 85	0	0.00	2	5.88	14	41.18	15	44.12
	Moderate	60 - 75	0	0.00	0	0.00	2	5.88	19	55.88
	Low	55 - 59	0	0.00	0	0.00	0	0.00	0	0.00
	Very Low	54	0	0.00	0	0.00	0	0.00	0	0.00

Description: F = Frequency (Number of Students); % = Percentage. Category Intervals are based on Diana *et al*. (2015).

DISCUSSION

The Effect of GENIUS Integrated Virtual Laboratory on Conceptual Understanding

Results of descriptive analysis indicate that during the pre-test phase, conceptual understanding scores across all groups were at a relatively equivalent, suboptimal level. In the post-test phase, all groups showed an increase in their average scores compared to the pre-test. Replication 1 achieved the highest average conceptual score, followed closely by Replications 2 and 3, with the control group having the lowest average. Inferential analysis further revealed that the implementation of the GENIUS-integrated Virtual Laboratory had a highly significant effect on students' conceptual understanding. The LSD post hoc test indicated that there were no significant differences among Replications 1, 2, and 3. However, all three replication classes differed significantly from the control group.

Learners engaging with the Ingenhousz Virtual Laboratory across the three parallel replications demonstrated a profound cognitive escalation, securing "High" N-Gain categories. In direct contrast, the conventional learning cohort stagnated within the "Moderate" effectiveness threshold. This stark disparity confirms that integrating structured ICT-based constructivist models provides a far superior scaffolding for complex biological concepts compared to traditional methodologies (Adnan et al., 2014; Hikmah et al., 2026; Ismayani et al., 2023).

The descriptive surges were mathematically validated through rigorous inferential testing. Following confirmation of data normality and homogeneity of variance, Analysis of Covariance (ANCOVA) yielded exceptionally high F-values with significance levels of 0.000 for both measured variables. This outcome definitively rejects the null hypothesis, isolating the instructional intervention as the primary catalyst for the observed cognitive variations. The implementation of structured, inquiry-based virtual laboratories consistently demonstrates the ability to elevate learning achievement and intrinsic motivation beyond the limits of physical classroom constraints (Adnan et al., 2014; Chen et al., 2026; Kusmawan, 2022).

To precisely map the intervention's impact, Least Significant Difference (LSD) analyses identified the replication cohorts as a distinct, high-performing statistical subset, separate from the control group. The lack of statistically significant differences among the experimental groups can be explained by the fact that all three parallel classes applied the same learning stages and uniform virtual materials. Executing identical GENIUS syntax stages within a blended learning environment across different classroom dynamics yields uniformly optimal outcomes. This demonstrates that the digital intervention's success relies on its systematic design rather than isolated classroom anomalies (Al-Nakhle, 2022; Khatimah et al., 2026; Muis & Bahri, 2018).

The mechanism driving this conceptual acceleration lies in the simulation's interactive architecture. Abstract biochemical principles governing photosynthesis, which typically induce heavy cognitive loads, are visually deconstructed into tangible, manipulable elements (Jančaříková & Jančařík, 2022). Learners exercise complete autonomy in calibrating light proximity, modifying thermal conditions via intuitive mechanics, and regulating sodium bicarbonate concentrations. This process can be explained through a constructivist perspective, which emphasizes that knowledge is actively constructed through direct interaction with scientific variables. When students manipulate these virtual parameters in the Ingenhousz modeling, cognitive conflict arises, prompting them to reorganize their prior knowledge into more scientifically accurate concepts. Immediate visual feedback from these manipulations directly mitigates the abstract nature of plant physiology. Digital platforms designed as interactive learning resources enable students to assimilate new biological knowledge into their existing cognitive frameworks seamlessly (Jufri et al., 2026; Xian et al., 2026).

The Effect of GENIUS-Integrated Virtual Laboratory on Science Literacy

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physiology. Digital platforms designed as interactive learning resources enable students to assimilate new biological knowledge into their existing cognitive frameworks seamlessly (Jufri et al., 2026; Xian et al., 2026).

CONCLUSION

Based on the empirical findings, this study concludes that integrating the Ingenhousz Experiment Virtual Laboratory with the GENIUS syntax within a Blended Learning framework is highly effective in enhancing students' conceptual understanding and science literacy regarding photosynthesis. The experimental cohorts consistently achieved a "High" N-Gain category, significantly outperforming the conventional learning group. Rigorous parametric evaluations using ANCOVA and Least Significant Difference post hoc tests confirmed that this digital instructional intervention yields a highly significant and uniform cognitive escalation across multiple parallel replications, demonstrating that the pedagogical success is a consistent statistical reality. The fundamental catalyst for this improvement lies in the interactive architecture of the digital simulation, which effectively deconstructs abstract physiological bioprocesses into tangible, manipulable elements. By guiding students to modify independent variables autonomously, the structured GENIUS environment successfully transforms learners into active scientific investigators who continuously evaluate empirical evidence and construct logical arguments. Ultimately, this technological synergy resolves the chronic constraints of limited physical laboratory access and establishes a highly scalable instructional standard for fostering critical scientific competencies.

The novelty of this research lies in the specific synergistic framework that integrates the GENIUS constructivist syntax directly with interactive biological simulations, an approach previously underexplored in high school demographics. Theoretically, this study contributes to the constructivist learning paradigm by demonstrating that active digital manipulation of physiological variables effectively bridges the cognitive gap between abstract biological theories and applied scientific reasoning. Pedagogically, these findings suggest that educators can reliably use this integrated virtual laboratory as a scalable alternative to address the limitations of physical facilities, equipment shortages, and time constraints in science education. However, this study acknowledges several limitations, primarily its restricted scope to a single biological topic (photosynthesis) and a specific geographical demographic at SMA Negeri 3 Makassar. Therefore, future research is highly recommended to expand the implementation of this instructional model across a broader range of complex science topics and more diverse student populations to establish its generalizability comprehensively.

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