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Digital application of science literacy measurement tools: Implementation of deep learning in shaping student sustainability literacy

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ABSTRACT

Sustainability literacy is a crucial topic because it supports the achievement of Sustainable Development Goals (SDGs). However, it is often not a priority for prospective elementary school teachers, who tend to understand this concept primarily from a theoretical perspective. This study aims to assist students in bridging the gap between theory and real-world practice through the implementation of a digital-based Science Literacy Measurement Tool supported by a deep learning approach. The research employs a quantitative method, utilizing a quasi-experimental design with a non-equivalent control group. The study involves 65 students from the Elementary School Teacher Education Study Program at Universitas Esa Unggul, selected through purposive sampling techniques. Data collection utilized a sustainability literacy questionnaire, supplemented with student responses, to illustrate the results of the sustainability literacy scale analysis and to categorize students accordingly. The results indicate that the Science Literacy Measurement Tool, which employs deep learning techniques, significantly aided students in enhancing their understanding of sustainability. Approximately one-third of the students demonstrated leadership in sustainability initiatives. These findings suggest that deep-learning digital tools can help students learn more about science and encourage them to take on leadership roles, thereby creating more opportunities in sustainability education. The implication is that integrating deep learning into science instruction could strengthen students' critical thinking, ecological awareness, and sense of responsibility for the environment. This learning model is worthy of consideration for wider implementation in schools, as it can help shape a more environmentally conscious generation.

Contribution/Originality: Incorporating deep learning into the Digital Science Literacy Measurement Tool has enhanced students' learning experiences. This approach has helped students connect scientific concepts to real-life situations, thereby facilitating a better understanding of sustainability-related issues. Additionally, it has encouraged students to take responsibility and become more actively involved in learning about sustainability.

1. INTRODUCTION

These efforts are important because global social, economic, and environmental challenges have made Education for Sustainable Development (ESD) a priority. As a result, universities are now training future teachers in different aspects of sustainability and how to teach it (Fischer et al., 2022). To help improve students' understanding of sustainability, Universitas Esa Unggul started the Elementary School Teacher Education Study Program. Elementary teachers play a key role in helping children develop positive attitudes and behaviors toward sustainability. For sustainable development practices to succeed, teachers need to remain engaged and incorporate sustainability principles into their lessons (Ferguson, Roofe, & Cook, 2021).

Sustainability literacy is a key part of teacher training and covers social, economic, and environmental concerns, skills, and attitudes (Adam, Permanasari, & Hamidah, 2021). Elementary teachers are expected to incorporate sustainability principles into every subject they teach. However, there is growing concern about how quickly and effectively this is happening in elementary education. Many assessment tools are considered inadequate (Elster, 2022). Most tools describe framework elements but do not focus much on practical use; technology is rarely utilized, and there are clear gaps in how students' sustainability literacy is assessed as they prepare to become teachers.

To assess how well students understand and utilize scientific concepts, the Science Literacy Measurement Tool was employed to identify and address issues in science education (Son & Ha, 2025). This tool makes it easier to assess students' technology and science skills and helps teachers use more engaging teaching methods (Hung & Wu, 2024). It uses fast computer programs that can learn and advanced methods for analyzing data (Qiao, Chen, Guo, & Yu, 2024).

The use of deep learning in higher education instructional design serves as a means to assess and enhance students' sustainability literacy, promoting more adaptive, interactive, and data-informed instructional and assessment practices (Li & Liu, 2021). Deep learning technologies in higher education play a crucial role in evaluating and enhancing students' sustainability literacy. These technologies complement student-centered strategies by offering formative assessments tailored to measure critical thinking, creativity, problem-solving skills, and the application of scientific principles in sustainability (Al Ka'bi, 2023). Moreover, deep learning goes beyond assessing achievement across various dimensions of scientific literacy by also calculating the remaining deficits and gaps in sustainability literacy (Shen & Chang, 2023). Thus, it performs the dual functions of a technology and a pedagogy for the fusion of scientific literacy and the principles of sustainability.

The Adaptation of the Science Literacy Measurement Tool has excellent potential for developing sustainability literacy among students, especially future elementary school teachers (Almasri, 2024). Students will understand and internalize sustainability literacy, encompassing environmental, social, and economic aspects, as well as a deep understanding of scientific principles (Chen & Techawitthayachinda, 2021). The tool encourages students to apply scientific knowledge to key sustainability principles (Valladares, 2021). The Science Literacy Measurement Tool serves as both an assessment and a bridge between sustainability literacy and effective teaching methods (Ke, Sadler, Zangori, & Friedrichsen, 2021).

According to Fortus, Lin, Neumann, and Sadler (2022), along with helping students understand the parts of sustainability, science literacy includes key skills. These include comprehension of a topic, information evaluation, problem-solving, and arriving at reasoned conclusions (Syofyan, Fadli, & Pappachan, 2025). For instance, students who are scientifically literate are able to articulate the interconnections between science and sustainability problems. Such outcomes are hallmarks of constructive learning (Osborne, 2023). A deeper understanding of scientific literacy also helps reveal students' skill levels and their connection to building sustainability literacy.

Previous research (Coppi, Fialho, & Cid, 2023; Effendi et al., 2021) indicates that current scientific literacy assessments are inadequate substitutes for evaluating sustainability literacy. Many existing tools lack innovation, are difficult to implement widely, and do not meet current pedagogical standards. There has been limited exploration into the intersection of scientific literacy and sustainability literacy, leaving this area under-researched. Pre-service teachers require tools that effectively demonstrate the practical application of scientific concepts and principles in everyday life challenges. The digital Science Literacy Assessment Tool enhances students' critical thinking skills at the evaluation, interpretation, and reflection levels by teaching sustainability principles and practices. As future primary educators, these students will be better prepared to teach sustainability and its applications within primary education, fostering a more environmentally conscious generation (Afnan, Munasir, Budiyanto, & Aulia, 2023). These tools provide assessment and learning opportunities, prompting students to understand the nexus of science and sustainability concepts. Student teachers need tools that demonstrate the applicability of scientific concepts to everyday practical problems. The digital-based Science Literacy Assessment Tool teaches important critical thinking skills as students evaluate, interpret, and reflect on sustainability. This tool teaches students the principles of sustainability and how they will be applied in future primary education.

The integration of scientific and sustainability literacy within the ESD framework is crucial to equip prospective teachers with adequate knowledge, as well as the right values and attitudes towards social and environmental stewardship (Fadli, Mujazi, Syofyan, & Rosyid, 2024; Lobo, 2025). Adding the Digital Scientific Literacy Measurement Tool is regarded as an innovative teaching method that helps improve assessments and supports students' higher-level thinking and problem-solving skills in real-world sustainability issues.

This research aims to clarify how the Digital Science Literacy Measurement Tool, which uses deep learning, enhances sustainability literacy. It seeks to assess the effectiveness of this digital tool in improving students' sustainability literacy within the Elementary School Teacher Education Program at Universitas Esa Unggul in Indonesia. The study also aims to develop a clearly defined rubric that evaluates the level of scientific literacy a student possesses while fostering active, critical, and reflective thinking processes in addressing sustainability issues. Additionally, the goal is to create an unambiguous rubric that assesses students' scientific literacy levels while promoting active, critical, and reflective thought regarding sustainability challenges. Serving both as an assessment method and a teaching aid for sustainability topics, the tool prepares future elementary teachers to effectively understand and apply Education for Sustainable Development (ESD) in their classrooms.

2. LITERATURE REVIEW

2.1. Deep Learning in Higher Education

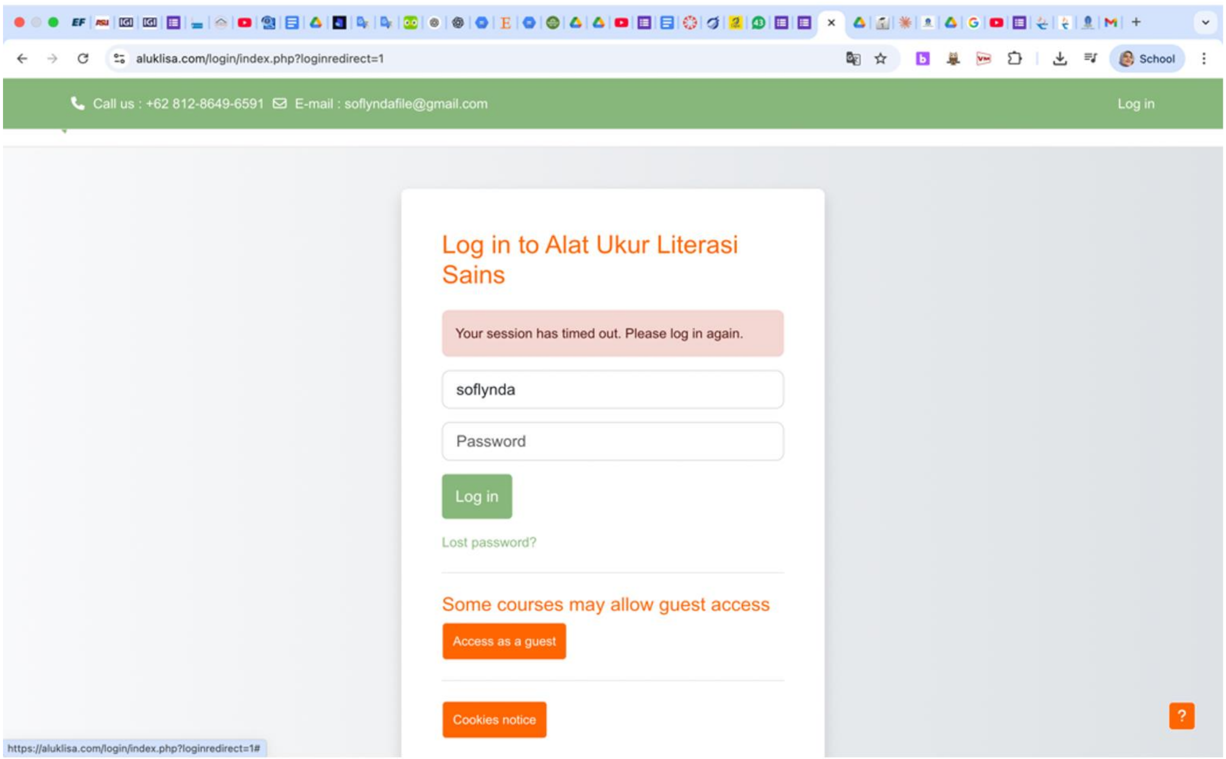
An example of immersive learning in higher education includes not only its mechanized approaches to AI but also its pedagogical skills that foster proactivity in students in grasping, integrating, and schemaizing new information through more purposeful and practical methods. Aguiar-Castillo, Clavijo-Rodriguez, Hernández-López, De Saa-Pérez, and Pérez-Jiménez (2021) note, 'immersive learning means going out of the gilt cage of rote memorization to the world of deep understanding and meaning making, where one seeks to learn, grasp, and build linkages of ideas and weave them into one's tapestry of life. Alshamaila et al. (2024) explain that immersive learning helps shape knowledge construction and critical reflection, where students address problems that matter in real life and contemporary contexts through the application of higher-order thinking skills. The purpose of engaging students in higher education with immersive learning activities is to produce individuals who are not only equipped with technical knowledge but also appreciate the importance of analysis and practical approaches to tackling real-world problems, such as those related to environmental sustainability. The immersive learning approach aims to foster both practical skills and strong analytical abilities.

Deep learning promotes the Mindful, Meaningful, and Joyful (MMJ) paradigm (Meng, 2022; Triwiyanto et al., 2023) with a focus on fulfilling the educational goals of the 21st century in Indonesia. The mindful learning approach is comprehensive, encompassing the entire process of receiving information, understanding, reflecting, and relating to real-life situations. The Meaningful pillar emphasizes the depth of learning, where learners engage actively with content and experiences that are relevant, useful, and purposeful, thereby fostering greater engagement. The Joyful pillar aims to create learning environments that are enjoyable, responsive, and conducive to self-initiated, stress-free, and relaxed inquiry and learning. Such environments support intrinsic motivation among students. Collectively, these three pillars encourage learners to experience transformative learning, develop critical thinking skills, and adopt constructive approaches that promote sustainability literacy (Matsuo et al., 2022; Sankaran et al., 2024).

Deep learning aligns with the goals of Education for Sustainable Development, focusing on fostering sustainability literacy (Boman, Omrcen, Weldemariam, Hanning, & Lodin, 2025; Zhu et al., 2021). Engaging with the ideas of deep learning is not about simply memorizing content; it is about grappling with ideas, probing, reflecting, and applying what is learned to the actual world. Learning, as a deep process, encompasses the multiplicity of relationships with science and sustainability, provokes thinking about their interplay, and permits the use of what is known to solve real-world problems. Learning in this way, with the pleasure derived from it, encourages the cultivation of deep awareness and socially responsible action to foster positive social and ecological change and promote sustainable development. The euphoria of lacking all of these elements would still ensure that the most valuable definition of deep learning in higher education rests on the development of educational literacy for sustainability as the most important outcome.

2.2. Digital Application of Scientific Literacy Measurement Tools

The Digital Science Literacy Measurement Tool is a state-of-the-art assessment designed to evaluate students' competencies comprehensively across the three principal domains of learning: cognitive, affective, and psychomotor (Kijkuakul & Bongkotphet, 2024). Cognitive focus is on understanding science as a field and the relationship of individuals to reasoning, critical thinking, and scientific problem solving. Affective aspects are concerned with learners' feelings, attitudes, and emotions, as well as the importance and appreciation of science and its contribution to sustainability (Asiyah, Febrini, Topano, Mustamin, & Hakim, 2024). Psychomotor is the use of theory and practical skills in the field of science that involves experimenting, carrying out simulations, and tackling a range of other projects (Asiyah et al., 2024). Psychomotor is the use of theory and practical skills in the field of science that involves experimenting, carrying out simulations, and tackling a range of other projects (Masfuah, Fakhriyah, Wilujeng, & Rosana, 2021). Digital Science Literacy Measurement Tool evaluates students' integrated science learning, extending beyond mere knowledge to encompass attitudes and skills.



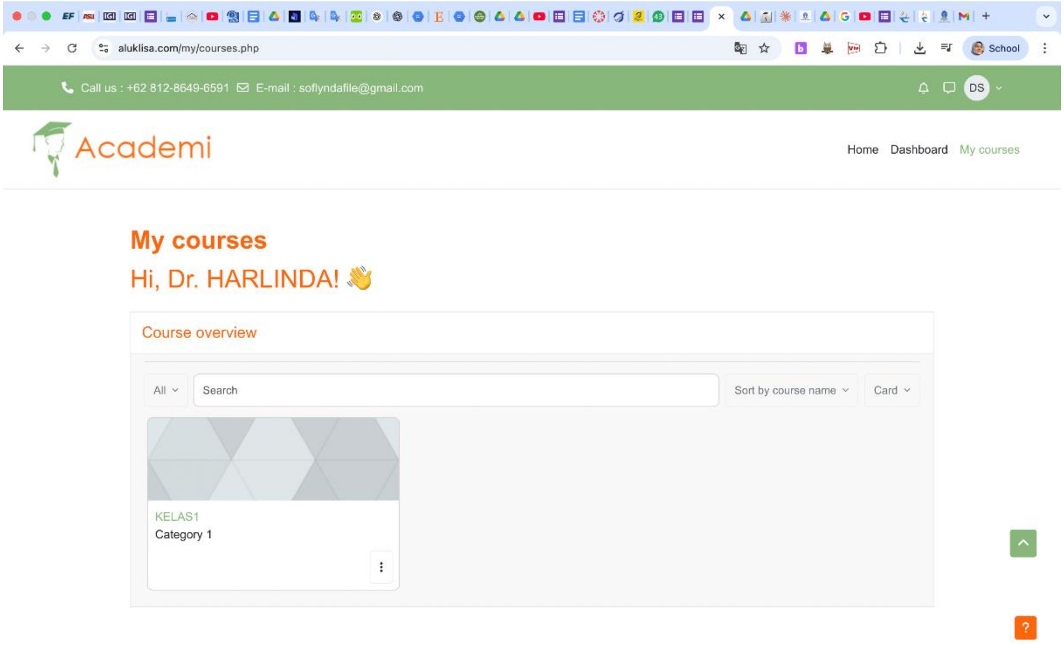


Figure 1. Digital application of science literacy measurement tools.

Figure 1 illustrates the Digital Application of Scientific Literacy Measurement Tools, a deep learning-based educational app designed to help students understand scientific concepts more thoroughly. Through interactive features, data-driven reflection, and contextual learning scenarios, this app not only assesses scientific literacy skills but also promotes sustainability literacy, which encompasses students' understanding and awareness of sustainability issues. This application functions both as a learning tool and an environmental character enhancer, encouraging students to comprehend scientific principles and actively participate in sustainability efforts in real life (https://aluklisa.com/).

The Interactive Scientific Literacy Measurement Tool creatively integrates assessment within the learning process. It incorporates assessment as a means of learning, and each evaluative document aims to serve as a meaningful learning activity for learners (Liu et al., 2024). The Interactive Scientific Literacy Measurement Tool creatively integrates assessment within the learning process. It incorporates assessment as a means of learning, and each evaluative document aims to serve as a meaningful learning activity for learners (Istyadji & Sauqina, 2023; Zhang, Liu, & Feng, 2023). Other forms of assessment included in the tool are adaptive quizzes, self-assessments, digital portfolios, and projects aimed at sustainability. Adopting this multi-faceted approach, the tool not only develops students' scientific literacy but also enhances their sustainability literacy, preparing them as educators to address the challenges of the 21st century. The Digital Science Literacy Measurement Tool application fosters students' reflective understanding of feedback in relation to their different assessment activities. While not fully developed, this application has helped students improve their scientific literacy as well as their understanding and competence in sustainability, which they can draw on as future educators.

2.3. Sustainability Literacy

Sustainability involves integrating knowledge in a rational and practical manner, transforming it into skills, attitudes, and values that enable individuals to identify and responsibly address issues related to sustainability in their daily activities. This approach encourages taking decisive actions concerning environmental, social, and economic challenges. (Ika Sari, Winasis, Pratiwi, Wildan, & Basrowi, 2024). Zizka and Varga (2021) emphasize that the foundation of sustainability lies in the philosophy of Education for Sustainable Development (ESD). ESD fosters understanding and engagement with the principles of sustainability across three interconnected dimensions: environmental, social, and economic. Similarly, Leiva-Brondo, Lajara-Camilleri, Vidal-Meló, Atarés, and Lull (2022) note that sustainability literacy encompasses behavioral change and the outcomes associated with adopting sustainable practices. Therefore, proponents argue that developing sustainability literacy in higher education is crucial, as students are viewed as change agents capable of addressing societal and environmental issues.

The enhancement of literacy on sustainability in higher education focuses on creative achievement of learning outcomes through technology. Sihombing, Rochintaniawati, Agustin, Muslim, and Rahman (2025) state that in sustainability literacy assessment, reflective, contextual, and knowledge application in real-life scenarios assessment is crucial. Incorporating deep learning theory means more freedom in assessment and higher potential cognitive complexity. In contrast, technology serves the aims of psychosocial development assessment theory, providing an overview summary of mental, affective, and psychomotor domains (Shidiq et al., 2025). Within a multidisciplinary framework focused on literacy and sustainability in the 21st century, the intersection of deep learning, technology aimed at science literacy, and sustainability literacy offers an integrated, strategic, and holistic approach. Combining deep learning with a technology-enhanced Science Literacy Measurement Tool results in an assessment that is more reflective, contextual, and application-based, thereby facilitating a deeper development of sustainability literacy. This approach enables universities to prepare teachers who are not only capable of explaining the principles of sustainability but also of applying them in teaching practice.

3. METHODOLOGY

3.1. Research Design Method

Together with evaluating the effectiveness of an intervention, this study also adopted a quantitative approach aimed at the acceptance of limitations arising from the inability to control extraneous variables during the study. These limitations having been described within a quasi-experimental framework (Johnson & Christensen, 2022; Teo, 2013). The designed used was that of a non-equivalent control group design comprising of two classes; one experimental class, which used digital applications as tools for assessment and learning, and one control class which used conventional learning method (Balnaves & Caputi, 2018). The two groups of data suggest that deep learning-based digital applications can improve the level of scientific literacy and deepen the sustainability literacy of students who are being trained to become elementary school teachers. The subsequent table delineates the phase of the research and its detailed implementation.

Table 1. Quantitative research design.

Class	Pretest	Treatment	Posttest
Experiment	E1	X	E2
Control	E1	-	E2

As presented in Table 1, the participants were classified into an experimental group and a control group. The members of the experimental group received an intervention using the Digital Application of the Science Literacy Measurement Tool, which serves as both an assessment and a learning instrument. The control group, on the other hand, continued learning through conventional methods without the use of digital tools. Both groups participated in a pretest (E1) as the initial phase, which assessed their level before any intervention (X), followed by a posttest (E2) in the second phase, where their learning achievements were evaluated. The courses, Science Learning and Basic Science Concepts, were predetermined based on their relevance to scientific literacy and their importance in enhancing prospective elementary teachers' sustainability literacy.

3.2. Population and Sample Characteristics

The students selected for this study were enrolled in the Elementary School Teacher Education Study Program at the Faculty of Teacher Training and Education at Universitas Esa Unggul. A purposive sampling technique was employed to select a sample of 65 students from this population. This technique specifically targets participants who meet the criteria aligned with the study's objectives and relevance. These students are particularly significant because they are future teachers at the elementary school level and Natural Science educators. At this level, teachers need to go beyond basic scientific literacy concepts to achieve mastery in sustainability literacy. This enables them to effectively pass on values, attitudes, and skills related to sustainability to their young learners. The focus on this specific group underscores the importance of scientific and sustainability literacy within the educational system at the elementary level, highlighting the critical role these future teachers will play in fostering sustainable development from an early age.

3.3. Data Collection Implementation Procedures

Students' achievement of learning outcomes from the implemented activities was assessed through the use of interviews and questionnaires administered as pre-tests and post-tests. The primary instrument of interest was a questionnaire based on a 5-point Likert scale, which was developed from existing literature and subsequently tailored through a literature review to ensure relevance and reliability within the context of the study (Fahmi, Chalisah, Istyadji, Irhasyuarna, & Kusasi, 2022; Schwartz, Lederman, & Enderle, 2023; Suwono, Maulidia, Saefi, Kusairi, & Yuenyong, 2022) concerning the integration of deep learning to enhance students' sustainability literacy through the Digital Application of Science Literacy Measurement Tools. The questionnaire consisted of 15 items and was translated into simple English to ensure that students could easily understand its intent while measuring respondents' attitudes, comprehension skills, and sustainability literacy skills. The use of Google Forms was anticipated to improve accuracy, broaden sample representation, and increase response rates. The data obtained are likely to reflect students' progress in sustainability literacy to some extent. All respondents were guided and instructed to use a rigorous set of instructions, which required them to utilize a Likert scale to select the response that best described the scenario. Response options ranged from "strongly agree" to "strongly disagree," including "agree," "neutral," and "disagree."

The instrument for data collection is developed in relation to the core dimensions of sustainability literacy and is centered on four constituent elements.

1. Conceptual awareness of sustainability issues focuses on students' understanding of the interrelationships between sustainability challenges and scientific phenomena.
2. Personal identity and values aligned with sustainability examine the extent to which students' attitudes and value systems are sustainability-oriented.
3. Competence in sustainability skills is an indicator that assesses students' capacity to evaluate and formulate scientifically sound and socially actionable problem-solving strategies.
4. Confidence in contributing to sustainability is an indicator that assesses students' perception of their capacity to solve sustainability problems and their intention to make effortful positive changes.

These four aspects, developed in the form of a research instrument grid, serve as the foundation for the indicators that have been created. They are designed to systematically gather valid and relevant data regarding students' levels of sustainability literacy. The following table illustrates the constructed instrument grid, providing a clear overview of the assessment framework (Aikowe & Mazancova, 2023; Örs, 2022).

Table 2 illustrates four key aspects of sustainability literacy: understanding sustainability concepts, personal values, analytical and problem-solving skills, and confidence in contributing to environmental solutions. These indicators provide a strong foundation: sustainability literacy is not just about knowing concepts; it also involves attitudes, skills, and readiness to act.

Table 2. Sustainability literacy research instruments.

Sustainability literacy aspects	Indicator
Conceptual awareness of sustainability issues	- Understand the relationship between sustainability issues and scientific concepts (ecology, energy, chemistry, physics). - Analyze sustainability issues supported by digital data (deep learning).
Personal identity and values aligned with sustainability	- Reflect on personal values aligned with sustainability principles. - Demonstrate commitment to acting based on scientific learning outcomes and digital feedback.
Competence in sustainability skills	- Analyze social and environmental impacts using a scientific literacy approach. - Design creative solutions and test them through digital simulations.
Confidence in contributing to sustainability	- Confidence in solving sustainability issues based on scientific foundations. - Confidence in one's ability to drive change through learning analytics-based monitoring.

3.4. Data Analysis Framework

Multiple statistical methods were employed in this study, including independent samples t-tests and calculations of N-gains, to evaluate changes in students' sustainability literacy after utilizing the deep learning-based Digital Application of the Science Literacy Measurement Tool. Learning outcomes were based on the pre- and post-test results of both the experimental and control groups. Assumption tests based on definitions were conducted prior to hypothesis testing to assess whether the data conformed to the framework for parametric sample analyses. These steps included tests for normality and homogeneity of variances. The Kolmogorov-Smirnov test was used to determine whether a data set was normally distributed, with a significance level of $p > .05$. Levene's Test, conducted through One-Way ANOVA, was used to assess the homogeneity of variances, also with $p > .05$ as the criterion. The overall results of these preliminary tests supported the analytical criteria and provided a rational basis for the hypothesis testing framework. All procedures adhered to a supportable and defendable rationale, ensuring the validity of the study outcomes.

The results of this research were analyzed using SPSS version 29 to ensure consistency and precision in the findings. Meaningful differences between the means of the experimental and control groups were assessed using independent samples t-test analyses, with $p < 0.05$ as the threshold for significance. The N-gain value determined the level of students' literacy in sustainability and categorized them as high ($g > 0.7$), moderate ($0.3 \leq g \leq 0.7$), and low ($g < 0.3$). This evidence demonstrates the extent to which the use of digital tools fosters students' scientific and sustainability literacy. This study also employed the Sustainability Literacy Scale to go beyond the analysis, including not only the cognitive dimension but also the sustaining attitude and awareness of the examined phenomena. The sustainability literacy scale used in this research is outlined below (Kuehl, Sparks, Hodges, & Smith, 2021).

Table 3. Research sustainability literacy scale.

Scale	Categorization	Criteria (% of correct answers in each category)
1	Non-awareness of environment and social impact	0 – 25%
2	Awareness of the environment and social impact	26 – 50%
3	Responsibility	51 – 75%
4	Taking on a leadership role for sustainability	76 – 100%

Table 3 presents a sustainability literacy assessment scale that groups students by their level of understanding, ranging from unawareness of environmental impacts to leadership on sustainability issues. This assessment scale can help determine student categories based on the percentage of correct answers at each proficiency level. The literacy table indicates individuals' types of awareness and their corresponding responsibilities within the identified socioenvironmental areas. Ozdemir (2021) states that a score of 0-25% reflects a state of non-awareness, while 26-50% suggests that an individual is aware but does not take action. A score of 51-75% indicates responsibility and support for relevant behaviors toward sustainability. Additionally, a score of 76-100% reflects awareness of strategy, where the individual not only takes responsibility but also advocates for positive and sustainable behaviors.

4. RESULTS

4.1. Statistical Analysis Results

The primary objective of these results is to analyze the average outcomes of all participants in both the experimental and control groups during the pre- and post-tests. Out of 65 subjects, 49 students enrolled in the control group and 16 students in the experimental group this allocation provides a fair assessment of the effectiveness of digital versus paper-based methods in developing sustainability literacy. Regarding the participants in the experimental group, the pre-test scores were 59.00 and 79.00, while the post-test scores were 61.00 and 93.00. The increase in scores indicates that participants benefited more from the digital learning strategy, demonstrating its potential to enhance learning outcomes in sustainability literacy.

The evidence demonstrates that the increased range of scores among experimental participants, with a minimum score improvement of +2 points (from 59.00 to 61.00) and a +14 point increase (from 79.00 to 93.00) in the maximum score, indicates an improvement in learning outcomes following the treatment. Conversely, the range of pre-test scores for the control group was 56.00 to 71.00, and post-test scores remained within the same range, with no change observed in either the minimum or maximum scores. For further clarity, a statistical summary is provided in the table that follows.

Table 4. Descriptive statistical analysis.

Descriptive statistics					
Class	**N**	**Minimum**	**Maximum**	**Mean**	**Std. deviation**
Experiment Pretest	49	59.00	79.00	69.092	9.009
Experiment posttest	49	61.00	93.00	77.128	8.029
Control pretest	16	56.00	71.00	63.529	6.412
Control posttest	16	56.00	71.00	63.492	8.007
Valid N (Listwise)	65				

Table 4 presents the results from the experimental group compared to the control group. In the experimental group, participants scored higher on the post-test than on the pre-test, whereas the control group showed no significant difference between the two tests. This indicates that the application of the digital-based Science Literacy Measurement Tool, combined with an aligned deep learning theory strategy, enhances students' literacy on sustainability more effectively than the use of the application alone. The control group, on the other hand, demonstrated a decreased learning curve, which highlights the limitations of the traditional learning model in achieving equal literacy on sustainability.

4.2. Parametric Assumption Test

To ensure that the dataset met the conditions required for a hypothesis test, a dataset was constructed from a set of complete records for which the Parametric Assumption Tests were conducted. The importance of this step lies in the fact that a parametric analysis must satisfy two basic conditions. First, the sample must be normally distributed, and second, the variances among the population groups must be equal. For this study, the parameters of interest were normally distributed and were tested accordingly. The normality test applied was the Kolmogorov-Smirnov test. Simultaneously, the homogeneity of variances was assessed through a One-Way ANOVA with Levene's Test to confirm that the dataset fulfilled the criteria necessary for valid parametric statistical analysis.

4.2.1. Normality Test

Normality was assessed using the Kolmogorov-Smirnov test, and the results for both the experimental group and the control group were 0.173. Since this value exceeds the significance level of 0.05 and the p-value is greater than 0.05, we can conclude that the data for both groups follow a normal distribution. This indicates that the assumption of normality has been satisfied, allowing for the subsequent use of parametric statistical tests. The detailed results of the normality test are presented in Table 5.

Table 5. Normality test results.

Class	N	Kolmogorov-Smirnov Statistic	df	Sig.	Description
Experiment	49	0.432	49	0.173	Normally distributed data
Control	16	0.324	16	0.167	Normally distributed data

4.2.2. Homogeneity Test

The significance level for the homogeneity test of both the experimental and control groups was 0.162. Since this value exceeds 0.05 ($p > 0.05$), it indicates that the differences between the two groups are not statistically significant. This suggests that the variations in learning outcomes between the groups may be due to the absence of variance inequality, thereby supporting the validity and reliability of subsequent analyses. The results of the homogeneity test are detailed in Table 6.

Table 6. Homogeneity test results.

Class	Levene Statistic	df1	df2	Sig.	Description
Experiment and control	6.509	1	65	0.162	Data homogen

4.3. Results of Research Hypothesis Testing through T-Test and N-Gain Scores

The analysis of the hypothesis was conducted using an independent samples t-test, and the corresponding two-tailed significance value for this analysis was 0.003. Although this value is between 0 and 1, it indicates a statistically significant difference in the mean sustainability literacy skills of learners who applied the deep learning-based Digital Science Literacy Measurement Tool Application compared to those who learned using conventional methods. This suggests a positive impact of digital applications on students' ability to improve their sustainability literacy, as opposed to traditional teaching methods. The implementation of digital applications can therefore provide a more effective influence on enhancing students' understanding of sustainability concepts. Integrating science literacy measurement tools into lessons is highly relevant and has a beneficial effect on achieving the objectives of Education for Sustainable Development (ESD). A detailed summary of the t-test results is presented in Table 7.

Table 7. Output of the independent sample t-test.

Variable	Levene's test F	Sig.	t	df	Sig. (2-tailed)	Mean difference	Std. error diff.
Sustainability literacy (assuming equal variances)	2.210	.457	5.323	65	.002	5.156	1.100
Sustainability literacy (assuming unequal variances)	–	–	7.122	57.093	.000	5.039	1.021

The independent samples t-test presented in Table 7 indicates that, within the Elementary School Teacher Education Program, there is a statistically significant difference in scientific learning outcomes between the experimental and control groups. The p-value associated with this test is less than 0.05, confirming that the observed difference is unlikely to be due to chance. This finding suggests that students' learning outcomes are positively influenced by the implementation of the deep learning-based Digital Science Literacy Measurement Tool Application, as compared to traditional instructional approaches. The analysis of average student outcomes demonstrates that students in the experimental group achieved a deeper understanding of scientific concepts and a more comprehensive grasp of sustainability principles. To further validate these results, N-gain score analysis was conducted, revealing that students who utilized the digital application during their sessions experienced greater learning gains than their counterparts in the control group. This evidence underscores the superior effectiveness of the digital application in enhancing scientific literacy and understanding among students. Table 8 provides a comprehensive overview of the efficacy of increased student sustainability literacy.

Table 8. N-gain score results summary.

Class	N-gain score	Criteria
Experiment 1	0.51	Moderate
Experiment 2	0.32	Moderate
Control	0.23	Low

The N-gain score analysis indicated that 'Experimental Class 1' achieved a score of 0.5, while 'Experimental Class 2' scored 0.3, both reflecting a 'low' level of improvement. Conversely, the Control Group's N-gain score of 0.2 also signifies a low level of progress. These findings suggest that the integration of the deep learning approach, combined with the Digital Science Literacy Measurement Tool Application, was more effective in enhancing students' sustainability literacy compared to other instructional methods. The results demonstrate that the Digital Science Literacy Measurement Tool Application, when used within the deep learning framework, can significantly promote students' sustainability literacy at a higher level than alternative techniques. This is evidenced by the greater improvement reported by students in the experimental groups, highlighting the potential of this combined approach to foster meaningful learning outcomes in sustainability education.

The results from the N-gain tests indicated that students' sustainability literacy improved following the implementation of the deep learning-based Digital Science Literacy Measurement Tool. Subsequent analyses using the 'Sustainability Literacy Scale' confirmed these findings by illustrating the distribution of students across different levels of awareness concerning the targeted sustainability literacy. The accompanying diagram visualizes the results of the scale on sustainability literacy.

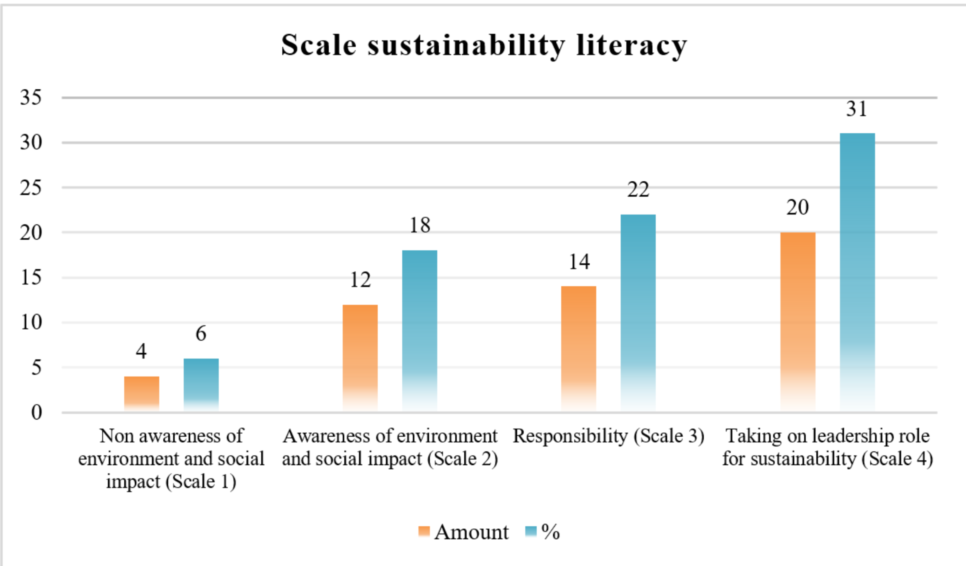


Figure 2. Sustainability literacy scale results diagram.

Figure 2 illustrates the results of the Sustainability Literacy scale analysis, indicating that very few students (6%) remain at the most primitive stage, characterized by a lack of awareness of environmental and social impacts. In comparison, the majority of students have progressed to the next levels: 18% are aware of environmental and social issues, 22% possess a sense of responsibility, and 31% assume leadership roles in sustainability initiatives. This suggests that the digital application of science literacy measurement tools, developed within a deep learning framework, effectively enhances students' cognitive scientific literacy. Additionally, it fosters, develops, and cultivates awareness, responsibility, and leadership, thereby promoting democratic learning practices related to sustainability.

5. FINDINGS

The application of mobile measurement tools based on deep learning approaches has a positive impact on students' sustainability literacy skills. This application helps students learn the theoretical aspects of a subject while also fostering an experiential learning paradigm that enhances their understanding, critical thinking, and reflective awareness of sustainability issues (Atasoy, 2022). According to Wu (2024), students learn to understand the scientific concepts within their socio-economic and socio-ecological systems. The deep learning approaches assist students in attaining higher-order thinking skills, where they make sense of and integrate new information and skills into their daily practices. Thus, this application is a practical example of the integration of theory and practice, science and socio-scientific responsible citizenship.

Based on the information, it was determined that the improvements in students' sustainability literacy were not solely cognitive in nature. Students, as cognitive thinkers, were able to reflect, think critically, analyze the consequences of their actions on sustainability, and act on sociocultural and environmental issues around them. This added value indicates a strong connection between the use of digital assessments and a deep learning approach to attitudinal and ecological behavioral change. Students' enhanced abilities to transfer some learning outcomes into action-oriented steps toward sustainability further confirm the extensive improvements students have achieved in their sustainability literacy. More advanced digital education tools, as noted above, can enhance social concern and empathy, which are often missing components in education for sustainable development.

The application also functions as a means of nurturing character traits related to sustainability in prospective elementary school teachers. Completion of assessments and participation in the nurturing process enable students to effectively develop and practice leadership, collaboration, and ethical decision-making competencies. The "take on a leadership role for sustainability" metric, which saw an increase of 31%, indicates sustained literacy growth, meaning that students have begun to value their future educators' roles as adopters and exemplars of best practice value systems of sustainability (Hogan & O'Flaherty, 2021; Husamah, Rahardjanto, Permana, & Lestari, 2025). Stated differently, these students have come to internalize the outcomes of educational engagements intended to embrace a digitally transformative deep learning pedagogy as evidence of their ability to cultivate a new generation of teachers who are socially sustainable and deeply invested in environmental and planetary sustainability.

6. DISCUSSION

Using digital deep learning tools to teach scientific literacy is a significant advancement in higher education, particularly in helping students better understand sustainability. These tools support various ways students think, feel, and act (Chen, An, Zheng, & Guan, 2022; Mulyana & Desnita, 2023). Recent reviews of scientific literacy also examine students' attitudes toward sustainability, changes in their behavior, and how they apply sustainability ideas in everyday life (Kuehl, Sparks, Hodges, & Smith, 2023). This type of model offers a holistic and contextualized approach to learning, where students' learning outcomes are evident in actual behavioral change (Qiu & Ishak, 2025).

The measurement tool has proven useful in assessing levels of sustainability literacy concerning the achievement of the Sustainable Development Goals (SDGs) (Tiantian, Razali, Zulkifli, & Jeyaraj, 2024). Sustainability literacy is not limited to the environment alone, but extends to the other three pillars of sustainability, that is, social and economic (Annelin & Boström, 2023; Dawodu et al., 2022). Students, particularly those studying to be teachers, are in a unique position to act as change agents to adopt and integrate sustainability practices in primary school teaching and learning (Ahuja & Jain, 2025). Using relevant sustainability literacy and pedagogical approaches to teaching, teachers are expected to nurture and mentor future generations of students to be environmentally responsible and active citizens capable of addressing the ever-increasing complexity of global issues (Lad & Akerlof, 2022).

The students have now obtained the necessary scientific literacy in sustainability to make essential cognitive leaps with the help of the Digital Measurement Tool, which includes components such as computers, online simulations, self and peer assessments, and PowerPoint presentations. Recognizably, sustainability literacy extends beyond the recognition, articulation, and application of scientific knowledge (Sartika, Nurlina, Mutmainna, Aris, & Musliana, 2023). To maintain a supportive discourse (Kelp, McCartney, Sarvary, Shaffer, & Wolyniak, 2023) assert that sustainability literacy refers to the degree to which an individual can rationally and constructively determine and act in a manner that supports sustainability. The incremental shifts in scientific literacy, facilitated by the use of sustainability-oriented digital instruments, extend students' reflection beyond the cognitive domain of learning. These shifts enhance social responsibility, pragmatic awareness, and action, as well as the skills and competencies necessary to address the challenges of sustainable development in the contemporary world (Adnan, Mulbar, Sugiarti, & Bahri, 2021; Ploj Virtič, 2022).

As with the use of any measurement approach in teaching, deep learning is a primary pedagogical method. The three pillars underpinning deep learning joyful, mindful, and meaningful add additional dimensions to the learning process (Mohammed & Kora, 2023; Zhou, Zhang, & Li, 2024). Joyful learning means that students are engaged and motivated, mindful learning encourages reflective awareness about what is being learned, and meaningful learning relates the experience to the context (Nayoga, Adipradana, Suryadi, & Suhartono, 2021; Prince, 2023). The digital application of measurement instruments aligns with the three pillars. In addition to serving as measuring instruments, they significantly enhance students' critical thinking, practical awareness, and skill development in response to 21st-century sustainability challenges (Ahmed et al., 2023).

Previous research Akerson and Bartels (2023); Kuehl et al. (2021); Li and Guo (2021) and Schwartz et al. (2023) has shown that studies on deep learning digital applications for science literacy measurement tools are scarce and typically conducted traditionally, without, for the most part, embracing digitalization. The current era of education necessitates more engaging and holistically integrated tools to assess and improve training. When digital tools are used to measure scientific literacy, they demonstrate the importance of having evaluative, sustainable, and customizable resources that support the learner's ongoing development.

Equipping students with reflective learning techniques is important due to their advanced skills. The need for students to learn how to think and behave sustainably should be embedded in the learning outcomes. Digital interventions aid in the learning and practice of behaviors that students can advocate for and practice sustainably. This aims to equip students with sustainable literacy skills and prepare them as pre-service primary science teachers with the ability to integrate the principles of sustainability into primary science education.

7. CONCLUSION

A scientific literacy measurement tool integrated into deep learning, packaged as a digital application, represents an innovative approach to effective science learning in higher education. This digital application-based scientific literacy measurement tool has demonstrated a positive and significant impact on students' sustainability literacy. The analysis results, obtained through an independent samples t-test with a p-value of less than 0.05, indicate a statistically significant difference in the use of the digital scientific literacy measurement tool in deep learning compared to traditional measurement methods. The research findings are further supported by a moderate N-gain score and the distribution of students' sustainability literacy levels, with 31% assuming leadership roles related to sustainability. Students' sustainability literacy has improved following the implementation of the digital, application-based scientific literacy measurement tool. This suggests that the instrument is not solely evaluative but also serves as a learning opportunity for students. Consequently, students develop critical consciousness, a sense of agency, and an understanding of global issues related to the Sustainable Development Goals (SDGs), Education for Sustainable Development (ESD), and environmental concerns.

This research has implications for evaluation patterns in science learning in higher education, integrated with deep learning, thereby enhancing students' competencies in the current digital era. The Digital Science Literacy Measurement Tool could be an innovative resource for lecturers and educators to help develop sustainability literacy, which is a crucial issue for the nation's future generations. Future research is recommended to expand the sample size by including multiple study programs or by not focusing solely on one university. Additionally, further exploration of implementation using mixed methods is suggested to ensure that the existing product becomes an essential tool for students' understanding of sustainability and the Sustainable Development Goals (SDGs)/Education for Sustainable Development (ESD).

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Institutional Review Board Statement: This study was approved by the Institutional Review Board of Esa Unggul University, Indonesia, under protocol number (0925-10.026/DPKE-KEP/FINAL-EA/UEU/X/2025), dated 28 October 2025. Informed verbal consent was obtained from all participants, and all data were anonymized to protect participant confidentiality.
Transparency: The authors state that the manuscript is honest, truthful, and transparent, that no key aspects of the investigation have been omitted, and that any differences from the study as planned have been clarified. This study followed all writing ethics.
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