

Eco-digital Indonesian language in elementary education: Ecological interest and technological perception

Mundakir^{a, 1, *}, Ade Hikmat^{a, 2}, Siti Zulaiha^{a, 3}

^a Universitas Muhammadiyah Prof. Dr. Hamka, Jakarta, Indonesia

¹ mundakir@uhamka.ac.id; ² ade_hikmat@uhamka.ac.id; ³ siti.zulaiha@uhamka.ac.id

* Correspondent author

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ABSTRACT

A This study examines the relationship between ecological interest and technological perception in shaping elementary students' support toward ecology-based digital Indonesian language modules. The research employed a quantitative cross-sectional survey involving 212 fifth- and sixth-grade students from an elementary school in Depok, Indonesia. Data were collected through a questionnaire developed based on the Technology Acceptance Model (TAM), focusing on ecological interest, technological perception, and students' support toward eco-digital learning modules. The findings indicate that most students demonstrated positive responses toward the integration of ecological themes into Indonesian language learning. Ecological interest emerged as the strongest factor associated with students' support, followed by technological perception and prior digital learning experience. Students with stronger ecological awareness and more positive perceptions of learning technology generally showed higher acceptance of eco-digital modules. However, several students still preferred contextual and experiential environmental learning activities alongside technology-based instruction. Overall, the study highlights the importance of integrating ecological literacy and accessible digital learning design in developing sustainability-oriented Indonesian language learning for elementary education.

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Introduction

Digital technology has increasingly transformed Indonesian language learning practices in elementary schools by creating more interactive, student-centered, and technology-supported learning environments. The integration of digital learning aligns with the demands of twenty-first-century education, which emphasize digital literacy, critical thinking, collaboration, creativity, and learner autonomy (Haleem et al., 2022). Previous studies have demonstrated that digital learning platforms can enhance student engagement, expand access to learning resources, and facilitate more meaningful learning experiences through multimedia-based instruction and interactive activities (Bond et al., 2021; Chiu, 2022; Howard et al., 2021). Moreover, technology-supported learning environments grounded in constructivist principles encourage students to actively construct knowledge, regulate their learning processes, and participate in collaborative interactions that promote deeper understanding (Falloon, 2020; Redecker, 2020; van Laar et al., 2020). Within Indonesian language education, digital technology also offers opportunities to strengthen critical literacy, communication skills, and contextual understanding by exposing learners to diverse forms of authentic texts and language practices (Falloon, 2020).

Alongside technological advancement, environmental education has become an increasingly important educational priority in response to global sustainability challenges and escalating ecological

concerns. Educational institutions are expected to cultivate environmental awareness, ecological responsibility, and sustainable behavior among students through instructional experiences that integrate environmental values into daily learning activities (Kopnina, 2020; UNESCO, 2021; Misiaszek, 2020; Sterling, 2021). Systematic evidence indicates that environmental education contributes positively to students' conservation knowledge, environmental attitudes, and environmentally responsible behaviors across various educational settings (Ardoin et al., 2020; Stevenson et al., 2021). In the context of Indonesian language learning, the incorporation of ecological themes enables students to engage with environmental narratives, persuasive texts, reflective writing, and literacy practices that encourage sustainability-oriented thinking. Consequently, Indonesian language instruction may function not only as a vehicle for linguistic development but also as an effective medium for strengthening environmental consciousness and social responsibility among elementary school students (Ardoin et al., 2020; UNESCO, 2021).

The rapid development of digital technologies has further created opportunities to support sustainability-oriented learning through contextual and interactive educational experiences. Environmental topics can be introduced through digital modules, multimedia storytelling, interactive reading materials, and project-based learning activities closely connected to students' surrounding environments. Ecology-based digital learning modules therefore possess considerable potential to enhance environmental literacy while simultaneously supporting students' adaptation to educational technologies (Tang et al., 2021; Ng et al., 2021; Falloon, 2020). Previous reviews have also indicated that successful implementation of educational technologies depends not only on technological availability but also on learners' attitudes and readiness to engage with technology-enhanced instruction (Granić & Marangunić, 2019; Rasheed et al., 2020; Howard et al., 2021).

The Technology Acceptance Model (TAM) provides a widely recognized framework for understanding users' acceptance of technological innovations in educational settings. According to TAM, individuals' intentions to adopt technology are primarily influenced by perceived usefulness and perceived ease of use (Davis, 1989). Students who perceive digital learning technologies as beneficial, practical, and easy to operate tend to demonstrate more favorable attitudes toward technology-supported instruction and exhibit greater willingness to utilize digital learning resources (Granić & Marangunić, 2019). In addition to technological factors, ecological interest may also influence students' responses toward sustainability-oriented learning materials. Learners with stronger environmental awareness and greater concern regarding ecological issues are more likely to appreciate educational experiences that promote environmentally responsible values and behaviors (Ardoin et al., 2020).

Despite growing scholarly interest in environmental education and digital learning integration, empirical studies investigating elementary students' support for ecology-based digital Indonesian language learning remain relatively limited. Existing studies have predominantly examined either technology acceptance within educational contexts or ecological literacy within sustainability education frameworks. Furthermore, only a limited number of studies have employed interpretable machine learning approaches, such as Extreme Gradient Boosting (XGBoost) and SHapley Additive exPlanations (SHAP), to explore predictive patterns and feature contribution mechanisms in educational contexts. Recent developments in educational artificial intelligence have highlighted the importance of explainable machine learning models for enhancing transparency, accountability, and educational decision-making processes (Holmes et al., 2019; Khosravi et al., 2022). Similarly, systematic reviews of artificial intelligence applications in education have emphasized the need for approaches that support meaningful interpretation of predictive outcomes while maintaining educational relevance and ethical considerations (Zawacki-Richter et al., 2019). Nevertheless, the application of explainable machine learning within Indonesian language education, particularly in sustainability-oriented contexts, remains underexplored.

This study addresses the existing research gap by integrating XGBoost predictive modeling with SHAP interpretability analysis within sustainability-oriented Indonesian language learning contexts in elementary education. Unlike previous investigations that primarily relied on conventional statistical techniques, the present study applies interpretable machine learning approaches to identify feature contribution patterns associated with students' support for ecology-based digital Indonesian language modules. Explainable artificial intelligence has increasingly been recommended in educational research because it enables researchers to understand how predictive models generate outcomes while maintaining transparency and interpretability (Lundberg & Lee, 2017; Khosravi et al., 2022; Viberg et al., 2023). In addition, interpretable machine learning approaches provide valuable opportunities for translating complex predictive information into educational insights that can support evidence-based instructional decision-making (Molnar, 2022). Predictive analytics and learning analytics have increasingly been recognized as valuable approaches for understanding student learning behaviors, identifying educational trends, and supporting continuous improvement initiatives through data-informed decision-making processes (Siemens & Long, 2011; Viberg et al., 2023; Viberg et al., 2024). Therefore, this study contributes

to the development of eco-digital pedagogy by integrating sustainability-oriented language learning perspectives with explainable educational analytics approaches.

Accordingly, this study aims to analyze the relationships between ecological interest, technological perception, and students' support for ecology-based digital Indonesian language modules. TAM is employed as the primary analytical framework because students' perceptions regarding usefulness and ease of use have consistently been identified as important determinants influencing educational technology acceptance (Davis, 1989; Granić & Marangunić, 2019). Simultaneously, sustainability-oriented learning serves as the pedagogical orientation underlying the design and implementation of eco-digital instructional materials intended to promote both language competencies and ecological awareness among elementary school students. To improve analytical interpretability and predictive understanding, this study applies XGBoost and SHAP analyses to identify feature contribution patterns within students' responses. The growing use of explainable machine learning approaches has strengthened educational analytics by enabling researchers to interpret predictive outcomes and understand the relative contributions of individual variables within complex educational datasets (Wang et al., 2021). Furthermore, predictive analytics and learning analytics have increasingly been recognized as valuable approaches for understanding student learning behaviors, identifying educational trends, and supporting continuous improvement initiatives through data-informed decision-making processes (Siemens & Long, 2011; Tang et al., 2021).

Rather than establishing causal relationships, this study seeks to generate predictive and interpretive insights into students' acceptance of sustainability-oriented digital learning environments. The findings are expected to contribute to scholarly discussions concerning eco-digital pedagogy while simultaneously providing practical implications for educators and instructional designers involved in developing environmentally oriented digital learning materials in elementary education. Such insights may support the creation of learning environments that effectively integrate technological innovation with sustainability principles to address contemporary educational challenges. Recent developments in educational analytics have emphasized the importance of prediction-oriented approaches for transforming educational data into meaningful insights that support evidence-based decision making and instructional improvement (Siemens & Long, 2011). Furthermore, Sustainability-oriented educational practices increasingly require the integration of digital innovation and ecological awareness to prepare students for the complex environmental and technological realities of the twenty-first century (Ardoin et al., 2020; Haleem et al., 2022; UNESCO, 2021).

Based on the proposed theoretical framework, this study assumes that ecological interest and technological perception are associated with students' support for ecology-based digital Indonesian language modules. Unlike previous studies that have examined ecological literacy and digital learning acceptance separately, the present research integrates the Technology Acceptance Model (TAM), ecological literacy perspectives, and interpretable machine learning approaches through the XGBoost-SHAP framework. TAM provides the theoretical basis for understanding how perceived usefulness and perceived ease of use influence technology acceptance in educational contexts (Davis, 1989; Granić & Marangunić, 2019), whereas ecological literacy emphasizes the development of environmental awareness, responsibility, and sustainability-oriented behaviors among learners (Kopnina, 2020). Moreover, the increasing application of explainable artificial intelligence in educational research highlights the value of interpretable machine learning techniques for identifying predictive patterns while maintaining analytical transparency (Wang et al., 2021). Through this integrated perspective, the study seeks to provide a more comprehensive understanding of the factors associated with elementary students' support for sustainability-oriented digital Indonesian language learning modules, as illustrated in Figure 1.

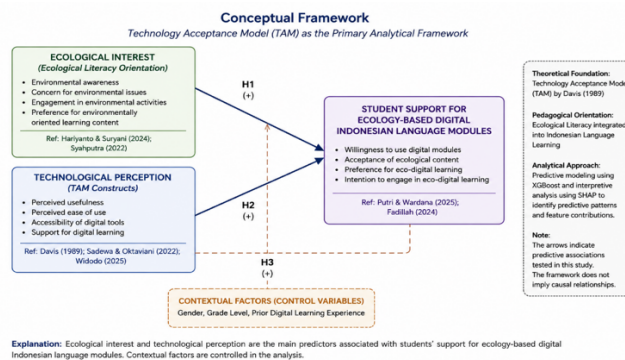


Fig. 1. Conceptual Framework of the Study

This study employs the Technology Acceptance Model (TAM) as the primary theoretical foundation for analyzing students' support for ecology-based digital Indonesian language modules. TAM proposes that technology acceptance is largely determined by users' perceptions of a technology's usefulness and ease of use (Davis, 1989). Within educational contexts, these two constructs have consistently been identified as important predictors of learners' willingness to adopt and utilize digital learning technologies (Granić & Marangunić, 2019). In the present study, ecological interest is conceptualized as students' environmental awareness, concern regarding ecological issues, participation in environmentally responsible activities, and preferences for sustainability-oriented learning content. Students who exhibit stronger ecological interest are assumed to demonstrate more positive attitudes toward environmentally oriented digital learning materials because ecological literacy may strengthen engagement with contextual and meaningful learning experiences that connect learning with real-world environmental challenges (Ardoin et al., 2020). Furthermore, the integration of ecological themes into Indonesian language learning is considered capable of promoting reflective literacy practices while simultaneously fostering environmental responsibility among elementary school students, thereby supporting the broader objectives of education for sustainable development (Kopnina, 2020).

In addition to ecological interest, technological perception is also positioned as an important predictor of students' support for eco-digital learning modules. Technological perception includes perceived usefulness, perceived ease of use, accessibility of digital platforms, and students' confidence in utilizing educational technology during learning activities. Students who perceive digital learning technologies as accessible, interactive, and beneficial are generally more likely to support and utilize digital learning modules effectively (Bond et al., 2021; Haleem et al., 2022). To strengthen the analytical framework, several contextual variables such as gender, grade level, and previous digital learning experience are incorporated as control variables because these factors may influence students' responses toward technology-supported learning environments (Tang et al., 2021). Overall, the conceptual framework emphasizes that ecological literacy orientation and positive technological perceptions jointly contribute to predicting students' support for ecology-based digital Indonesian language learning modules within sustainability-oriented elementary education.

Method

Research Design

This study employed a quantitative cross-sectional survey design to examine the predictive relationships among ecological interest, technological perception, and students' support for ecology-based digital Indonesian language modules. A cross-sectional approach was considered appropriate because the study aimed to identify associative and predictive patterns within students' responses at a single point in time rather than establish direct causal relationships. Quantitative survey methods have been widely utilized in educational technology research because they enable researchers to systematically investigate students' perceptions, attitudes, and behavioral tendencies toward digital learning environments (Creswell & Creswell, 2018; Fraenkel et al., 2019). In sustainability-oriented educational contexts, survey-based approaches also provide valuable insights into students' environmental awareness, ecological engagement, and environmentally responsible attitudes (Ardoin et al., 2020; UNESCO, 2021). Furthermore, contemporary digital learning ecosystems increasingly emphasize the importance of adaptive and technology-supported learning environments capable of accommodating students' diverse learning needs and experiences (Haleem et al., 2022; Falloon, 2020). Understanding students' perceptions is therefore essential for evaluating their support for ecology-based digital learning innovations, particularly within elementary education contexts where technology integration and sustainability-oriented learning are still evolving (Bond et al., 2021).

To strengthen predictive analysis, this study applied Extreme Gradient Boosting (XGBoost), a machine learning algorithm recognized for its ability to identify complex nonlinear relationships and high-dimensional interaction patterns within educational datasets. XGBoost has increasingly been employed in educational data mining because of its strong predictive performance, computational efficiency, and capability to effectively manage structured educational data (Chen & Guestrin, 2016). Previous machine learning studies have also demonstrated the effectiveness of boosting-based algorithms in improving predictive performance when handling structured datasets containing diverse feature characteristics (Prokhorenkova et al., 2018). Furthermore, SHapley Additive exPlanations (SHAP) were utilized to interpret the contribution of each predictor variable to the prediction outcomes, thereby enhancing model transparency, interpretability, and explainable machine learning analysis (Lundberg & Lee, 2017; Wang et al., 2021; Khosravi et al., 2022). Recent developments in explainable artificial intelligence have further shown that SHAP can provide both local and global interpretations of tree-based models, enabling

researchers to better understand feature contribution patterns and overall model behavior (Lundberg et al., 2020). The use of explainable machine learning is increasingly recommended in educational research because it improves transparency and supports evidence-based educational decision-making processes (Molnar, 2022). Therefore, the integration of XGBoost and SHAP enabled this study not only to predict students' support for eco-digital learning modules but also to identify the relative importance of individual predictor variables within the analytical framework.

The analytical framework of this study was grounded in the Technology Acceptance Model (TAM), which explains that perceived usefulness and perceived ease of use significantly influence individuals' acceptance of digital technologies in educational environments (Davis, 1989; Granić & Marangunić, 2019). TAM was employed to examine students' technological perceptions toward ecology-based digital Indonesian language learning modules, particularly regarding the accessibility, usefulness, and practicality of digital learning platforms. Previous studies have consistently demonstrated that positive technological perceptions are strongly associated with students' engagement, satisfaction, and willingness to participate in digital learning activities (Bond et al., 2021; Haleem et al., 2022; Howard et al., 2021). Consequently, students who perceive digital learning systems as beneficial, practical, and easy to use are more likely to exhibit positive support for sustainability-oriented digital learning environments.

In addition, ecological literacy served as the pedagogical foundation of this study by emphasizing students' environmental awareness, ecological responsibility, and sustainable behavioral orientations within digital learning contexts. Ecological literacy is increasingly recognized as an essential component of contemporary education because it encourages learners to develop environmentally responsible attitudes and sustainability-oriented perspectives through contextual learning experiences (Kopnina, 2020; Misiaszek, 2020). Evidence from previous studies has further indicated that environmental education contributes positively to students' environmental knowledge, conservation attitudes, and environmentally responsible behaviors (Ardoin et al., 2020). Therefore, the integration of ecological literacy and digital learning technologies was expected to support the development of environmentally oriented Indonesian language learning materials that are responsive to current educational challenges and sustainability demands. Through this approach, Indonesian language learning may function not only as a medium for linguistic development but also as a vehicle for fostering environmental awareness, reflective literacy practices, and sustainability-oriented citizenship among elementary school students.

Participants and Sampling

The participants in this study consisted of 212 fifth and sixth-grade students from SDIT Miftahul Ulum. The school was purposively selected because it had implemented digital learning practices alongside environmental education programs that were relevant to the objectives of this research. Purposive sampling was considered appropriate because the study specifically focused on students who had previous experience with ecology-oriented digital learning activities within Indonesian language instruction (Campbell et al., 2020). In educational research, purposive sampling is frequently employed to obtain participants who possess characteristics and learning experiences directly related to the research context, thereby improving the relevance and validity of the collected data (Creswell & Creswell, 2018). Furthermore, the integration of sustainability-oriented learning and technology-assisted instruction within the selected school provided a suitable context for examining students' support toward ecology-based digital learning modules (Haleem et al., 2022).

The selection of the research site was also influenced by the school's implementation of environmentally oriented educational activities and the integration of digital learning media into classroom instruction. These educational practices were considered relevant because previous studies have indicated that environmental education programs contribute positively to students' environmental awareness, ecological responsibility, and sustainability-oriented behaviors (Ardoin et al., 2020). Likewise, students' previous experiences with digital learning environments have been shown to influence their perceptions, engagement, and acceptance of technology-supported instruction (Bond et al., 2021). Therefore, the participants in this study consisted of Grade 5 and Grade 6 students who had previously engaged in digital learning activities and environmental literacy initiatives integrated within Indonesian language learning contexts. This participant selection strategy was intended to ensure that the collected data accurately reflected students' actual experiences, perceptions, and responses toward eco-digital learning environments. Consequently, the selected participants were considered appropriate for providing contextual insights into students' acceptance of ecology-based digital Indonesian language learning modules can be seen in Table 1.

Table 1. Participant Characteristics

<i>Characteristics</i>	<i>Frequency</i>	<i>Percentage</i>
Grade 5 Students	95	44.8%
Grade 6 Students	111	52.4%
Unidentified/Incomplete Class Data	6	2.8%
Total Participants	212	100%

The participant distribution shows that the study involved a total of 212 students, with the majority coming from Grade 6 students, who accounted for 111 participants or 52.4% of the sample. Meanwhile, Grade 5 students contributed 95 participants or 44.8%, indicating a relatively balanced representation between the two grade levels. In addition, there were 6 participants (2.8%) whose class information was unidentified or incomplete. Overall, the data suggest that the study predominantly reflects the perspectives of upper elementary students, particularly those in Grade 6, while still maintaining substantial representation from Grade 5 students.

The participant selection process emphasized the compatibility between the educational context and the implementation of ecology-based digital learning. Therefore, the selected sample was considered relevant for analyzing students' ecological interest, technological perceptions, and support for ecology-based digital Indonesian language modules.

Instrumentation

Data in this study were collected using a structured questionnaire developed based on the Technology Acceptance Model (TAM) and ecological literacy perspectives. The instrument was designed to measure three main constructs, namely ecological interest, technological perception, and students' support for ecology-based digital Indonesian language modules. The development of questionnaire indicators referred to previous studies concerning technology acceptance in educational settings, environmental literacy, and technology-supported learning environments (Davis, 1989; Granić & Marangunić, 2019). Questionnaire-based instruments are widely employed in educational research because they enable researchers to systematically examine students' attitudes, perceptions, and responses toward learning innovations in a measurable and structured manner (Creswell & Creswell, 2018). Moreover, structured questionnaires provide an efficient approach for collecting large amounts of data while maintaining consistency across respondents and facilitating quantitative analysis (Fraenkel et al., 2019).

The ecological interest construct consisted of indicators related to environmental awareness, environmental concern, participation in ecological activities, and students' engagement with sustainability-oriented learning materials. These indicators were intended to identify students' attitudes and levels of interest toward environmental issues integrated into Indonesian language learning content. Previous studies have indicated that ecological literacy encompasses not only environmental knowledge but also concern, values, and behavioral orientations that encourage environmentally responsible actions (Ardoin et al., 2020). Ecological literacy has increasingly become an important component of contemporary education because it promotes sustainability-oriented perspectives and environmentally responsible behavior through contextual learning experiences (Kopnina, 2020). Therefore, integrating ecological themes into language learning materials was expected to support both literacy development and environmental awareness among elementary school students.

Technological perception indicators were adapted from the TAM framework, which identifies perceived usefulness and perceived ease of use as the primary determinants of technology acceptance within educational settings (Davis, 1989; Granić & Marangunić, 2019). Additional indicators included accessibility of digital learning platforms, students' readiness to participate in technology-supported learning, and confidence in using digital learning tools during classroom activities. Previous studies have demonstrated that positive perceptions toward educational technology significantly influence students' engagement, participation, and willingness to adopt digital learning systems (Bond et al., 2021; Haleem et al., 2022). Consequently, technological perception was considered an important variable for predicting students' support toward ecology-based digital learning modules.

Meanwhile, the student support construct measured students' acceptance, willingness, preference, and positive responses toward the implementation of ecology-based digital Indonesian language modules. This construct was employed to evaluate students' perceptions regarding the integration of ecological literacy and digital learning media into classroom instruction. The incorporation of sustainability-oriented digital learning is increasingly recognized as an effective approach for promoting interactive learning experiences while simultaneously strengthening environmental awareness and contextual literacy among students (Ardoin et al., 2020; UNESCO, 2021; Chiu, 2022). Furthermore, positive support toward educational innovations has been associated with learners' perceptions of relevance, usability, and meaningful learning experiences within technology-enhanced environments (Granić & Marangunić, 2019;

Howard et al., 2021; Bond et al., 2021). Through this construct, the study sought to identify the extent to which students supported environmentally oriented digital learning innovations in Indonesian language education.

All questionnaire items employed a five-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree). Prior to data collection, the instrument underwent expert judgment and content validation procedures to ensure the relevance, clarity, readability, and appropriateness of each item for elementary school students. Content validation procedures are essential in educational research because they improve measurement accuracy and ensure that questionnaire items adequately represent the intended constructs (Taherdoost, 2018; Boateng et al., 2018; DeVellis & Thorpe, 2021). Reliability analysis further demonstrated that all constructs achieved Cronbach's Alpha coefficients exceeding the minimum acceptable threshold of 0.70, indicating satisfactory internal consistency for educational research instruments (Taber, 2018; Hair et al., 2021). Therefore, the questionnaire was considered valid and reliable for measuring ecological interest, technological perception, and students' support toward ecology-based digital Indonesian language modules.

In addition, a pilot testing procedure was conducted before the main data collection process to identify potential ambiguities and improve the comprehensibility of questionnaire items for elementary school students. The pilot study involved a small group of students with characteristics similar to those of the main participants to ensure that the wording, instructions, and response categories could be easily understood by the target population. This preliminary testing process also enabled the refinement of several questionnaire statements to improve linguistic clarity and contextual suitability within Indonesian language learning environments (Fraenkel et al., 2019; Presser et al., 2004). Such procedures are important for minimizing response bias, enhancing respondents' understanding of questionnaire items, and improving the overall quality of quantitative educational data collection (Cohen et al., 2018). The results of the instrument validity and reliability analyses are presented in Table 2.

Table 2. Instrument Indicators

<i>Variable</i>	<i>Indicators</i>
Ecological Interest	awareness, concern, engagement
Technological Perception	usefulness, ease of use, accessibility
Student Support	acceptance, willingness, preference

The study consisted of three main variables with several indicators for each construct. Ecological Interest was measured through students' awareness, concern, and engagement toward environmental issues. Technological Perception included indicators such as usefulness, ease of use, and accessibility of digital learning media. Meanwhile, Student Support was assessed based on students' acceptance, willingness, and preference toward the implementation of ecology-based digital learning modules in Indonesian language learning.

Data Analysis

The collected data were analyzed using descriptive statistics, Extreme Gradient Boosting (XGBoost) classification modeling, and SHapley Additive exPlanations (SHAP) interpretation analysis. Descriptive statistical analysis was initially conducted to summarize students' responses related to ecological interest, technological perception, and support toward ecology-based digital Indonesian language modules. Descriptive statistics are commonly employed in quantitative educational research because they provide systematic summaries of response distributions, measures of central tendency, and participant characteristics that facilitate data interpretation and reporting (Creswell & Creswell, 2018; Field, 2018). Through descriptive analysis, this study sought to identify general trends and patterns within students' perceptions regarding sustainability-oriented digital learning environments prior to conducting predictive modeling procedures.

The predictive analysis employed Extreme Gradient Boosting (XGBoost) to identify classification patterns associated with students' support toward eco-digital learning modules. XGBoost was selected because of its capability to manage complex nonlinear relationships, reduce overfitting through regularization mechanisms, and improve predictive accuracy when analyzing datasets involving multiple interacting variables (Chen & Guestrin, 2016). Previous studies have demonstrated that machine learning algorithms such as XGBoost provide strong predictive performance in educational data mining and learning analytics because of their computational efficiency and ability to process structured educational data effectively (Khan & Ghosh, 2021). The independent variables included ecological interest, technological perception, previous digital learning exposure, and environmental learning experience, whereas the dependent variable focused on students' support toward ecology-based digital Indonesian language modules.

To evaluate model performance and generalizability, the dataset was divided into training and testing datasets using an 80:20 ratio. This approach is widely applied in machine learning research to minimize overfitting, improve model stability, and ensure that predictive models can generalize effectively to unseen data (Géron, 2022). The training dataset was used to construct and optimize the predictive model, while the testing dataset was utilized to evaluate the classification performance of the model on new observations. In educational predictive analytics, data splitting procedures are essential because they help ensure the reliability and robustness of machine learning predictions across different learning contexts (Baker & Inventado, 2021).

Furthermore, SHapley Additive exPlanations (SHAP) analysis was employed to improve model interpretability by identifying the contribution of each predictor variable within the classification framework (Lundberg & Lee, 2017). SHAP values were interpreted as indicators of feature contribution to prediction outcomes rather than evidence of causal relationships. Explainable artificial intelligence approaches such as SHAP have become increasingly important in educational research because they enable researchers to understand how predictive models generate classification decisions while identifying the relative importance of individual variables within analytical frameworks (Wang et al., 2021). Recent developments have further demonstrated that SHAP can provide both local and global explanations of tree-based models, thereby improving transparency and supporting evidence-based educational decision making (Lundberg et al., 2020). Consequently, the present analysis emphasized predictive tendencies, feature interaction patterns, and variable contribution mechanisms associated with students' support toward eco-digital learning modules.

Model performance was evaluated using Receiver Operating Characteristic (ROC) analysis and Area Under the Curve (AUC) scores. ROC-AUC evaluation was employed to assess the classification capability of the predictive model in distinguishing students' levels of support toward ecology-based digital Indonesian language modules (Saito & Rehmsmeier, 2015). A higher AUC score indicates better classification performance and stronger discrimination ability between categories within the predictive model. In this study, the interpretation of analytical results focused primarily on predictive performance, model reliability, and classification accuracy rather than establishing direct causal explanations. Such an approach aligns with recent developments in educational analytics that emphasize prediction-oriented and interpretable machine learning frameworks for understanding student learning behavior and educational technology acceptance (Tang et al., 2021).

In addition, hyperparameter optimization procedures were conducted to improve model effectiveness and classification stability. Several parameters, including learning rate, maximum tree depth, and number of boosting iterations, were adjusted iteratively to obtain the most optimal predictive performance. Hyperparameter tuning is considered an important stage in machine learning analysis because appropriate parameter settings may significantly influence model accuracy, prediction consistency, and computational efficiency (Prokhorenkova et al., 2018). Through this optimization process, the study sought to ensure that the XGBoost classification model produced reliable and interpretable predictive outcomes for analyzing students' support toward ecology-based digital Indonesian language learning modules.

Ethical Consideration

This study adhered to ethical principles in educational research by ensuring voluntary participation, anonymity, confidentiality, and the protection of participants' rights throughout the research process. Prior to data collection, formal permission to conduct the study was obtained from SDIT Miftahul Ulum as the research site. Students and teachers were informed that the collected data would be used exclusively for academic purposes and would not influence students' academic evaluations or learning outcomes. Ethical principles emphasizing informed participation and the minimization of potential risks are considered fundamental requirements in educational research involving school-aged participants (Creswell & Creswell, 2018; American Educational Research Association [AERA], 2011; Cohen et al., 2018; Israel & Hay, 2021).

To protect participants' privacy, all questionnaire responses were collected anonymously, and no personally identifiable information was recorded during the research process. The implementation of the study was also carefully designed to avoid disrupting regular classroom learning activities. Participants completed the questionnaires independently without coercion, pressure, or any form of inducement. Previous ethical guidelines for social and educational research involving children have emphasized the importance of safeguarding confidentiality, respecting participants' autonomy, and ensuring that participation remains entirely voluntary (BERA, 2018; Alderson & Morrow, 2020). Therefore, the data collection procedures adopted in this study were intended to uphold participants' dignity and well-being throughout the research process.

Furthermore, all research data were analyzed collectively and reported in aggregate form to ensure that individual participants could not be identified. Data management procedures, including secure storage

and restricted access to research records, were implemented to maintain confidentiality and prevent unauthorized disclosure of information. The ethical procedures employed in this study followed established principles for educational and social science research involving children and school-based participants, including respect for persons, beneficence, and justice (Creswell & Creswell, 2018; AERA, 2011; Resnik, 2020; Israel & Hay, 2021). Accordingly, the study sought to maintain ethical integrity while generating scientifically rigorous findings relevant to sustainability-oriented educational innovation.

Analytical Framework

The analytical framework of this study examined the relationship between ecological interest, technological perception, environmental learning experience, prior exposure to digital learning, and students' support toward ecology-based digital Indonesian language modules. The framework was developed based on the integration of the Technology Acceptance Model (TAM) and ecological literacy perspectives.

Ecological interest, technological perception, environmental learning experience, and prior digital learning exposure functioned as independent variables, whereas students' support toward eco-digital Indonesian language modules served as the dependent variable. This framework enabled the identification of predictive tendencies associated with students' acceptance of sustainability-oriented digital learning within elementary education contexts.

The framework also emphasized the role of ecological literacy in shaping students' environmental awareness and engagement, while TAM provided the theoretical basis for understanding students' perceptions toward digital learning technology (Davis, 1989). Through this analytical framework, the study sought to explore how ecological and technological factors jointly contributed to students' support for eco-digital learning innovation in Indonesian language education.

Machine Learning and SHAP Analysis

The study employed Extreme Gradient Boosting (XGBoost) classification analysis because of its capability to handle complex and non-linear relationships within educational datasets (Chen & Guestrin, 2016). The dataset was divided into 80% training data and 20% testing data to evaluate model performance and generalizability. Hyperparameter optimization was conducted to maintain model stability and interpretability.

To improve analytical interpretability, SHapley Additive exPlanations (SHAP) analysis was employed to examine variable contribution tendencies within the classification models (Lundberg & Lee, 2017). SHAP values were interpreted as indicators of explanatory contribution rather than evidence of causal influence. Explainable artificial intelligence approaches have become increasingly important in educational analytics because they facilitate understanding of how predictive models generate decisions and reveal the relative importance of individual predictor variables (Wang et al., 2021). Furthermore, SHAP has been shown to provide both local and global interpretations of tree-based models, thereby enhancing model transparency and supporting evidence-based educational decision making (Lundberg et al., 2020). Visualization outputs, including SHAP summary plots and dependence plots, were utilized to identify interaction tendencies among predictor variables.

Model performance was evaluated using confusion matrices, Receiver Operating Characteristic (ROC) curves, and Area Under the Curve (AUC) scores. ROC-AUC analysis was employed to assess the classification capability of the predictive model in distinguishing different levels of students' support toward ecology-based digital Indonesian language modules (Saito & Rehmsmeier, 2015; Chicco & Jurman, 2020). Confusion matrices further provided information regarding classification accuracy across outcome categories and enabled more comprehensive interpretation of prediction outcomes beyond overall accuracy measures (Powers, 2020). The interpretation of model performance emphasized predictive capability, classification accuracy, and explanatory patterns rather than causal inference. This analytical orientation aligns with recent developments in educational analytics that increasingly advocate prediction-oriented and interpretable machine learning approaches for understanding student learning behavior and educational technology acceptance (Tang et al., 2021; Khosravi et al., 2022; Viberg et al., 2023). Recent studies have further emphasized that interpretable predictive analytics may support educational decision-making by providing transparent insights into student learning patterns and facilitating more reliable evaluation of educational interventions can be seen in Table 3 (Holmes et al., 2019; Siemens & Baker, 2022).

Table 3. Machine Learning Model and Analytical Configuration

<i>Component</i>	<i>Description</i>
Machine Learning Algorithm	Extreme Gradient Boosting (XGBoost)
Data Splitting Technique	80% training data and 20% testing data
Hyperparameter Optimization	Conducted to maintain model stability and interpretability
Learning Rate	0.01
Number of Iterations	1,000
Maximum Tree Depth	Five levels
Complementary Analysis	SHAP interpretation analysis
Model Evaluation	Confusion matrix, ROC curve, and AUC score

The study employed the Extreme Gradient Boosting (XGBoost) algorithm as the primary machine learning model to analyze students' support for ecology-based digital learning modules. The dataset was divided into 80% training data and 20% testing data to ensure balanced model validation. Hyperparameter optimization was conducted to maintain model stability and interpretability, with a learning rate of 0.01, 1,000 iterations, and a maximum tree depth of five levels. In addition, SHAP interpretation analysis was applied as a complementary approach to identify the contribution of each variable to the prediction results. Model performance was evaluated using a confusion matrix, Receiver Operating Characteristic (ROC) curve, and Area Under the Curve (AUC) score to assess classification accuracy and predictive capability.

Data Processing and Validation

Data analysis was conducted using Python 3.x with scikit-learn and XGBoost libraries. Cross-validation and data screening procedures were performed prior to analysis to improve model consistency and reliability. Outlier screening procedures were also conducted to identify inconsistent response patterns before model training and evaluation.

Results and Discussion

Result

Descriptive Statistics

The descriptive findings showed that most participating students demonstrated positive responses toward the integration of ecological themes into Indonesian language learning. A total of 85.8% of students agreed that environmental topics should be incorporated into classroom instruction, while 77.8% expressed favorable attitudes toward the use of digital learning modules. These findings indicate that ecology-based digital learning was generally well accepted among the participants can be seen in Figure 2 and Figure 3.

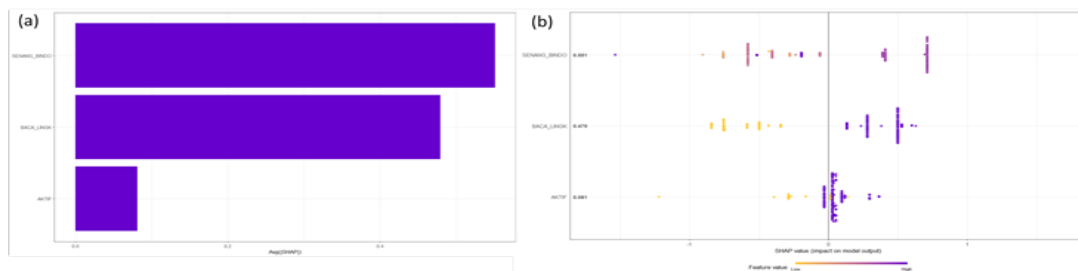


Fig 2. (a) Variable Importance Plot Model 1; (b) SHAP Summary Plot Model 1

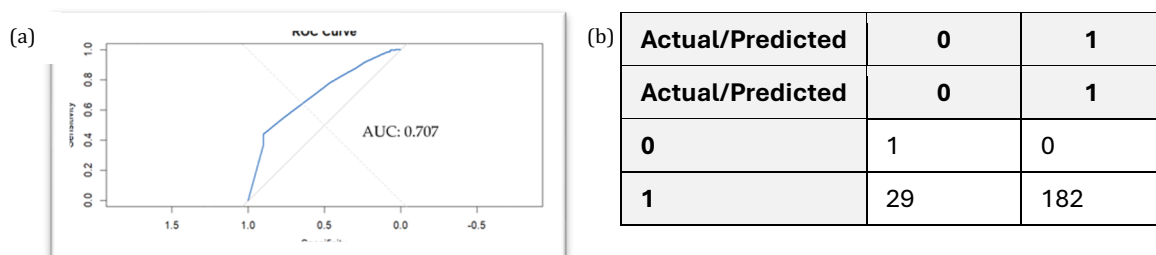


Fig 3. (a) Variable Importance Plot Model 1; (b) SHAP Summary Plot Model

The XGBoost classification models demonstrated acceptable predictive performance in identifying patterns associated with students’ support toward ecology-based digital Indonesian language modules. The models produced AUC values of 0.707 and 0.852, indicating moderate and relatively strong classification performance. These results suggest that the predictive models were capable of classifying student support patterns with acceptable accuracy and effectively capturing nonlinear relationships within educational datasets (Chen & Guestrin, 2016; Géron, 2022; Molnar, 2022). Feature importance analysis showed that ecological interest emerged as one of the strongest predictive variables associated with students’ support toward eco-digital learning modules. Technological perception also appeared as an important predictive feature within the classification models. Previous studies have suggested that feature importance analysis and interpretable machine learning approaches can reveal meaningful educational patterns and support understanding of how different variables contribute to prediction outcomes in educational contexts (Lundberg et al., 2020; Molnar, 2022; Khosravi et al., 2022).

SHAP Interpretation Analysis

SHAP analysis was conducted to examine the contribution patterns of predictor variables within the classification models. The SHAP summary plots indicated that ecological interest consistently demonstrated positive contribution tendencies toward prediction outcomes (Molnar, 2022). Technological perception also contributed meaningfully to the prediction of students’ support toward eco-digital learning environments (Baker & Inventado, 2021).

The SHAP dependency patterns additionally revealed variations in prediction tendencies among students with different levels of ecological engagement and technological perception. Several cases demonstrated relatively high ecological engagement accompanied by lower prediction tendencies toward fully digital instructional environments. Overall, the XGBoost and SHAP analyses demonstrated that ecological interest and technological perception were among the most influential predictive variables associated with students’ support toward ecology-based digital Indonesian language modules can be seen in Figure 4 and Figure 5.

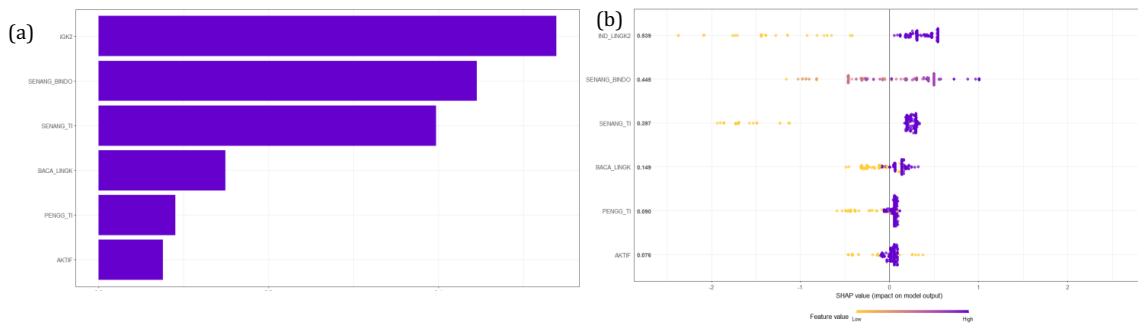


Fig. 4. (a) Variable Importance Plot Model 2;(b) SHAP Summary Plot Model 2

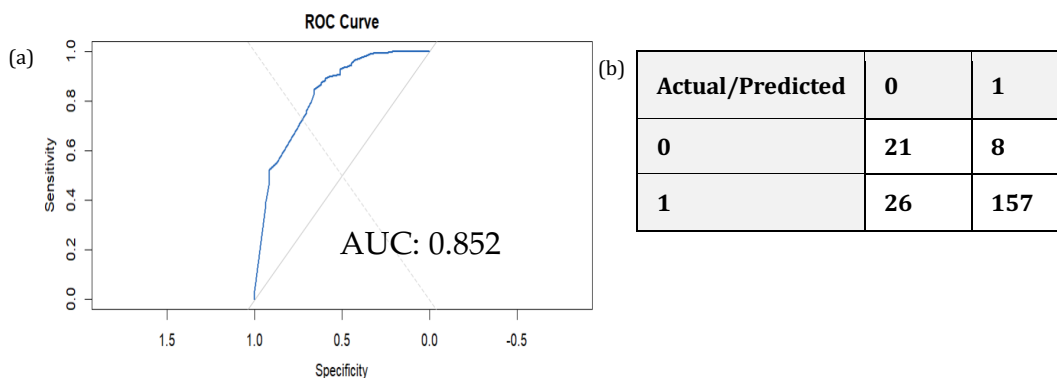


Fig 5. The Confusion Matrix of Model 2

Discussion

The results of this study demonstrated that ecological interest and technological perception were positively associated with students' support for ecology-based digital Indonesian language modules. Students who exhibited stronger environmental awareness, concern for ecological issues, and interest in sustainability tended to express more favorable attitudes toward environmentally oriented digital learning materials. Similarly, students who perceived digital technologies as useful, accessible, interactive, and easy to use showed higher levels of acceptance toward eco-digital learning environments. These findings are consistent with the Technology Acceptance Model (TAM), which emphasizes the importance of perceived usefulness and perceived ease of use in shaping individuals' acceptance of educational technologies (Granić & Marangunić, 2019). Previous studies have also reported that positive perceptions of digital technologies contribute to increased student engagement, motivation, and participation in technology-enhanced learning activities (Bond et al., 2021; Haleem et al., 2022; Howard et al., 2021; Chiu, 2022). Moreover, digital literacy has increasingly been recognized as a key competency that supports learners' adaptation to technology-rich educational environments and promotes meaningful participation in digitally mediated learning experiences (Falloon, 2020; Ng et al., 2021; van Laar et al., 2020).

The findings further suggest that ecological literacy can serve as an important pedagogical foundation for Indonesian language learning. Integrating environmental themes into language instruction enables students to participate in contextual learning experiences while fostering awareness of sustainability issues and environmental responsibility (Ardoin et al., 2020). Ecology-based digital modules provide opportunities for students to explore environmental narratives, engage in contextual reading activities, develop reflective writing skills, and participate in sustainability-oriented communication tasks connected to real-world ecological challenges. These findings support previous studies indicating that ecological pedagogy promotes meaningful learning experiences and strengthens students' environmental consciousness (Kopnina, 2020; Misiaszek, 2020). Furthermore, integrating ecological literacy into language learning can enhance students' ability to connect linguistic competencies with environmental awareness and sustainability-oriented behaviors (Ardoin et al., 2020; UNESCO, 2021). Therefore, Indonesian language instruction may function not only as a medium for language development but also as a vehicle for cultivating environmentally responsible literacy practices among elementary school students.

The SHAP interpretation results revealed variations in students' responses toward eco-digital learning environments. Although many students with strong ecological engagement demonstrated positive attitudes toward eco-digital learning, some exhibited relatively lower preferences for fully digital instructional approaches. This finding suggests that direct environmental interaction, experiential learning opportunities, and face-to-face engagement remain important components of sustainability-oriented education. Consequently, blended learning approaches that combine digital learning modules with authentic environmental activities may better accommodate diverse student preferences and learning needs. Similar conclusions have been reported in studies emphasizing the importance of balancing technological innovation with contextual and experiential learning experiences to improve student participation and understanding (Tang et al., 2021; Kopnina, 2020; Rasheed et al., 2020). Therefore, technology should complement rather than replace authentic environmental learning experiences within sustainability-oriented educational contexts.

The application of Extreme Gradient Boosting (XGBoost) and SHapley Additive exPlanations (SHAP) contributed substantially to identifying predictive patterns and understanding the relative influence of predictor variables within educational datasets. SHAP analysis enhanced model interpretability by illustrating how individual variables contributed to prediction outcomes and classification tendencies (Lundberg & Lee, 2017). Recent studies have highlighted the growing importance of explainable artificial intelligence in educational analytics because transparent models enable researchers and educators to better understand decision-making processes generated by machine learning algorithms (Wang et al., 2021; Zawacki-Richter et al., 2019; Khosravi et al., 2022; Viberg et al., 2023). The use of educational analytics further aligns with the broader objective of transforming educational data into meaningful insights that support evidence-based decision making and instructional improvement (Siemens & Long, 2011). Nevertheless, these analytical methods should be interpreted as predictive and interpretive tools rather than mechanisms for establishing causal relationships.

This study also contributes to the growing discussion on eco-digital pedagogy by integrating perspectives from technology acceptance and ecological literacy within the context of elementary Indonesian language education. While previous studies have generally examined technology acceptance and environmental literacy as separate constructs, this research explored their combined role in shaping students' support for sustainability-oriented digital learning environments. The incorporation of machine learning techniques into educational research additionally provides methodological value by

demonstrating how predictive analytics can be utilized to investigate complex educational phenomena. Such approaches are increasingly recognized as valuable tools for examining multidimensional educational relationships and improving analytical precision in educational research (Baker & Inventado, 2014; Siemens & Long, 2011; Viberg et al., 2024). However, these contributions should be interpreted within the scope of predictive educational analysis rather than theory-building or causal explanation.

Several limitations should be acknowledged. First, the study was conducted within a single educational setting, which may limit the generalizability of the findings to other schools and educational contexts. Second, the cross-sectional design captured students' perceptions at a single point in time and therefore could not identify changes in attitudes or behaviors over extended learning periods (Creswell & Creswell, 2018). Third, the predictive performance of machine learning models depends on the characteristics of the available dataset and may not fully represent broader contextual, social, and behavioral factors influencing educational outcomes. Future studies are encouraged to involve larger participant populations, longitudinal research designs, and comparative educational settings to obtain a more comprehensive understanding of eco-digital learning acceptance and sustainability-oriented digital pedagogy. Future research may also investigate blended ecological learning models that combine digital technologies with experiential environmental education to enhance student engagement and contextual learning experiences (Rasheed et al., 2020).

Additionally, future investigations could examine the influence of teachers' digital competence, parental involvement, and school technological infrastructure on students' acceptance of ecology-based digital learning modules. These contextual factors may play a significant role in shaping students' learning experiences and technological adaptation within sustainability-oriented educational settings. The inclusion of qualitative methods, such as interviews, classroom observations, and reflective learning journals, may also provide deeper insights into students' experiences, emotions, and learning behaviors during eco-digital learning activities (Falloon, 2020; Redecker, 2020). Such multidimensional approaches would contribute to a more comprehensive understanding of the implementation and effectiveness of environmentally oriented digital learning within elementary Indonesian language education.

Conclusion

This study concludes that ecological interest and technological perception are closely associated with elementary school students' support for ecology-based digital Indonesian language modules. Students with stronger environmental awareness and more positive perceptions of digital technology tend to show greater acceptance of sustainability-oriented digital learning resources. These findings highlight the importance of integrating environmental literacy with accessible, engaging, and age-appropriate digital learning environments. Practically, educators and instructional material developers are encouraged to design eco-digital learning materials that combine ecological themes, interactive digital features, and contextual real-world environmental activities. However, the study is limited by its single educational setting, cross-sectional survey design, and associative predictive model, which restrict generalization and causal interpretation. Future research should involve larger and more diverse participants, apply longitudinal approaches, and examine various educational contexts to better understand students' acceptance of eco-digital learning over time. Overall, this study underscores the need for sustainability-oriented digital learning that balances ecological content, technological accessibility, and meaningful contextual learning experiences in elementary education.

Declarations

- Author contribution** : Mundakir: Design the research, conducting experiment, data collection, data analysis, writing the article draft; Ade Hikmat: Design the research, securing the research funding, supervising the research, data validation, data curation, data analysis, writing the article draft, final draft; Siti Zulaiha: Design the research, supervising the research, data validation, writing the article draft, final draft.
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- Conflict of interest** : Both authors declare that they have no competing interests.
- Ethics Approval** : The protocol for this study received approval from the Ethics Committee of UHAMKA's Institute for Research, Community Service, and

Publication. The approval aligns with the committee's outlined guidelines for conducting research involving human participants.

Additional information : No additional information is available for this paper.

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