

Research Article

From scientific and technological literacy to pro-environmental behavior: The role of 21st-century skills in biology education

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This study examined how scientific and technological literacy relate to self-reported pro-environmental behavior through the mediating role of 21st-century skills among 578 undergraduate Biology Education students from 16 universities in Eastern Indonesia. Drawing on Social Cognitive Theory and the Action Competence Framework, creativity, critical thinking, collaboration, and communication were conceptualized as an integrated competence-enactment mechanism linking literacy to behavioral tendencies. Data were collected using a structured questionnaire and analyzed using PLS-SEM with SmartPLS 4. The 21st-century skills construct was modeled as a second-order mediating variable using the disjoint two-stage approach. The measurement model confirmed satisfactory reliability, convergent validity, and discriminant validity. The structural model showed that scientific literacy and technological literacy significantly predicted 21st-century skills, which emerged as the strongest predictor of self-reported pro-environmental behavior. Scientific literacy retained a small but significant direct effect, indicating complementary partial mediation, whereas technological literacy showed no significant direct effect, indicating indirect-only mediation. The mediated model explained 65.1% of the variance in pro-environmental behavior, compared with 50.6% in the direct-effect model. These findings demonstrate that 21st-century skills function as the key mediating mechanism through which literacy competencies are transformed into environmental behavioral tendencies and support the integration of scientific understanding, purposeful technology use, and action-oriented 4C learning in Biology Education curricula.

Keywords: 21st-century skills; Biology education; PLS-SEM; Pro-environmental behavior; Scientific literacy; Technological literacy

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1. Introduction

Environmental degradation, climate change, biodiversity loss, pollution, and unsustainable consumption have increased the urgency of preparing students who can understand

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environmental problems scientifically and translate that understanding into responsible action. Within this context, science education has an important role in developing forms of scientific and environmental literacy that extend beyond conceptual knowledge toward critical engagement with sustainability-related problems and participation in environmental action (Guerrero & Sjöström, 2025). This need is particularly relevant to Biology Education because prospective biology teachers engage directly with ecological systems, biodiversity, environmental change, conservation, and sustainability and may later influence how these issues are understood and addressed in school contexts.

However, environmental knowledge does not automatically result in pro-environmental behavior. Pro-environmental behavior broadly refers to actions intended to reduce negative environmental impacts or contribute to environmental sustainability (Mateer et al., 2022). Research has consistently demonstrated a gap between what individuals know about environmental problems and how they behave in response to them. Environmental knowledge may show only weak associations with reported behavior when it is considered independently of affective, motivational, or action-oriented factors (Maurer & Bogner, 2020). Liu et al. (2020), for example, showed that environmental knowledge was linked to pro-environmental behavior primarily through environmental attitudes and behavioral intentions rather than through a direct pathway. More recently, Chen and Erfanian (2026) found that environmental knowledge did not significantly predict pro-environmental behavior directly but contributed indirectly through environmental attitude. Evidence from university students in Kazakhstan similarly revealed a persistent knowledge-action gap despite relatively high levels of environmental awareness and knowledge (Abiltayeva et al., 2026). These findings suggest that explaining pro-environmental behavior requires attention not only to what students know but also to the competencies through which knowledge can become behaviorally meaningful.

Scientific and technological literacy represent two important cognitive resources within this process. Scientific literacy enables students to interpret scientific information, evaluate evidence and claims, and reason about complex socio-environmental problems. Contemporary approaches increasingly emphasize that scientific literacy should extend beyond canonical scientific knowledge toward critical participation and engagement with environmental and societal challenges (Guerrero & Sjöström, 2025). In Biology Education, such literacy can support students in interpreting ecological evidence, evaluating sustainability-related claims, and making informed decisions about environmental problems. Nevertheless, conceptual understanding alone may have limited behavioral implications when students lack the capacity or opportunity to apply what they know in authentic situations (Maurer & Bogner, 2020). Technological literacy similarly provides resources for accessing, evaluating, using, and communicating information through technological environments. Yet access to technology or environmental information should not be assumed to produce environmentally responsible behavior directly. Related evidence concerning internet use indicates that its relationship with pro-environmental behavior may operate through intervening factors such as environmental concern rather than through a simple direct pathway (Teng et al., 2025). Thus, both scientific and technological literacy may require additional competencies that support the enactment of knowledge in environmental contexts.

This study proposes that 21st-century skills provide such a competence-enactment pathway. Critical thinking, creativity, collaboration, and communication are increasingly conceptualized as interconnected rather than independent capabilities, with their coordinated functioning supporting complex problem solving, decision making, participation, and knowledge application (Thornhill-Miller et al., 2023). In sustainability contexts, critical thinking can support the evaluation of competing evidence and environmental claims; creativity can facilitate the generation of context-sensitive alternatives; collaboration can enable participation in collective environmental initiatives; and communication can support the articulation and dissemination of sustainability-related ideas. Evidence from sustainability education further indicates that reflective and project-based learning can promote critical and creative thinking when these capabilities are

explicitly embedded in authentic learning activities (O'Toole et al., 2026). More broadly, sustainability research has emphasized the importance of competencies that enable learners to move from understanding complex problems toward participation in transformative action (Redman & Wiek, 2021). From this perspective, the 4C skills can be conceptualized not merely as general educational outcomes but as mutually reinforcing capabilities through which literacy-based resources may be enacted.

Bandura's (1997) Social Cognitive Theory provides the overarching theoretical foundation for this proposed relationship. The theory explains behavior through reciprocal interactions among personal cognitive factors, behavioral processes, and environmental conditions and emphasizes individuals' capacity to regulate and enact behavior. Within the present study, scientific and technological literacy represent cognitive resources for understanding and evaluating environmental issues, whereas pro-environmental behavior represents the behavioral domain in which these resources may become expressed. The Action Competence Framework provides a complementary perspective by emphasizing learners' capacity to understand possibilities for action and participate purposefully in addressing environmental and sustainability problems (Jensen & Schnack, 1997). Recent evidence is consistent with this competence-based explanation. Sziva et al. (2026), for example, found that action competence mediated associations between students' experiences of Education for Sustainable Development and self-reported pro-environmental behavior across three national contexts. Similarly, research on university students has demonstrated that psychological and agentic factors such as environmental self-efficacy can contribute to the relationship between sustainability education and pro-environmental behavior (Zhang & Cao, 2025). Together, these perspectives suggest that the transition from literacy to behavior may depend on capabilities that enable individuals to evaluate, apply, communicate, and act on what they know.

Despite these developments, an important theoretical gap remains. Research on the knowledge-behavior relationship has largely explained the translation of environmental knowledge into behavior through affective and motivational mechanisms such as attitudes, behavioral intentions, perceived behavioral control, and self-efficacy (Chen & Erfanian, 2026; Liu et al., 2020; Zhang & Cao, 2025). Action competence research has further demonstrated that action-oriented capabilities may mediate relationships between sustainability education and pro-environmental behavior (Sziva et al., 2026). However, these approaches do not fully explain how scientific and technological literacy may be enacted through an integrated set of higher-order capabilities involving environmental problem solving, collective participation, and communication. At the same time, research on 21st-century skills frequently examines critical thinking, creativity, collaboration, and communication as educational competencies or graduate capabilities rather than as an integrated mediating mechanism connecting literacy resources with environmental behavioral tendencies (O'Toole et al., 2026; Thornhill-Miller et al., 2023). Thus, the central unresolved theoretical issue concerns the competence-enactment process through which different literacy resources become behaviorally meaningful.

To address this gap, the present study proposes a literacy-competence enactment-behavior pathway in which scientific and technological literacy are conceptualized as cognitive resources and the integrated 4C skills are positioned as action-oriented capabilities through which these resources may be applied. Rather than examining critical thinking, creativity, collaboration, and communication as isolated educational outcomes, the study models 21st-century skills as a second-order construct. This specification reflects the theoretical proposition that environmentally meaningful action may require the coordinated functioning of cognitive and social capabilities: evaluating environmental evidence, generating alternatives, participating collaboratively, and communicating ideas effectively. This conceptualization is consistent with the view that the 4Cs are dynamically interconnected (Thornhill-Miller et al., 2023) and with broader competency-based approaches that emphasize the application of knowledge to complex sustainability challenges (Redman & Wiek, 2021). Accordingly, the contribution of the study lies not simply in combining

scientific literacy, technological literacy, 21st-century skills, and pro-environmental behavior, but in examining whether an integrated competence-enactment pathway helps explain how literacy resources are associated with environmental behavioral tendencies.

The study examines this proposed pathway among undergraduate Biology Education students in Eastern Indonesia. This context provides an important extension to the existing literature because research on teacher education for sustainable development remains unevenly distributed internationally, with knowledge production concentrated predominantly in higher-income settings and comparatively limited representation from the Global South (Yang & Hu, 2026). The inclusion of 578 Biology Education students from 16 universities also enables the proposed relationships to be examined across a multi-institutional rather than a single-institution setting. Their status as prospective biology teachers is particularly relevant because the scientific, technological, and sustainability-related competencies developed during teacher education may subsequently inform their classroom practices and students' engagement with environmental issues. Accordingly, this study examines the direct relationships of scientific and technological literacy with self-reported pro-environmental behavior and investigates whether 21st-century skills function as a second-order mediating construct in these relationships. In doing so, it tests whether scientific and technological literacy show similar or distinct pathways toward pro-environmental behavioral tendencies through an integrated set of 21st-century skills.

2. Conceptual Framework and Hypothesis Development

The conceptual framework of this study is grounded in Bandura's (1997) Social Cognitive Theory [SCT], which explains behavior through the triadic reciprocal interaction among personal cognitive factors, behavioral patterns, and environmental influences. Within SCT, cognitive resources operate within reciprocal interactions involving personal agency, behavioral processes, and environmental conditions rather than through a single predetermined pathway (Bandura, 1997). This framework is further supported by the Action Competence Framework (Jensen & Schnack, 1997; Sziva et al., 2026), which emphasizes learners' capacity to understand possibilities for action and participate purposefully in addressing environmental and sustainability problems. The knowledge-behavior gap perspective further explains why scientific or environmental knowledge may not automatically result in pro-environmental behavior. Environmental knowledge can influence behavior through intervening affective, motivational, and agentic mechanisms, including attitudes, behavioral intentions, and self-efficacy (Chen & Erfanian, 2026; Liu et al., 2020; Zhang & Cao, 2025). Accordingly, this study focuses on a competence-action pathway rooted in SCT, in which scientific literacy and technological literacy serve as cognitive resources, 21st-century skills serve as competence-enactment capabilities, and self-reported pro-environmental behavior serves as the behavioral outcome.

In this formulation, the 4C skills are not treated as direct measures of self-efficacy. Rather, creativity, critical thinking, collaboration, and communication represent applied capabilities through which cognitive resources and personal agency may be enacted in environmental tasks. Because these capabilities are conceptually interconnected rather than fully independent, they can be considered an integrated competence system in the present model (Thornhill-Miller et al., 2023). This distinction allows literacy to be interpreted as a cognitive resource, 21st-century skills as a competence-enactment mechanism, and self-reported pro-environmental behavior as the associated behavioral tendency.

H1: Scientific literacy has a positive effect on self-reported pro-environmental behavior.

Scientific literacy refers to students' ability to understand scientific concepts, interpret evidence, evaluate scientific information, and apply scientific reasoning to real-world problems (Guerrero & Sjöström, 2025). In Biology Education, scientific literacy enables students to understand ecological processes, biodiversity loss, conservation issues, pollution, and socio-scientific issues related to sustainability. Scientifically literate students are more likely to recognize environmental problems as evidence-based issues, evaluate the consequences of human activities, and justify responsible

environmental choices (Liu et al., 2020). Therefore, students with higher scientific literacy are expected to demonstrate stronger self-reported pro-environmental behavior because they possess the conceptual and evidence-based understanding needed to make informed environmental decisions.

H2: Technological literacy has a positive effect on self-reported pro-environmental behavior.

Technological literacy refers to students' ability to access, evaluate, use, and communicate information through technology in a critical, ethical, and productive manner (Yao & Lin, 2026). In environmental learning, technological literacy enables students to use digital platforms, environmental databases, simulations, virtual laboratories, digital observation tools, social media, and learning management systems to obtain and share sustainability-related information (Trevisan et al., 2024). Nevertheless, technological literacy should not be assumed to directly produce pro-environmental behavior. Digital competence may remain behaviorally inert when it is limited to information access, operational tool use, or passive exposure to environmental content (Yang & Hu, 2026). Therefore, technological literacy becomes environmentally meaningful when students use digital resources for critical evaluation, creative problem solving, collaborative inquiry, and sustainability communication (Hakkarainen et al., 2024).

H3: Scientific literacy has a positive effect on 21st-century skills.

Scientific literacy is also expected to strengthen 21st-century skills because scientific learning requires students to observe phenomena, analyze problems, interpret evidence, evaluate claims, construct explanations, and communicate arguments (Xie & Yusuf, 2026; Yang & Hu, 2026). In Biology Education, these processes support ecological data interpretation, inquiry, argumentation, conservation problem analysis, and evidence-based discussion (Guerrero & Sjöström, 2025). Thus, scientific literacy functions not only as disciplinary knowledge but also as a cognitive foundation for developing integrated 21st-century skills (O'Toole et al., 2026).

H4: Technological literacy has a positive effect on 21st-century skills.

Technological literacy is expected to enhance 21st-century skills because effective technology use requires students to search for information, evaluate digital credibility, organize ideas, collaborate through digital platforms, and communicate findings (Ramdana et al., 2026). In Biology Education, the use of biodiversity databases, ecological simulations, virtual laboratories, learning management systems, and online collaborative media can strengthen students' higher-order competencies (Butera & Mukamwambali, 2026). Thus, technological literacy provides a digital foundation for developing 21st-century skills when technology is used for inquiry, problem solving, collaboration, and environmental communication (Priadi et al., 2025).

H5: 21st-century skills have a positive effect on self-reported pro-environmental behavior.

In this study, 21st-century skills are conceptualized as a second-order construct consisting of four dimensions: creativity, critical thinking, collaboration, and communication (Thornhill-Miller et al., 2023). This conceptualization is appropriate because pro-environmental behavior requires an integrated competency structure rather than isolated skills (Sziva et al., 2026). Creativity supports the design of alternative environmental solutions; critical thinking enables students to evaluate ecological evidence and misinformation; collaboration facilitates collective sustainability action; and communication helps students disseminate environmental ideas and mobilize participation (O'Toole et al., 2026; Wang et al., 2022). Therefore, 21st-century skills are expected to function as action-oriented competencies that transform literacy into environmental behavioral tendencies (Lewis & Bader, 2026).

H6: 21st-century skills mediate the relationship between scientific literacy and self-reported pro-environmental behavior.

The mediating role of 21st-century skills is central to this model. Scientific literacy may improve students' understanding of environmental problems, but such understanding does not automatically produce behavioral commitment (Guerrero & Sjöström, 2025). Through creativity,

critical thinking, collaboration, and communication, scientific literacy can be transformed from evidence-based understanding into self-reported pro-environmental behavior.

H7: 21st-century skills mediate the relationship between technological literacy and self-reported pro-environmental behavior.

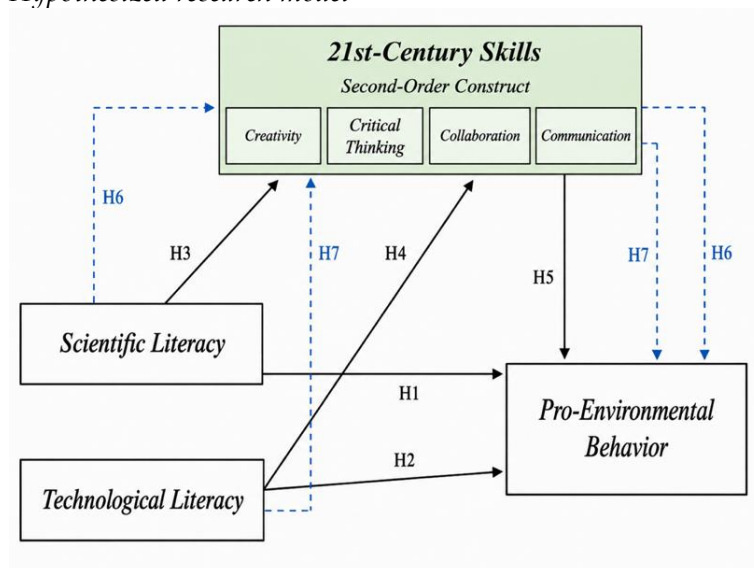
Similarly, technological literacy may provide access to environmental information and digital tools, but its behavioral effect depends on how students use those resources (Yang & Hu, 2026). Technological literacy becomes behaviorally meaningful when it is converted into critical, creative, collaborative, and communicative competencies for environmental action (O'Toole et al., 2026).

Overall, the proposed framework positions scientific literacy and technological literacy as exogenous constructs, 21st-century skills as a second-order mediating construct, and self-reported pro-environmental behavior as the endogenous construct (Herlinawati et al., 2024). This model addresses the knowledge-behavior and competence-action gaps by explaining how literacy-based competencies are transformed into pro-environmental behavioral tendencies through the integrated 4C skills: creativity, critical thinking, collaboration, and communication.

Figure 1 presents the hypothesized research model derived from the preceding theoretical arguments and hypotheses. The model positions scientific literacy and technological literacy as exogenous constructs, 21st-century skills as a second-order mediator comprising creativity, critical thinking, collaboration, and communication, and self-reported pro-environmental behavior as the endogenous construct.

Figure 1

Hypothesized research model



The solid paths represent the proposed direct relationships (H1–H5), whereas the indirect paths represent the mediating role of 21st-century skills (H6–H7). The model therefore tests whether literacy resources are associated with pro-environmental behavioral tendencies directly and through the coordinated enactment of the 4C skills.

3. Method

3.1. Research Design

This study employed a quantitative explanatory survey design to examine the direct and indirect associations among scientific literacy, technological literacy, 21st-century skills, and self-reported pro-environmental behavior. Partial Least Squares Structural Equation Modeling was used because the study tested a predictive mediation model involving multiple latent constructs (Sarstedt & Moisesescu, 2024). Scientific literacy and technological literacy were positioned as exogenous constructs, 21st-century skills as a mediating construct, and self-reported pro-

environmental behavior as the endogenous construct (Hair & Alamer, 2022). A direct-effect model without the mediator was also tested to compare whether the inclusion of 21st-century skills improved the explanatory power of the model. Because the study used cross-sectional data, the relationships should be interpreted as associations rather than definitive causal effects.

Sample size adequacy was assessed using both PLS-SEM-oriented and regression-based power considerations. Following the inverse square root method proposed by Kock and Hadaya (2018), the present sample size of 578 respondents provides adequate statistical power for detecting small standardized path coefficients of approximately .10–.11 at a 5% significance level and 80% statistical power. In addition, based on Cohen (1992) guidelines for multiple regression with three predictors, a minimum of 77 respondents is required to detect a medium effect size ($f^2 = 0.15$), whereas approximately 550 respondents are required to detect a small effect size ($f^2 = 0.02$) at 80% power. Therefore, the final sample of 578 respondents was considered sufficient for estimating the proposed PLS-SEM model and testing the hypothesized relationships.

Ethical considerations were addressed by ensuring voluntary participation, informed consent, anonymity, and confidentiality of responses. Before completing the questionnaire, participants were informed about the purpose of the study, the voluntary nature of their participation, their right to withdraw, and the use of the data for academic research purposes only. No personally identifiable information was collected, and all responses were analyzed in aggregate form. The study was conducted as an anonymous, minimal-risk educational survey and did not include experimental treatment, clinical intervention, or sensitive personal data collection.

3.2. Participants and Sampling

The participants in this study were 578 undergraduate Biology Education students from 16 universities in Eastern Indonesia. Biology Education students were selected because their academic background is closely related to ecosystems, biodiversity, conservation, environmental change, and sustainability issues. Participants were recruited using purposive convenience sampling through lecturer-facilitated online survey distribution. Purposive sampling was used because respondents were required to meet specific eligibility criteria, whereas convenience sampling was applied because the questionnaire was distributed through lecturers, classes, and student communication networks.

The inclusion criteria were active enrollment in a Biology Education program, participation in biology-related learning activities, and voluntary agreement to complete the questionnaire. After data screening, 578 valid responses were retained for analysis. All responses were complete, no duplicate entries were identified, and response patterns were examined before analysis. As an initial assessment, the sample exceeded the minimum requirement indicated by the ten-times rule for PLS-SEM analysis (Hair & Alamer, 2022). With 578 respondents, the sample was considered adequate for estimating the proposed structural model involving scientific literacy, technological literacy, 21st-century skills, and self-reported pro-environmental behavior.

Table 1 presents the distribution of participants across the 16 universities, whereas Table 2 summarizes their demographic characteristics. The study involved 578 participants from public universities ($n = 260$, 44.98%) and private universities ($n = 318$, 55.02%) located across Sulawesi, Papua, Maluku, and North Maluku. The sample comprised 495 female students (85.64%) and 83 male students (14.36%). Regarding age, the largest group consisted of students aged 19–20 years ($n = 286$, 49.48%), followed by those aged 21–22 years ($n = 199$, 34.43%), 18 years or younger ($n = 57$, 9.86%), and 23 years or older ($n = 36$, 6.23%). Participants were enrolled in Semester II ($n = 132$, 22.84%), Semester IV ($n = 144$, 24.91%), Semester VI ($n = 218$, 37.72%), and Semester VIII ($n = 84$, 14.53%), representing different stages of the undergraduate program. All participants were enrolled in Biology Education programs ($n = 578$, 100%), ensuring disciplinary consistency with the constructs examined in this study.

Table 1

Distribution of Participants across the 16 Universities

No.	University	<i>n</i>	%
1	UIN Alauddin Makassar	60	10.38
2	Universitas Puangrimaggalatung	55	9.52
3	Universitas Negeri Makassar	50	8.65
4	Universitas Muhammadiyah Makassar	49	8.48
5	Universitas Patompo	49	8.48
6	Universitas Muhammadiyah Bone	43	7.44
7	Universitas Cokroaminoto Palopo	42	7.27
8	Universitas Sulawesi Barat	42	7.27
9	Universitas Perjuangan Republik Indonesia	45	7.79
10	Universitas Papua	36	6.23
11	Universitas Muhammadiyah Parepare	35	6.06
12	Universitas Sembilanbelas November Kolaka	20	3.46
13	UIN Abdul Muthalib Sangadji Ambon	15	2.60
14	Universitas Cenderawasih	15	2.60
15	IAIN Ternate	12	2.08
16	Universitas Khairun Ternate	10	1.73

Table 2

Demographic Characteristics of Participants

Category	<i>n</i>	%
University type		
Public university	260	44.98
Private university	318	55.02
Gender		
Female	495	85.64
Male	83	14.36
Age		
18 years or younger	57	9.86
19–20 years	286	49.48
21–22 years	199	34.43
23 years or older	36	6.23
Semester		
Semester II	132	22.84
Semester IV	144	24.91
Semester VI	218	37.72
Semester VIII	84	14.53
Study program		
Biology Education	578	100.00

Because participation was voluntary and the survey was distributed through lecturer- and student-facilitated communication networks, the sample may have been affected by self-selection and accessibility biases. Students with greater academic engagement, better digital access, or stronger interest in environmental and sustainability issues may have been more likely to participate. Although participants were recruited from 16 universities, this institutional and geographic coverage does not establish statistical representativeness because probability-based sampling was not employed. Consequently, the findings should be interpreted as reflecting the characteristics of the participating undergraduate Biology Education students and should not be generalized to all Biology Education students in Eastern Indonesia or Indonesia as a whole.

3.3. Instruments and Data Collection

Data were collected using a structured questionnaire comprising 49 items across four constructs. The items were adapted and synthesized from established instruments and competency frameworks rather than adopted verbatim from a single scale. Scientific literacy was measured using seven items developed from the Scientific Literacy Survey for College Preparedness in STEM, the Test of Scientific Literacy Skills, and a PISA-based scientific literacy instrument (Benjamin et al., 2017; Gormally et al., 2012; Zhang et al., 2023). The items assessed the application of scientific concepts, explanation of phenomena, interpretation of data, evaluation of scientific information, use of evidence, formulation of investigable questions, and contextual scientific problem solving. Technological literacy was measured using seven items based primarily on DigComp 2.2 and the Students' Digital Competence Scale (Vuorikari et al., 2022), covering digital device and application use, information access and management, credibility evaluation, content processing, adaptation to new technologies, digital ethics and safety, and digital communication and collaboration.

The 21st-century skills construct was modeled as a second-order construct comprising four first-order dimensions: critical thinking, creativity, collaboration, and communication. Each dimension contained seven items, resulting in 28 items. The indicators were adapted mainly from the Student Instrument for Measuring Confidence in Key Skills, with additional critical-thinking indicators informed by the Critical Thinking Assessment-Scale Short Form (Bray et al., 2020; Payan-Carreira et al., 2022). Self-reported pro-environmental behavior was measured using seven items adapted and contextualized from the Pro-Environmental Behavior Scale, the Integrated Pro-Environmental Behaviours Scale, an Indonesian evaluation of environmentally friendly behavior, and research on sustainable paper consumption among university students (Curcio et al., 2025; Markle, 2013; Muliadi et al., 2025; Sopha, 2013). The items covered plastic reduction, waste sorting, water and energy conservation, environmental participation, sustainable transportation, informal environmental advocacy, and paper reduction. All 49 items were rated on a five-point Likert scale ranging from 1 = strongly disagree to 5 = strongly agree. Table 3 summarizes the constructs, dimensions, number of items, representative items, and principal sources.

The source instruments and competency frameworks were originally available in English. The selected indicators and item statements were translated into Indonesian by an expert and reviewed for semantic equivalence, language clarity, construct relevance, and contextual suitability for undergraduate Biology Education students. The adaptation process involved simplifying technical expressions, replacing school-specific or general contexts with academic and environmental contexts where necessary, and retaining the intended meaning of each construct. The Indonesian version was subsequently reviewed by an expert in Biology Education before administration.

Content validation was conducted by an expert in Biology Education using 10 criteria covering content relevance, construct clarity, language appropriateness, presentation, and overall feasibility, with a maximum score of 50 for each instrument. Scientific literacy and technological literacy each obtained 49/50 ($M = 4.90/5.00$), whereas 21st-century skills and self-reported pro-environmental behavior each obtained 48/50 ($M = 4.80/5.00$). Across the four instruments, the combined score was 194/200 ($M = 4.85/5.00$), indicating high content suitability. Minor revisions were made to item wording, contextual examples, and readability based on the expert's recommendations. A separate pilot test involving an independent sample was not conducted. Instead, the questionnaire underwent a final language and readability review before the main survey, and its psychometric properties were subsequently evaluated using the complete sample of 578 participants through indicator loadings, internal consistency reliability, convergent validity, and discriminant validity. The absence of an independent pilot sample is acknowledged as a methodological limitation.

Table 3

Instrument Sources, Dimensions, Number of Items, and Representative Items

<i>Construct/dimension</i>	<i>Measured indicators</i>	<i>Items</i>	<i>Representative item</i>	<i>Principal source(s)</i>
Scientific literacy	Concept application; explaining phenomena; interpreting data; evaluating sources and claims; using evidence; scientific questioning; contextual problem solving	7	"I am able to analyze and interpret scientific data presented in tables, graphs, or diagrams."	Benjamin et al. (2015); Gormally et al. (2012); Zhang et al. (2023)
Technological literacy	Device and application use; information search and management; credibility evaluation; content processing; technological adaptability; ethics and safety; digital communication and collaboration	7	"I am able to compare and evaluate the credibility, accuracy, and reliability of digital information before using it."	Tzafilkou et al. (2022); Vuorikari et al. (2022)
Critical thinking	Problem identification; comparison of perspectives; source evaluation; logical reasoning; argument analysis; critical questioning; evidence-based inference	7	"I am able to analyze an argument by considering both supporting and opposing evidence."	(Bray et al. (2020); Payan-Carreira et al. (2022)Bray et al. (2020)
Creativity	Idea fluency; alternative solutions; originality; synthesis; experimentation; perspective flexibility; elaboration	7	"I am able to combine different information, concepts, or experiences into a new idea or product."	Bray et al. (2020)
Collaboration	Shared goals; active contribution; respect for perspectives; role division; peer support; conflict management; shared responsibility	7	"I am able to work with group members to achieve mutually agreed goals."	Bray et al. (2020)
Communication	Oral communication; message organization; audience adaptation; multimodal communication; active listening; questioning; constructive feedback	7	"I am able to express ideas orally in a clear, coherent, and understandable manner."	Bray et al. (2020)
Self-reported pro-environmental behavior	Plastic reduction; waste sorting; water and energy conservation; environmental participation; sustainable transportation; environmental advocacy; paper reduction	7	"I reduce paper use by using digital technology in academic activities."	Curcio et al. (2025); Markle (2013); Muliadi et al. (2025); Sopha (2013)

3.4. Common Method Bias

Because all variables were measured using a self-report questionnaire at a single point in time, common method bias was addressed both procedurally and statistically. Procedural controls included anonymous responses, voluntary participation, clear item wording, and separation of constructs in the questionnaire to reduce respondents' tendency to provide uniform answers. Statistical assessment was conducted using the full collinearity VIF approach by examining the VIF values in the model. The results showed that the inner model VIF values ranged from 2.049 to 3.620. In general, these values were below the threshold of 5.00, indicating no serious collinearity problem.

3.5. Data Analysis

Data were analyzed using SmartPLS 4 with the partial least squares structural equation modeling [PLS-SEM] approach. PLS-SEM was used because this study aimed to examine predictive relationships among latent variables, analyze mediation effects, and evaluate a higher-order construct in a model involving several reflective constructs (Hair & Alamer, 2022). The analysis was conducted in two main stages: evaluation of the measurement model and evaluation of the structural model.

The measurement model was evaluated based on outer loadings, Cronbach's alpha, rho_A, composite reliability, average variance extracted, HTMT, the Fornell Larcker criterion, and cross-loadings. Indicators were considered to meet convergent validity when their outer loadings exceeded .70 and AVE values exceeded .50 (Dash & Paul, 2021). Construct reliability was considered adequate when Cronbach's alpha, rho_A, and composite reliability values were above .70. Discriminant validity was established when HTMT values were below .85 or .90, the square root of AVE was higher than the inter-construct correlations, and each indicator showed the highest loading on its intended construct (Sarstedt & Moisesescu, 2024).

The second-order construct of 21st-century skills was analyzed using the disjoint two-stage approach (Sarstedt et al., 2019). In the first stage, the four first-order dimensions creativity, critical thinking, collaboration, and communication were evaluated for reliability and validity (Hair & Alamer, 2022). In the second stage, the latent scores of these four dimensions were used to estimate 21st-century skills as a higher-order construct (Sarstedt & Moisesescu, 2024).

The structural model was evaluated using collinearity statistics, path coefficients, R^2 , f^2 , $Q^2/Q^2_{predict}$, total effects, and mediation analysis (Hair & Alamer, 2022). VIF values below 5.00 were considered acceptable, whereas values exceeding the more conservative threshold of 3.30 were interpreted cautiously. The significance of relationships among variables was tested using a bootstrapping procedure with 5,000 resamples (Hair & Alamer, 2022). Relationships were considered significant when $p < .05$ and the bootstrap confidence interval did not include zero. Mediation effects were evaluated through specific indirect effects. A significant direct effect and a significant indirect effect in the same direction were classified as complementary partial mediation, whereas a non-significant direct effect accompanied by a significant indirect effect was classified as indirect-only mediation.

4. Results

The results of the construct reliability and validity assessment show that all constructs in this study met the criteria for reliability and convergent validity (see Table 4). All outer loading values were above the threshold of .70, ranging from .777 to .929, indicating that all items were valid in representing their respective constructs. Scientific Literacy obtained a Cronbach's alpha value of .930, composite reliability rho_a of .933, rho_c of .943, and AVE of .705. Technological Literacy demonstrated very strong reliability, with Cronbach's alpha and rho_a values of .946, rho_c of .956, and AVE of .756. Furthermore, 21st Century Skills also met excellent criteria, with Cronbach's alpha of .936, rho_a of .936, rho_c of .954, and AVE of .838. Pro-Environmental Behavior obtained a Cronbach's alpha value of .936, rho_a of .939, rho_c of 0.948, and AVE of .724. Overall, all

Cronbach's alpha and composite reliability values exceeded .70, and all AVE values were above .50, indicating that the research instruments had high internal consistency and adequate convergent validity for structural model analysis.

The assessment of discriminant validity using the heterotrait-monotrait ratio confirmed that all constructs met the required criteria (see Table 5). The HTMT value between scientific literacy and technological literacy was .761, between 21st-century skills and scientific literacy was .848, and between 21st-century skills and technological literacy was .830. The HTMT values between self-reported pro-environmental behavior and scientific literacy, technological literacy, and 21st-century skills were .721, .672, and .856, respectively. All HTMT values were below .90, indicating adequate conceptual and empirical distinctiveness among the constructs

Table 4

Construct Reliability and Convergent Validity of the Measurement Model

<i>Construct/Item</i>	<i>OL</i>	<i>α</i>	<i>ρA</i>	<i>ρC</i>	<i>AVE</i>
Scientific Literacy		.930	.933	.943	.705
SL 1	.826				
SL 2	.863				
SL 3	.777				
SL 4	.853				
SL 5	.865				
SL 6	.837				
SL 7	.851				
Technological Literacy		.946	.946	.956	.756
TL 1	.847				
TL 2	.880				
TL 3	.838				
TL 4	.881				
TL 5	.896				
TL 6	.864				
TL 7	.847				
21st Century Skills		.936	.936	.954	.838
Creativity	.904				
Critical Thinking	.910				
Collaboration	.919				
Communication	.929				
Pro-Environmental Behavior		.936	.939	.948	.724
PEB 1	.820				
PEB 2	.856				
PEB 3	.867				
PEB 4	.862				
PEB 5	.798				
PEB 6	.893				
PEB 7	.857				

Note. OL = outer loading; α = Cronbach's alpha; ρA = composite reliability (rho_A); ρC = composite reliability (rho_C); AVE = average variance extracted.

Table 5

Discriminant Validity Assessment Using the Heterotrait-Monotrait Ratio

<i>Construct</i>	<i>Scientific Literacy</i>	<i>Technological Literacy</i>	<i>21st Century Skills</i>	<i>Pro-Environmental Behavior</i>
Scientific Literacy	—			
Technological Literacy	.761	—		
21st Century Skills	.848	.830	—	
Pro-Environmental Behavior	.721	.672	.856	—

The Fornell-Larcker criterion further confirmed the discriminant validity of the model (see Table 6). The square roots of AVE for scientific literacy, technological literacy, 21st-century skills, and self-reported pro-environmental behavior were .839, .869, .915, and .851, respectively, and each exceeded the corresponding inter-construct correlations. The correlation between scientific literacy and technological literacy was .715, between scientific literacy and 21st-century skills was .794, and between scientific literacy and self-reported pro-environmental behavior was .678. The correlation between technological literacy and 21st-century skills was .782, between technological literacy and self-reported pro-environmental behavior was .634, and between 21st-century skills and self-reported pro-environmental behavior was .804. These findings indicate adequate discriminant validity and support further structural analysis.

Table 6

Discriminant Validity Assessment Using the Fornell-Larcker Criterion

Construct	Scientific Literacy	Technological Literacy	21st Century Skills	Pro-Environmental Behavior
Scientific Literacy	.839			
Technological Literacy	.715	.869		
21st Century Skills	.794	.782	.915	
Pro-Environmental Behavior	.678	.634	.804	.851

The cross-loading results, as presented in Table 7, also supported discriminant validity, as all indicators had the highest loading on their intended constructs compared with their loadings on other constructs.

Table 7

Cross-Loading Analysis for Discriminant Validity Assessment

Item Variable	Scientific Literacy	Technological Literacy	21st Century Skills	Pro-Environmental Behavior
Creativity	.748	.675	.904	.698
Critical Thinking	.753	.755	.910	.721
Collaboration	.693	.707	.919	.762
Communication	.713	.724	.929	.762
PEB 1	.570	.515	.644	.820
PEB 2	.596	.545	.692	.856
PEB 3	.562	.548	.678	.867
PEB 4	.607	.602	.732	.862
PEB 5	.485	.452	.595	.798
PEB 6	.618	.578	.750	.893
PEB 7	.586	.525	.683	.857
SL 1	.826	.602	.680	.600
SL 2	.863	.570	.639	.565
SL 3	.777	.523	.543	.462
SL 4	.853	.611	.698	.594
SL 5	.865	.644	.701	.573
SL 6	.837	.625	.681	.567
SL 7	.851	.617	.701	.605
TL 1	.598	.847	.675	.540
TL 2	.639	.880	.702	.572
TL 3	.621	.838	.656	.549
TL 4	.616	.881	.661	.552
TL 5	.644	.896	.703	.562
TL 6	.598	.864	.666	.532
TL 7	.636	.877	.692	.551

The indicators of Creativity, Critical Thinking, Collaboration, and Communication loaded most strongly on the 21st Century Skills construct, with values ranging from 0.904 to 0.929. These values were higher than their loadings on Scientific Literacy, which ranged from 0.693 to 0.753, Technological Literacy, which ranged from 0.675 to 0.755, and Pro-Environmental Behavior, which ranged from 0.698 to 0.762. Similarly, the PEB 1-PEB 7 indicators loaded most strongly on Pro-Environmental Behavior, with values ranging from 0.798 to 0.893. The SL 1-SL 7 indicators showed the highest loadings on Scientific Literacy, ranging from 0.777 to 0.865, while the TL 1-TL 7 indicators loaded most strongly on Technological Literacy, ranging from 0.838 to 0.896. These results indicate that each indicator empirically reflected its intended latent construct more strongly than other constructs in the model.

The collinearity statistics based on the Variance Inflation Factor showed that the structural model did not suffer from multicollinearity among predictor constructs (see Table 8). The VIF values for the paths from Scientific Literacy to 21st Century Skills and from Technological Literacy to 21st Century Skills were both 2.049. Meanwhile, the VIF values for the paths from Scientific Literacy to Pro-Environmental Behavior, Technological Literacy to Pro-Environmental Behavior, and 21st Century Skills to Pro-Environmental Behavior were 2.884, 2.743, and 3.620, respectively. All VIF values were below the critical threshold of 5.00, indicating that the relationships among constructs did not show problematic collinearity that could distort parameter estimation. Therefore, Scientific Literacy, Technological Literacy, and 21st Century Skills were appropriate predictors in the structural model, as each provided independently interpretable contributions to Pro-Environmental Behavior.

Table 8

Collinearity Assessment of the Structural Model Using Variance Inflation Factor (VIF)

Construct	Scientific Literacy	Technological Literacy	21st Century Skills	Pro-Environmental Behavior
Scientific Literacy	—	—	2.049	2.884
Technological Literacy	—	—	2.049	2.743
21st Century Skills	—	—	—	3.620
Pro-Environmental Behavior	—	—	—	—

The direct hypothesis testing results showed that scientific literacy had a positive and significant association with 21st-century skills ($\beta = .480$, $t = 10.767$, $p < .001$). Technological literacy also had a positive and significant association with 21st-century skills ($\beta = .438$, $t = 9.730$, $p < .001$). These results indicate that both forms of literacy were important predictors of 21st-century skills, with scientific literacy showing a slightly stronger contribution in the model.

Regarding direct associations with self-reported pro-environmental behavior, scientific literacy showed a small positive and significant coefficient ($\beta = .110$, $t = 1.993$, $p = .046$) (see Table 9).

Table 9

Direct Path Coefficients and Hypothesis Testing Results

Structural Path	β	M	SD	t	p
Scientific Literacy → 21st Century Skills	.480	.479	.045	10.767	< .001
Scientific Literacy → Pro-Environmental Behavior	.110	.109	.055	1.993	.046
Technological Literacy → 21st Century Skills	.438	.439	.045	9.730	< .001
Technological Literacy → Pro-Environmental Behavior	-.012	-.011	.045	.267	.790
21st Century Skills → Pro-Environmental Behavior	.726	.726	.061	11.911	< .001

Note. β = standardized path coefficient (original sample); M = bootstrap sample mean; SD = standard deviation; $t = t$ statistic; $p = p$ value.

In contrast, technological literacy did not show a significant direct association ($\beta = -.012$, $t = 0.267$, $p = .790$). Meanwhile, 21st-century skills showed the strongest positive and significant association

with self-reported pro-environmental behavior ($\beta = .726$, $t = 11.911$, $p < .001$). These findings suggest that the association between technological literacy and self-reported pro-environmental behavior operates primarily through 21st-century skills rather than through a direct pathway.

As shown in Table 10, the indirect-effect results showed that scientific literacy had a positive and significant association with self-reported pro-environmental behavior through 21st-century skills ($\beta = .349$, $t = 7.364$, $p < .001$). Technological literacy also had a positive and significant indirect association through 21st-century skills ($\beta = .318$, $t = 7.887$, $p < .001$). These results confirm that 21st-century skills function as a strong mediating mechanism linking scientific and technological literacy with self-reported pro-environmental behavior.

Table 10

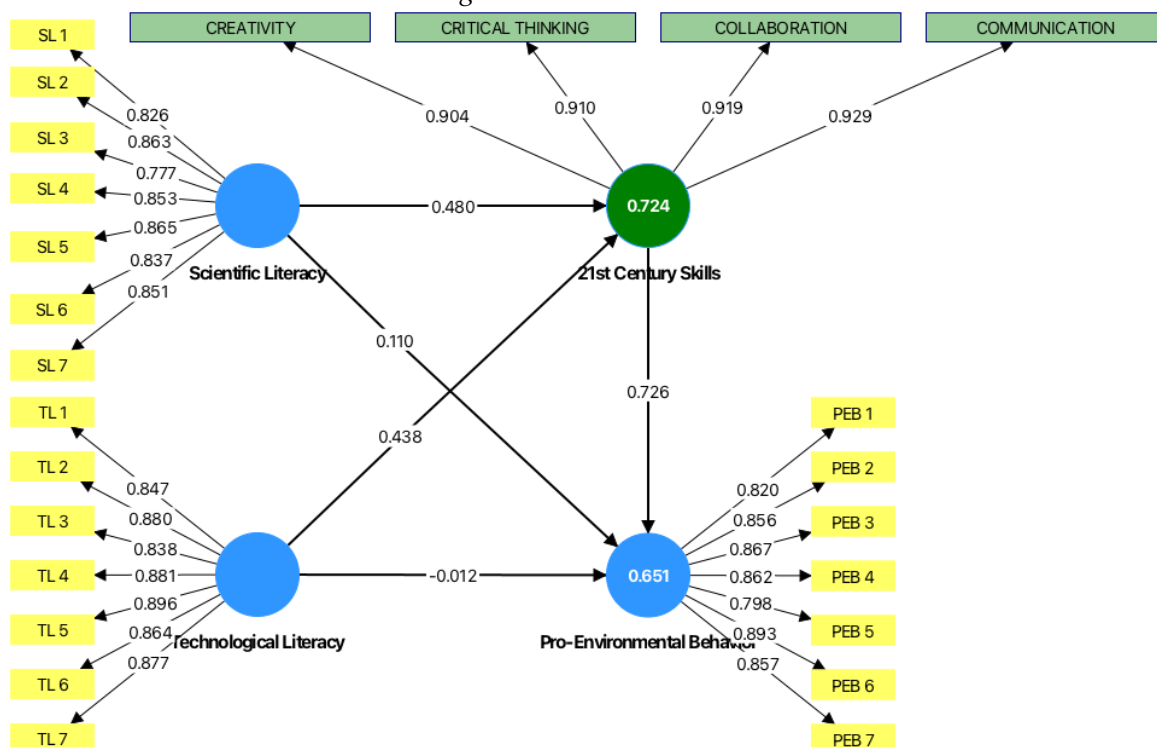
Indirect Path Coefficients and Mediation Testing Results

Structural Path	β	M	SD	t	p
Scientific Literacy → Pro-Environmental Behavior	.349	.348	.047	7.364	< .001
Technological Literacy → Pro-Environmental Behavior	.318	.319	.040	7.887	< .001

Note. β = standardized total effect (original sample); M = bootstrap sample mean; SD = standard deviation; t = t statistic; p = p value.

The structural model estimation showed that scientific literacy and technological literacy were positively associated with 21st-century skills, with path coefficients of .480 and .438, respectively. Together, these constructs explained 72.4% of the variance in 21st-century skills ($R^2 = .724$). Scientific literacy, technological literacy, and 21st-century skills explained 65.1% of the variance in self-reported pro-environmental behavior ($R^2 = .651$). The strongest coefficient was observed for 21st-century skills (.726), followed by scientific literacy (.110), whereas technological literacy showed a very small negative direct coefficient (-.012). Indicator loadings ranged from .777 to .865 for scientific literacy, .838 to .896 for technological literacy, .904 to .929 for 21st-century skills, and .798 to .893 for self-reported pro-environmental behavior. These findings, as shown in Figure 2, demonstrate the model's explanatory capacity and the central bridging role of 21st-century skills.

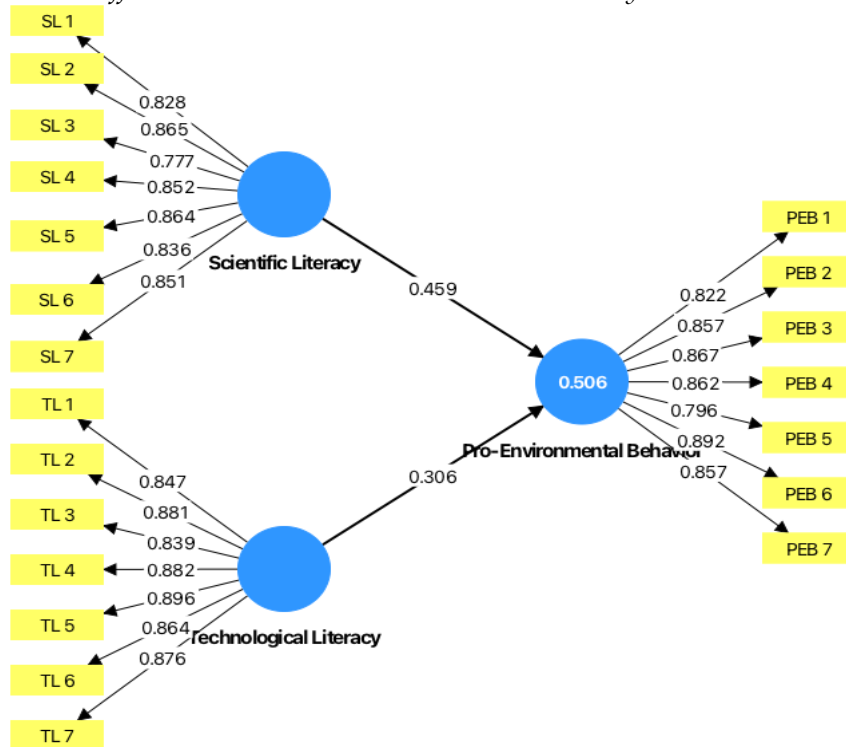
Figure 2

Structural Model with as a Mediating Variable

The alternative structural model without 21st-century skills (see Figure 3) showed positive coefficients from scientific literacy and technological literacy to self-reported pro-environmental behavior (.459 and .306, respectively). Together, the two constructs explained 50.6% of the variance in self-reported pro-environmental behavior ($R^2 = .506$). Indicator loadings ranged from .777 to .865 for scientific literacy, .839 to .896 for technological literacy, and .796 to .892 for self-reported pro-environmental behavior. These findings indicate that scientific literacy contributed more strongly than technological literacy in the direct-effect model.

Figure 3

Direct-Effect Structural Model without 21st Century Skills as a Mediating Variable



5. Discussion

The findings of this study demonstrate that the inclusion of 21st-century skills substantially improves the explanatory power of the model. In the direct-effect model, scientific literacy and technological literacy explained 50.6% of the variance in pro-environmental behavior. However, when 21st-century skills were included as a mediator, the explained variance increased to 65.1%. This improvement indicates that students' literacy competencies are more strongly associated with self-reported pro-environmental behavior when they are transformed into action-oriented competencies. In other words, scientific and technological literacy do not operate merely as independent knowledge resources; rather, their behavioral relevance becomes stronger when students are able to apply them through creativity, critical thinking, collaboration, and communication. This finding supports the competence-action perspective, which suggests that knowledge and literacy must be converted into practical competencies before they can meaningfully shape environmental behavioral tendencies (Olsson et al., 2022).

The significant effects of scientific literacy and technological literacy on 21st-century skills indicate that both forms of literacy provide important foundations for developing higher-order competencies. Scientific literacy had a slightly stronger effect, suggesting that interpreting evidence, evaluating scientific claims, and reasoning about environmental issues provide a cognitive basis for critical thinking, creativity, collaboration, and communication (Sun et al., 2022). Recent research supports this interpretation. Guo et al. (2026) reported that scientific reasoning and argumentation in socio-scientific contexts were associated with critical and integrative thinking,

while Guerrero and Sjöström (2025) emphasized that critical scientific literacy can extend disciplinary understanding toward environmental agency and collective action. For Biology Education students, scientific literacy supports the interpretation of ecological data, analysis of biodiversity loss, evaluation of conservation problems, and explanation of environmental phenomena using scientific evidence (Pessoa et al., 2024). Recent reviews further suggest that concept-focused pedagogies alone may be insufficient for developing action-oriented competencies (Xie & Yusuf, 2026), whereas reflective and project-based sustainability learning can support critical and creative thinking (O'Toole et al., 2026). Thus, scientific literacy should be understood not only as mastery of biological concepts but also as a foundation for inquiry, argumentation, problem-solving, and evidence-based environmental decision-making.

Although scientific literacy showed a statistically significant direct effect on pro-environmental behavior, the coefficient was small and close to the conventional significance threshold. This result should therefore be interpreted cautiously. The small direct effect suggests that scientific literacy alone may not be sufficient to produce strong pro-environmental behavioral tendencies. This finding is consistent with the knowledge-behavior gap, where students may understand environmental problems scientifically but may not automatically translate that understanding into daily environmental practices (Mago et al., 2025). Recent evidence further supports this interpretation. Mago et al. (2025) demonstrated that the relationship between environmental knowledge and pro-environmental behavior requires serial mediation through attitude and sensitivity. The stronger indirect effect of scientific literacy through 21st-century skills indicates that the contribution of scientific literacy is primarily mediated by students' ability to think critically, design solutions creatively, collaborate with others, and communicate environmental ideas effectively (Chen & Erfanian, 2026; Olsson et al., 2022). Therefore, the role of scientific literacy in environmental education should be strengthened through learning experiences that require students to apply scientific reasoning in authentic environmental contexts (Guo et al., 2026).

The non-significant direct effect of technological literacy on pro-environmental behavior represents one of the most important findings of this study. Technological literacy did not directly predict self-reported pro-environmental behavior, indicating that the ability to access or use technology does not automatically lead to environmentally responsible behavior (Yang & Hu, 2026). This result suggests that technological literacy may remain behaviorally inert if it is limited to operational digital skills, information access, or general technology use (Azennoud, 2022). Students may be competent in using digital platforms, online resources, or social media, but such competence may not necessarily result in waste reduction, energy conservation, environmental participation, or sustainable daily practices (Wang et al., 2022). Recent research further indicates that digital technology in education does not inherently produce sustainability-oriented engagement when it is used merely for information access or operational tool use. Instead, digital innovations become more meaningful when they are embedded in authentic, experiential, and sustainability-oriented learning contexts that support critical evaluation, creative problem solving, collaboration, and environmental communication (Noor, 2026; Saputri et al., 2026; Uluçınar & Sezer, 2026). Therefore, technological literacy becomes environmentally meaningful only when it is converted into critical evaluation, creative problem solving, collaboration, and communication (Herlinawati et al., 2024; Uluçınar & Sezer, 2026).

The significant indirect effect of technological literacy through 21st-century skills strengthens this interpretation. The mediation result shows an indirect-only mediation pattern, meaning that technological literacy contributes to pro-environmental behavior only through 21st-century skills. This finding provides an important contribution to sustainability education and digital learning research. It suggests that technological competence should not be treated as an automatic driver of environmental behavior; rather, its contribution depends on pedagogical design, sustainability-oriented contexts, and opportunities for learners to transform digital competence into action-oriented capabilities (Saputri et al., 2026). Technology therefore needs to be pedagogically directed

toward environmental inquiry, sustainability projects, digital collaboration, ecological data interpretation, and environmental communication. When these tools are integrated into inquiry-based or project-based learning, technological literacy can support students in evaluating environmental information, developing creative solutions, collaborating in sustainability activities, and communicating environmental messages (Yarmi et al., 2026).

The dominant direct effect of 21st-century skills on pro-environmental behavior confirms the central role of integrated higher-order competencies in environmental education. Pro-environmental behavior requires more than knowledge acquisition; it requires students to analyze ecological problems, generate solutions, work collectively, and communicate ideas to others (Sass et al., 2025). Critical thinking enables students to evaluate scientific evidence, identify misinformation, and assess environmental risks. Creativity enables them to design alternative solutions to ecological problems. Collaboration supports participation in group-based environmental initiatives, while communication helps students disseminate sustainability messages and influence others (Guerrero & Sjöström, 2025; O'Toole et al., 2026). Thus, the 4C dimensions, creativity, critical thinking, collaboration, and communication function as the practical mechanism through which literacy is transformed into environmental behavioral tendencies (Lewis & Bader, 2026). Recent evidence further indicates that action competence and integrated sustainability competencies provide important pathways through which educational experiences are translated into environmental engagement (Olsson et al., 2022; Sziva et al., 2026). This supports the decision to conceptualize 21st-century skills as a second-order construct rather than as isolated competencies.

The mediation analysis provides a more nuanced explanation of how literacy competencies influence pro-environmental behavior. For scientific literacy, the results indicate complementary partial mediation because both the direct and indirect effects were significant and positive. However, because the direct effect was small, the substantive contribution of scientific literacy appears to operate mainly through 21st-century skills. This interpretation is consistent with Mago et al. (2025), who reported that the relationship between environmental knowledge and pro-environmental behavior operates through affective and evaluative pathways rather than knowledge alone. It also aligns with Social Cognitive Theory, which emphasizes that cognitive resources require transformation through self-efficacy and applied competencies before influencing purposeful behavior (Bandura, 1997). For technological literacy, the results indicate indirect-only mediation because the direct effect was not significant, whereas the indirect effect through 21st-century skills was significant. This distinction is theoretically important because it shows that scientific literacy retains a small direct association with environmental behavior, while technological literacy requires conversion into action-oriented competencies before it becomes behaviorally relevant. This finding is supported by Yang and Hu (2026), who showed that digital literacy influences green-oriented behavior through psychological and awareness-related mechanisms, and by Sass et al. (2025), who demonstrated that action competence mediates the pathway from sustainability education to pro-environmental behavior. Taken together, these findings show that 21st-century skills are not merely learning outcomes but a mediating mechanism that explains how literacy-based competencies become environmental behavioral tendencies (Sziva et al., 2026).

The different mediation patterns provide a domain-sensitive refinement of the competence-action perspective. Scientific literacy showed complementary partial mediation: it retained a small direct association with self-reported pro-environmental behavior while also operating substantially through 21st-century skills. This pattern suggests that scientific reasoning and evidence evaluation may have some immediate relevance for environmental judgment, but their behavioral relevance becomes stronger when enacted through critical, creative, collaborative, and communicative capabilities. This interpretation is consistent with contemporary scientific literacy perspectives that emphasize movement from disciplinary understanding toward agency, public participation, and environmentally responsible action (Guerrero & Sjöström, 2025). In contrast,

technological literacy showed indirect-only mediation, indicating that access to digital information and the ability to use technological resources function as enabling conditions rather than automatic behavioral drivers. Technological literacy becomes environmentally meaningful when students use digital resources to assess information credibility, investigate environmental problems, develop alternatives, collaborate with others, and communicate sustainability messages. This asymmetry extends existing knowledge-behavior models by challenging the assumption that all literacy domains become behaviorally relevant through an equivalent process; instead, the findings support a domain-sensitive literacy-competence enactment-behavior explanation (Sziva et al., 2026).

These findings have important implications for Biology Education. Biology Education programs should not rely solely on conceptual instruction about ecosystems, biodiversity, pollution, conservation, and climate change. Instead, learning should provide opportunities for students to apply scientific and technological literacy in authentic environmental contexts (Markula & Aksela, 2022). For example, students can be engaged in ecological field projects, campus waste audits, biodiversity mapping, conservation campaigns, laboratory waste reduction initiatives, environmental data interpretation, and community-based sustainability projects. Such activities can help students connect biological knowledge with real environmental problems while simultaneously developing creativity, critical thinking, collaboration, and communication (Tang et al., 2020; Xi & Wang, 2022). This approach is especially important for future biology teachers, who are expected to transfer sustainability-oriented learning practices to schools and communities.

At the curricular level, the findings suggest that environmental education should integrate scientific literacy, technological literacy, and 21st-century skills in a coherent learning design (Landolfi, 2023; Lewis & Bader, 2026; Sziva et al., 2026). Recent studies reinforce this curricular direction by showing that sustainability education is more effective when it moves beyond knowledge transmission toward competency-based and action-oriented learning. Sass et al. (2025) demonstrated that action competence represents an important pathway connecting sustainability education with pro-environmental behavior, while O'Toole et al. (2026) found that reflective and project-based learning approaches can strengthen critical thinking and creativity in sustainability contexts. Inquiry-based learning, project-based learning, socio-scientific issue-based learning, STEM-integrated learning, and LMS-supported collaborative learning are particularly relevant because they require students to investigate problems, use evidence, apply digital tools, work in teams, and communicate solutions (Markula & Aksela, 2022; O'Toole et al., 2026; Wang et al., 2022). Assessment should also move beyond measuring conceptual knowledge alone by including students' ability to analyze environmental issues, evaluate digital information, design sustainability solutions, collaborate in environmental projects, and communicate evidence-based recommendations (Landolfi, 2023; Qhobela et al., 2027; Sass et al., 2025). This competency-oriented assessment approach is consistent with recent perspectives emphasizing that scientific and technological literacy should be evaluated through students' capacity to apply knowledge, participate in sustainability actions, and respond to complex socio-environmental challenges (Xie & Yusuf, 2026). Such assessment practices would better capture the competence pathway through which literacy is transformed into pro-environmental behavioral tendencies.

The findings also have implications for higher education policy and sustainability-oriented institutional programs. Universities seeking to promote sustainable behavior should integrate digital transformation with their sustainability strategies rather than treating these as separate institutional agendas, as digital technologies can support sustainability competencies, innovation, and broader sustainable development efforts in higher education (Trevisan et al., 2024). This integration should move beyond the general use of technology toward authentic, discipline-based learning experiences that connect digital tools with environmental inquiry and engagement. For example, technology-enhanced nature projects can strengthen preservice teachers' environmental awareness, technological self-efficacy, and pedagogical knowledge (Uluçınar & Sezer, 2026), while multimedia-based approaches can support achievement and retention in undergraduate

environmental education (Eze et al., 2026). Technological literacy is therefore particularly valuable when students can use digital technologies purposefully for learning and communication rather than merely operate digital tools (Azennoud, 2022). More broadly, evidence that technology-enhanced learning can improve academic outcomes further supports the purposeful pedagogical integration of digital tools rather than technology use for its own sake (Güler et al., 2022). Accordingly, Biology Education curricula should incorporate digitally supported environmental inquiry, sustainability-oriented practical work, and interdisciplinary projects that connect disciplinary knowledge with environmentally responsible decision-making and authentic environmental contexts (Qhobela et al., 2026).

Despite its contributions, this study has several limitations. First, the cross-sectional survey design limits causal interpretation, so the relationships among constructs should be understood as associative rather than definitive causal effects. Second, pro-environmental behavior was measured using self-reported questionnaire data rather than direct behavioral observation. Third, because all data were collected from the same respondents using the same instrument, common method bias should be acknowledged as a potential limitation. Fourth, the sample was limited to Biology Education students, which may restrict the generalizability of the findings. Future studies should use longitudinal, observational, multi-source, or mixed-method designs with broader samples to further validate the proposed model.

This study contributes to environmental education by showing that scientific literacy and technological literacy are important but insufficient foundations for pro-environmental behavior unless they are transformed into action-oriented competencies. The central finding is that 21st-century skills serve as the key mediating mechanism linking literacy to self-reported pro-environmental behavior. Scientific literacy contributes directly and indirectly, although its direct contribution is small, whereas technological literacy contributes only indirectly through 21st-century skills. These findings highlight that technological competence becomes behaviorally meaningful only when students use it for critical, creative, collaborative, and communicative environmental action. Therefore, environmental education in Biology Education should be designed to integrate literacy development, digital competence, and 4C-based learning experiences to foster stronger sustainability-oriented behavioral tendencies.

6. Implications

The findings of this study offer theoretical, pedagogical, and practical implications for Biology Education. Theoretically, the results confirm that scientific literacy and technological literacy do not automatically shape pro-environmental behavior, but need to be transformed through 21st-century skills. Thus, creativity, critical thinking, collaboration, and communication serve as key mechanisms linking literacy competencies to sustainability-oriented behavioral tendencies.

Pedagogically, Biology learning should be designed to integrate scientific literacy, technological literacy, and 21st-century skills in authentic environmental contexts. Activities such as conservation projects, environmental data analysis, campus waste audits, socio-scientific issue-based learning, and digital environmental campaigns can encourage students to apply knowledge and technology to real action.

At the curriculum and institutional levels, Biology Education programs should strengthen inquiry-based, project-based, socio-scientific issue-based, STEM-integrated, and digitally supported learning oriented toward sustainability. Assessment should also move beyond conceptual mastery to include students' ability to analyze environmental issues, design solutions, collaborate, and communicate evidence-based recommendations. These findings also suggest that future research should test this model using longitudinal, experimental, or observational designs to capture actual pro-environmental behavior.

7. Conclusion

This study demonstrates that scientific literacy, technological literacy, and 21st-century skills

provide an integrated framework for explaining self-reported pro-environmental behavior among Biology Education students. The findings indicate that scientific literacy and technological literacy contribute to the development of 21st-century skills, which represent the strongest pathway toward pro-environmental behavior. While scientific literacy retained a small but significant direct effect, technological literacy influenced pro-environmental behavior indirectly through 21st-century skills. These findings highlight that literacy competencies become behaviorally meaningful when transformed into creativity, critical thinking, collaboration, and communication.

The main contribution of this study lies in demonstrating the mediating role of 21st-century skills as a competence-based pathway linking literacy and environmental behavior. The findings suggest that pro-environmental behavior is not formed solely through knowledge acquisition or digital capability, but through the development of action-oriented competencies that enable students to analyze environmental problems, design solutions, collaborate in sustainability initiatives, and communicate environmental messages. Therefore, Biology Education programs should integrate scientific literacy, technological literacy, and 21st-century skills through inquiry-based learning, project-based learning, STEM-integrated learning, socio-scientific issue-based learning, and digital environmental learning experiences.

Despite these contributions, several limitations should be acknowledged. The cross-sectional design limits causal interpretation, and the use of self-reported measures may have introduced social desirability bias, leading participants to overstate environmentally responsible practices and potentially inflate some observed relationships. Actual behavior may also differ from reported behavior because environmental actions are shaped by infrastructure, cost, convenience, institutional policies, and situational opportunities. Therefore, the findings should be interpreted as associations with perceived pro-environmental behavioral tendencies rather than as evidence of objectively verified environmental actions. Because all constructs were measured from the same respondents using a single self-report questionnaire, common method bias cannot be completely ruled out, while the focus on Biology Education students limits broader generalizability. Future studies should employ longitudinal, observational, multi-source, or mixed-method designs and triangulate self-reports with behavioral observations, activity logs, or institutional records.

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Declaration of interest: The authors declare no conflict of interest.

Ethics declaration: This study involved undergraduate Biology Education students who participated voluntarily. Before completing the questionnaire, participants were informed about the purpose of the study, the voluntary nature of participation, the anonymity and confidentiality of their responses, and their right to withdraw at any time without penalty. Informed consent was

obtained from all participants, and all data were analyzed and reported anonymously. Formal ethics committee approval was not required for this study under the applicable institutional guidelines, as the research involved anonymous survey data and did not include any intervention or collection of sensitive personal information.

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