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Development and validation of an education for sustainable development integrated STEM module

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ABSTRACT

Education for sustainable development (ESD) faces significant implementation challenges in science, technology, engineering, and mathematics (STEM) classrooms, including limited hands-on learning tools, disconnected curricula, and insufficient teacher training in sustainability integration. This study addresses these gaps by developing and evaluating the ESD I-STEM module, a novel approach that integrates ESD, STEM, and digital learning tools to teach biodiversity. Designed using the ASSURE instructional model and adopting a mixed-methods design, the module incorporates digital comics, interactive games, digital posters, and problem-based learning (PBL) to enhance student engagement, digital literacy, and sustainability awareness. Expert validation by eight specialists confirmed the module's excellent content validity (95%), significantly exceeding standard benchmarks. Reliability analysis of student responses showed strong internal consistency (Cronbach's alpha=0.820). Practical implementation revealed high usability, with mean evaluation scores ranging from 4.43 to 4.93 on a 5-point Likert scale. The ESD I-STEM module effectively addresses key gaps in sustainability education through a well-validated and classroom-ready framework for ESD-STEM integration. Results demonstrate its effectiveness as a rigorously tested and usable educational resource that promotes meaningful engagement with sustainability concepts while supporting STEM learning objectives. This study offers educators a proven model for delivering integrated ESD-STEM instruction that prepares students to address real world environmental challenges.

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1. INTRODUCTION

Education for sustainable development (ESD) has emerged as a transformative approach that equips learners with the knowledge, skills, values, and attitudes needed to address complex environmental and social challenges [1], [2]. Anchored in Sustainable Development Goal (SDG) 4, particularly target 4.7, ESD promotes inclusive and high-quality education that fosters global citizenship, critical thinking, and sustainability-oriented action [3], [4]. Previous studies have demonstrated that embedding ESD principles into secondary education can strengthen students' environmental awareness, behavioral intentions toward conservation, and motivation to learn through digital tools such as tablets and interactive resources [5]–[8]. However, despite increasing policy attention, the integration of ESD in formal schooling remains limited due to systemic, institutional, and pedagogical challenges [9], [10].

To address these global challenges in ESD implementation, science, technology, engineering, and mathematics (STEM) education has increasingly been positioned as a strategic pedagogical approach for advancing sustainability learning. STEM education centered on science, technology, engineering, and mathematics offers a promising avenue to advance the objectives of sustainable development [11]. Beyond preparing students for a technology-driven future, STEM fosters critical thinking, innovation, and problem-solving skills essential for addressing real-world sustainability issues [12], [13].

Recent empirical studies further support the effectiveness of integrating ESD within STEM instruction. For instance, Abdurrahman *et al*. [14] demonstrated that STEM-based learning activities centered on renewable energy significantly enhanced students' systems thinking and problem-solving skills by situating learning within authentic sustainability contexts. Similarly, Budiarti *et al*. [15] reported that ESD-integrated STEM science modules focusing on environmental pollution improved students' science literacy and fostered high levels of learning independence. Collectively, these findings highlight the pedagogical potential of ESD-integrated STEM modules, while also underscoring the need for systematically designed and empirically validated instructional models suitable for secondary school contexts.

Within this global educational landscape, national education systems play a critical role in translating ESD-STEM aspirations into classroom practice. In Malaysia, national policies such as the Malaysian Education Development Plan emphasize the importance of STEM in preparing a future-ready workforce while also supporting gender equity, teacher competency, and quality instruction [16], [17]. Moreover, student engagement in contextualized, project-based STEM activities promotes confidence, autonomy, and digital literacy, all of which contribute to holistic development and sustainable learning practices [18]–[20]. Such experiences not only cultivate communication and teamwork skills but also encourage students to connect scientific inquiry with real-world sustainability issues.

Despite strong policy support and growing empirical evidence, challenges persist in the practical integration of ESD principles within STEM education. Many teachers lack adequate training and confidence to deliver interdisciplinary content that combines environmental science and sustainability concepts [21]–[23]. These constraints are further intensified by limited professional development opportunities [24], overreliance on traditional teacher-centered pedagogy [25], and insufficient teacher competence in designing ESD-infused lessons [26]. In addition, resource shortages, financial constraints, and inadequate institutional readiness impede efforts to embed sustainability within STEM learning experiences [27], [28].

Addressing these challenges requires innovative, research-based instructional designs that meaningfully connect ESD and STEM in classroom practice. Scholars have emphasized the importance of structured professional development, access to instructional resources, and curricula that link theory with authentic sustainability issues [29]–[31]. However, although existing studies have explored theoretical ESD-STEM connections, empirical research focusing on the systematic design, validation, and evaluation of integrated instructional modules remains scarce [32]. Furthermore, persistent difficulties in assessing students' STEM-based problem-solving abilities and effectively embedding digital tools highlight the lack of robust, validated instructional frameworks that embed sustainability principles in STEM learning [33], [34].

Therefore, a systematic instructional design approach is needed to bridge the gap between ESD theory and STEM classroom practice. In response to these gaps, this study develops and validates the ESD I-STEM module an innovative teaching tool designed to integrate sustainability concepts within the Malaysian Form 2 science curriculum. Grounded in the analyze learners; state learning objectives; select technology, media and materials; utilize technology, media, and materials; require learner participation; and evaluate and revise (ASSURE) instructional design framework, the module incorporates digital and problem-based learning (PBL) elements to promote meaningful engagement, digital literacy, and sustainability awareness among students. Specifically, the objectives of this study are to design an ESD-integrated STEM module aligned with national curriculum standards and to evaluate its content validity, face validity, reliability, and usability. The findings contribute a validated, research-based instructional model that supports educators in implementing ESD through STEM pedagogy, addressing key barriers to sustainability integration in secondary education.

2. METHOD

2.1. Research design

This study employed a mixed-methods approach to develop, validate, and evaluate the ESD I-STEM module, which integrates ESD with STEM. The module was tailored for the Malaysian Form 2 science curriculum, with a focus on biodiversity. The module was developed using the ASSURE instructional design model, selected for its structured yet flexible approach to embedding digital tools in classroom instruction. This model aligns well with a mixed-methods research framework, allowing both quantitative data (e.g., Likert-scale evaluations and reliability scores) and qualitative insights (e.g., open-ended student feedback) to guide iterative refinement. The ASSURE model is a systematic instructional design framework for developing comprehensive educational materials and engaging learning activities [35]. Figure 1 outlines the sequential phases of the ASSURE model used in this study: i) analyze learners; ii) state learning objectives; iii) select technology, media and materials; iv) utilize technology, media, and materials, and v) require learner participation; and vi) evaluate and revise. For example, in the analyze learners' phase, the Form 2 students' prior knowledge, learning needs, and familiarity with STEM concepts related to biodiversity were examined through preliminary classroom observations and baseline assessments, which informed subsequent instructional decisions.

Figure 1. Steps in ASSURE model

2.2. Module structure and curriculum mapping

The development of the ESD I-STEM module is strategically aligned with the evolving needs of contemporary education, particularly within the context of Form 2 science under the biodiversity topic. The mapping process is grounded in the principles of PBL, which encourages active student inquiry, collaborative learning, and a student-centered approach core elements of the Malaysian STEM education framework. Designed to integrate ESD and STEM components, the module ensures that students not only acquire scientific knowledge but also develop the skills and values necessary to address real-world sustainability challenges. The structure of the module is closely tied to the curriculum and assessment standard document (DSKP), ensuring relevance and compliance with national education standards as shown in Table 1.

Table 1. Mapping for ESD I-STEM module

Unit	Module topic	Duration	Learning standards (ESD I-STEM)	Module activities	Relevant SDGs
1	Let's discover biodiversity	1 hour	- Explain the meaning of biodiversity - Discuss the importance of biodiversity - Relate prior knowledge to biodiversity loss	- Read a digital comic on biodiversity - Group discussion based on comic content - Write findings and reflection	SDG 4.7, SDG 15
2	Our mission: managing biodiversity	1 hour	- Justify the need for effective biodiversity management - Explain methods of conservation and preservation - Select resources from the Internet and share on Padlet	- Read comic as stimulus - Choose and upload images with descriptions to Padlet - Write activity reflections	SDG 4.7, SDG 15
3	Exploring BioD venture: a digital game on organism classification	2 hours	- Classify organisms using dichotomous keys - Describe major taxonomic groups - Apply classification knowledge using a digital game	- Introductory explanation on organism classification - Play the BioD Venture digital game - Complete worksheet and write reflections	SDG 4.7, SDG 15
4	Global warrior mission: PBL	1 hour	- Discuss biodiversity threats through PBL - Integrate knowledge, attitudes, and behaviors of global citizenship - Use technology for information gathering	- Introduction to PBL and global citizenship - Instruction on creating posters - Guide on using Google Scholar - Group discussions using a PBL template	SDG 4.7
5	ESD awareness mission	2 hours	- Demonstrate ESD awareness in daily life (knowledge, attitude, behavior) - Justify the need for ESD and global citizenship in biodiversity - Communicate ESD awareness through digital posters	- Explain assessment rubrics - Group poster presentations and discussion session - Document findings from other groups' presentations and write reflections	SDG 4.7

3. RESULTS AND DISCUSSION

3.1. Step 1: analyze learners

The first step in the ASSURE model is analyzing learner characteristics, which is essential to ensure that the development of the module meets the specific needs of the learners [36]. Using purposive sampling, this study involved 60 Form 2 students from a public secondary school in the Seremban district, selected based on their enrollment in the target science curriculum and demonstrated access to digital learning tools. To protect confidentiality during analysis, all questionnaires were pseudonymized and stripped of identifying information prior to data processing [37]. This sampling approach ensured participants represented the intended user population with shared characteristics. Based on the framework proposed by Smaldino *et al*. [38], the analysis focused on three main aspects: i) general learner characteristics; ii) prior knowledge; and iii) learning styles. In terms of general characteristics, the target students were 14 years old and represented diverse socioeconomic backgrounds from the Seremban area. Findings showed that 93% of the students were Malay, while 7% were Indian. The gender distribution comprised 33 male students (55%) and 27 female students (45%). These findings highlight the need for an inclusive and context-sensitive instructional design to ensure that all learners have equitable access to effective teaching and learning processes.

In terms of prior knowledge, the study analyzed responses from a questionnaire using a 5-point Likert scale (1=strongly disagree to 5=strongly agree) with SPSS Version 29, employing descriptive statistics. The findings revealed that students demonstrated varying degrees of competence and inclination in areas related to technology, learning methods, and environmental awareness. The highest mean scores were for the items related to technological competence, with “skilled at using mobile phones or tablets” (mean=4.33), “skilled at using computers” (mean=4.07), and “comfortable using technology for learning” (mean=4.10), indicating high levels of confidence in using digital tools. However, in terms of independent learning, lower mean scores were recorded, such as “I am able to study independently” (mean = 3.08) and “I need help from the teacher for explanations” (mean=3.73), suggesting a continued reliance on teacher support. Students also showed interest in new learning methods, with a relatively high mean of 4.13.

When it comes to environmental awareness, students showed lower levels of prior knowledge, particularly for “I know the importance of biodiversity” (mean=2.92) and “I often keep up with global sustainability issues” (mean=2.67). Nevertheless, a moderate level of understanding was recorded for the statement “I understand that animals and plants are threatened by human actions” (mean=3.45). In summary, the findings indicate that the students have strong digital literacy skills, moderate capacity for self-directed learning, and relatively low prior awareness of environmental issues. These insights are critical in guiding the development of the ESD I-STEM Module to better align with the learners’ profiles and enhance the effectiveness of instruction in sustainability education.

Furthermore, the findings from the learning style analysis revealed clear tendencies among the students. A total of 47% of the students showed a preference for the visual learning style, followed by 35% who were more comfortable with the kinesthetic style, and 18% exhibited an auditory learning preference. This module was designed taking into account the students’ learning profiles, which are predominantly visual (47%) and kinesthetic (35%) learners. To address the needs of visual learners, the module integrates various innovative digital components, including digital comics that combine narrative elements with scientific content, as well as educational digital games that enable virtual exploration. Meanwhile, to cater to kinesthetic learners, the module offers group activities involving a PBL approach that includes data collection, cooperative group discussions, hands-on projects such as creating infographic posters, all of which can be conducted within the classroom setting.

3.2. Step 2: state learning objectives

Based on the needs analysis conducted, the topic of biodiversity from the Form 2 science syllabus was selected as the primary focus for the ESD I-STEM Module. This selection was made with reference to the Ministry of Education Malaysia’s DSKP for Form 2 science, which outlines two main subtopics under the biodiversity chapter. However, for the purpose of this module, the researcher developed learning objectives that not only cover the existing curriculum content but also integrate elements of ESD and global citizenship as added value and novelty to the study. To ensure structured cognitive progression, the learning objectives were developed using action verbs aligned with Bloom’s taxonomy [39], [40], systematically advancing from lower-order to higher-order thinking skills across the module units. These objectives were designed to ensure that students not only understand scientific concepts related to biodiversity but also connect them to global environmental issues and their roles as responsible global citizens. The learning objectives for the ESD I-STEM Module are summarized in Table 2.

Table 2. Learning objectives for the module

No.	Unit and theme	Learning objectives
1	Unit 1: let's get to know biodiversity	Students are able to define the meaning and importance of biodiversity through digital comic activities
2	Unit 2: our mission! Managing biodiversity	Students are able to explain methods of biodiversity management through digital comics and Padlet activities
3	Unit 3: Exploration of BioD venture-digital organism classification game	Students are able to classify organism using the BioD venture digital game
4	Unit 4: global warrior mission: PBL	Students are able to evaluate the concepts of global citizenship and ESD awareness through PBL activities
5	Unit 5: ESD awareness mission	Students are able to communicate and propose actions about global biodiversity threats and practice ESD awareness through digital poster activities

3.3. Step 3: selecting strategies, technology, media, and materials

The ESD I-STEM module applies the 5E learning model [41] as the foundation for inquiry-based instructional design. This model consists of five main phases: i) engage, aimed at stimulating students' interest and activating their prior knowledge; ii) explore, guiding students to conduct active investigations; iii) explain, assisting students in constructing conceptual understanding; iv) elaborate, encouraging the application of knowledge in new contexts; and v) evaluate, designed to holistically assess learning achievement. Each phase is systematically designed to facilitate teachers in implementing inquiry-based approaches while ensuring students actively participate in STEM-oriented learning activities [42]. Table 3 provides a summarized overview of the strategies, media, and materials selected for the ESD I-STEM Module, aligned with each phase of the 5E learning model. To further illustrate how these digital tools are integrated across the learning process, Figure 2 presents the infographic showing the interconnection of digital comics, games, Padlet activities, and digital poster tasks across the five phases of the 5E learning model.

Table 3. Phases of the 5E learning model

5E phase	Learning objective	Technology/media and materials used
Engage	To stimulate interest and trigger initial inquiry on the topic	Digital comics (PDF)
Explore	Students explore issues/topics through personal and collaborative experiences before explanation	Padlet, BioD venture game (genially and educaplay), and internet browser
Explain	Students explain findings, teacher provides scientific explanations based on student data	Padlet, PowerPoint, and YouTube videos/interactive infographics
Elaborate	Applying knowledge in new contexts; solving real-world problems	Padlet and poster digital (Canva)
Evaluate	Assessing student understanding and providing reflections on learning	Rubric forms (Google Form/PDF) and written/video reflections

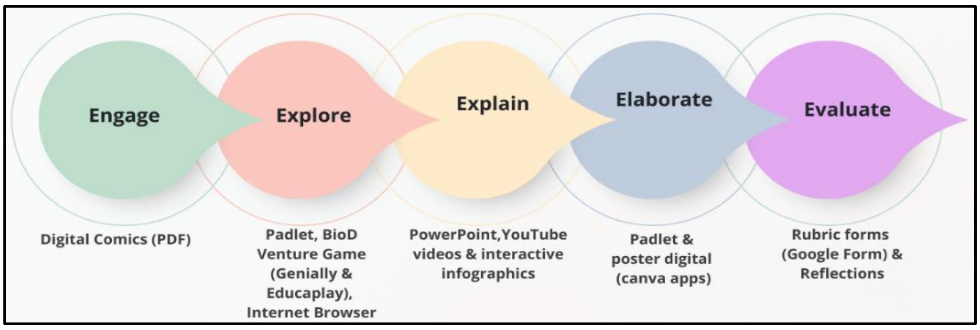

Figure 2. Integration of technology, media, and materials across 5E learning model

3.4. Step 4: use of technology, media, and materials

The successful implementation of teaching and learning relies heavily on carefully planned technology, media, and materials [43], [44]. Following the ASSURE instructional design model, five key steps (5Ps) guide the integration of technology to align with students' needs and learning objectives. The steps are: i) preview the materials; ii) prepare the materials; iii) prepare the learning environment; iv) prepare the learners; and v) provide the learning experience.

3.5. Step 5: require learner participation

Active student engagement is essential for meaningful learning [45]. The ESD I-STEM module encourages student participation through reflection and group discussions after each major activity. After activities, students complete self-reflections to assess their understanding of biodiversity, global citizenship, and ESD awareness, connecting new knowledge to their prior experiences. Small group discussions help students identify strengths and weaknesses in their work and improve communication skills by sharing constructive feedback [46]. Teachers facilitate post-presentation question and answer sessions to deepen understanding and evaluate mastery, promoting critical thinking and interactive dialogue. This reflective, collaborative, and interactive approach, grounded in constructivist and cognitive theories, helps students build new knowledge while developing soft skills like communication, critical thinking, and problem-solving, preparing them for real-world challenges. For example, during the unit 5 activity, students were required to present a digital poster, which was assessed using a rubric-based evaluation framework as in Table 4. Performance was rated on a four-point scale ranging from 1 (weak) to 4 (excellent), ensuring transparency in assessment and supporting active learner participation and reflective learning.

Table 4. Digital poster presentation assessment rubric

Criteria	Descriptor	Score (1-4)
Poster content	Information presented is accurate and relevant to the theme “Global Biodiversity Threats and ESD Awareness”. Relevant facts are clearly explained.	1 2 3 4
Poster design	The poster is neat, visually appealing, and well organized. Text, images, and visual elements are easy to read and effectively arranged. Creative use of Canva is evident.	1 2 3 4
Clarity of presentation	Information is presented clearly and fluently using appropriate and easily understood language. Visual aids are used effectively to support the presentation.	1 2 3 4
Understanding of topic	Demonstrates a strong understanding of global biodiversity threats and conservation strategies. Able to respond to questions confidently and accurately.	1 2 3 4
Interaction and feedback	Responds appropriately to questions and feedback from peers. Actively engages peers in constructive discussion.	1 2 3 4
Group collaboration	All group members contribute to the presentation and demonstrate effective teamwork and coordination.	1 2 3 4

3.6. Step 6: evaluation and improvement

This step represents the final phase of the ASSURE instructional design model, aimed at evaluating and improving the developed module. The evaluation of the ESD I-STEM module was conducted by obtaining content validation from experts and face validation to assess language and module design aspects. In this phase, the researcher also assessed the reliability and usability of the module. Improvements were made based on feedback from both experts and students as users.

3.6.1. Content validity of the module

The developed module must undergo a validation process by experts to assess the suitability of the content and clarity of language used [47]. According to Lynn [48], a panel of 6 to 10 experts is generally sufficient to establish content validity, ensuring reliable consensus without overextending the process. In this study, eight experts from various fields related to the module content were appointed to evaluate it using a 5-point Likert scale (1=strongly disagree to 5=strongly agree). The experts included specialists in environmental education, STEM education, citizenship studies, digital education, and science curriculum development. Among them, three were university lecturers holding PhDs from Public Higher Education Institutions (IPTA), one lecturer from Kolej Permata Insan, two assistant district education officers, and the remaining were experienced teachers including excellent teachers and senior subject teachers. All experts provided comprehensive feedback on the module’s content, pedagogical approach, and appropriateness of activities according to students’ cognitive levels. Each expert was provided with the ESD I-STEM module mapping and a content validation form for evaluation. Content validation was conducted using SPSS Version 29, with expert ratings analyzed to establish instrument validity. The mean scores ranging from 4.38 to 4.88 as shown in Table 5 indicate strong expert agreement across all validated components. The feedback was used by the researcher to make improvements before the module’s intervention implementation.

Using the content validity formula employed in previous module validation research [49], the content validity index (CVI) was calculated by dividing the total score given by experts by the maximum possible score, then multiplying by 100%. The ESD I-STEM module achieved a high content validity score of 95%, well above the commonly accepted threshold of 70% for strong validity. This confirms that the module’s content is appropriate and suitable for teaching and learning in schools. The decimal validity coefficient of 0.95 further supports the module’s statistical reliability.

Table 5. Mean scores for content validation of module

No	Statement	Mean score
1	This module content can increase students' knowledge of global citizenship	4.75
2	This module content can increase students' knowledge of global biodiversity threats through PBL activities	4.50
3	This module content can increase students' knowledge of their responsibilities as global citizens	4.75
4	This module content can enhance students' communication skills related to global sustainability issues	4.50
5	This module content can improve students' self-reflection skills on global sustainability in the context of biodiversity	4.63
6	This module content can improve students' digital literacy through digital learning platforms and STEM integration	4.75
7	This module content can improve students' skills in using digital technology and the internet	4.75
8	This module content can improve students' skills in searching, evaluating, and presenting information through digital platforms such as digital comics and digital games on biodiversity topics	4.63
9	This module content can improve students' skills in accessing scientific information and using it to understand global and local sustainability issues	4.75
10	This module content can improve students' communication skills through digital scientific posters	4.75
11	This module content can increase students' ESD awareness in the context of biodiversity threats	4.63
12	This module content can help students relate ESD awareness and global citizenship in the biodiversity context	4.63
13	This module content can foster students' responsible attitudes towards environmental sustainability	4.63
14	This module content can help students communicate ESD awareness through digital posters	4.88
15	The teaching and learning strategies used in this module are based on constructivist theory	4.88
16	The teaching and learning strategies used in this module are based on behaviorist theory	4.63
17	The teaching and learning strategies used in this module are based on cognitive load theory	4.50
18	The teaching and learning strategies used in this module are based on cognitive theory of multimedia learning	4.88
19	The teaching and learning strategies used in this module are based on theory of planned behavior	4.63
20	The teaching and learning strategies use the 5E instructional model	4.88
21	The teaching and learning strategies use the ASSURE model	4.88
22	The learning objectives in the module are suitable for students	4.38
23	The content of this module fits within the allocated time	4.75
24	The activities in this module enable students to collaborate in groups	4.63
25	This module is suitable to be used as learning material	4.75
	Overall mean score	4.73

3.6.2. Face validity of the module

In addition to content validity, the study also assessed the module's face validity, focusing on language clarity and design suitability. As the module is written entirely in the Malay language and contains numerous scientific terms, three experts from the content validation panel, together with an additional Malay language expert, reviewed the language style, scientific terminology, and design aspects. The face validity assessment employed a 5-point Likert scale covering language factors such as sentence clarity, term accuracy, and appropriateness for students' cognitive levels. The mean scores for language aspects ranged from 4.75 to 5.00, demonstrating a high degree of validity. For design aspects, evaluations focused on font type, font size, graphic colors, and the usability of the user guide. Mean scores for these design elements ranged between 4.5 and 5.00, also indicating strong validity.

3.6.3. Reliability of the module

We assessed the reliability of the module using the Cronbach's alpha coefficient based on feedback from students who participated in the module intervention activities. The 30 students who completed the module activities responded to a reliability questionnaire. The questionnaire evaluated students' perceptions of the module structure, clarity of instructions, effectiveness of activities, and suitability of materials for their learning level. Our analysis yielded a Cronbach's alpha coefficient of 0.820 for the overall module. According to Fraenkel and Wallen [50], an instrument is considered highly reliable if the Cronbach's alpha coefficient exceeds 0.700. Therefore, this result indicates that the ESD I-STEM module demonstrates high reliability and can be used consistently in the current study context as well as in future teaching and learning implementations.

3.6.4. Usability of the module

Using a 5-point Likert scale (1=strongly disagree to 5=strongly agree), the evaluation showed consistently high usability scores for the ESD I-STEM Module, with all individual items scoring between 4.43 and 4.93 and an overall mean of 4.81. These results indicate that participants strongly agreed with statements about the module's usability, as all scores fell between the 'agree' (4.0) and 'strongly agree' (5.0) ranges. The high scores across all items demonstrate that the module is not only theoretically sound but also practically feasible, user-friendly, and ready for classroom implementation.

The positive usability ratings were supported by students' open-ended feedback, which emphasized the module's effectiveness in promoting meaningful, student-centered learning. Students appreciated the use of digital tools, which enhanced their understanding of biodiversity and global citizenship while encouraging collaboration and critical thinking core elements of both PBL and ESD. Students noted increased awareness of environmental issues, particularly species extinction, and expressed a stronger appreciation for biodiversity conservation. The narrative-driven digital comic and immersive BioD Venture game were especially effective in fostering emotional engagement and contextual understanding.

> "*This module helps me understand biodiversity concepts through engaging digital activities like games and information searches. I enjoy learning through group activities*." (Student A)
> "*I like the reflection activity after learning. It helps me think more deeply about why biodiversity is important*." (Student C)
> "*I didn't realize so many animals have become extinct. Now I better understand the importance of protecting the environment*." (Student D)

These responses highlight the module's success in integrating ESD and STEM content through technology-enhanced, reflective, and collaborative strategies. Figure 3 displays the module cover and an overview of the ESD I-STEM module's key components.

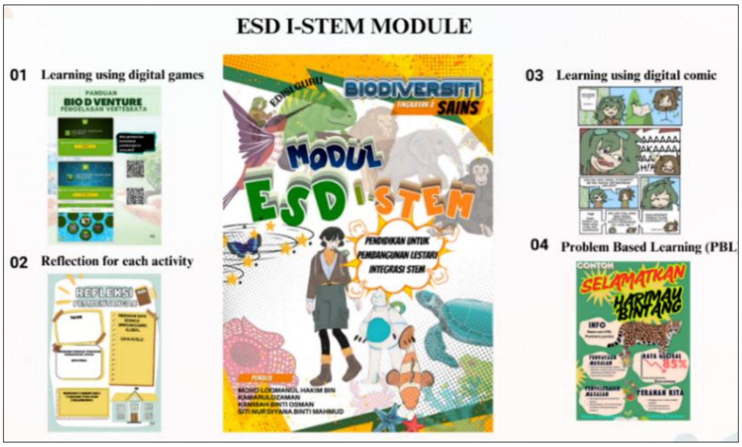

Figure 3. Overview of the ESD I-STEM module's key components

4. CONCLUSION

In conclusion, the ESD I-STEM Module, developed through the systematic ASSURE instructional design model, successfully integrates ESD with STEM education to align with Malaysia's Form 2 science curriculum. Rigorous evaluations confirmed its high content validity, reliability and usability with multidisciplinary experts endorsing its clear structure, quality, and relevance. By embedding PBL and interactive digital elements, the module fosters active student engagement, enhances conceptual understanding of biodiversity, and cultivates sustainability values, social responsibility, and future-ready skills. From a policy and practice perspective, the findings suggest that the ESD I-STEM Module can inform curriculum enrichment initiatives under the Malaysian secondary science curriculum by providing a practical model for integrating ESD principles into STEM instruction. The module may also serve as a reference framework for teacher professional development and pre-service teacher training programs, particularly in strengthening teachers' capacity to design ESD-integrated STEM pedagogy supported by digital tools.

Nevertheless, this study acknowledges certain limitations, including its implementation within a single district school context and a modest sample size, which may limit the generalizability of the findings. Importantly, this research represents the development and validation phase of the module. Subsequent phases of this research will focus on evaluating its effectiveness in enhancing students' knowledge, skills, and pro-environmental behaviors across more diverse educational settings. Future research may include longitudinal studies to examine changes in students' ESD awareness, attitudes, and behaviors over time, as well as cross-country comparative studies to explore the adaptability and impact of the module across different educational systems and cultural contexts. Overall, the findings provide a strong foundation for broader implementation and continued refinement, contributing to the cultivation of environmentally literate and globally competent secondary school learners.

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AUTHOR CONTRIBUTIONS STATEMENT

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C : **C**onceptualization	I : **I**nvestigation	Vi : **Vi**sualization
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So : **So**ftware	D : **D**ata Curation	P : **P**roject administration
Va : **Va**lidation	O : Writing - **O**riginal Draft	Fu : **Fu**nding acquisition
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CONFLICT OF INTEREST STATEMENT

The authors declare that there are no conflicts of interest between the module developers and the expert validators.

INFORMED CONSENT

We have obtained informed consent from all individuals included in this study. Informed consent was secured from student participants, with parental or guardian consent obtained through the school administrator.

ETHICAL APPROVAL

This research has obtained official permission from the Educational Policy, Planning, and Research Division (EPRD), Ministry of Education Malaysia, prior to data collection and analysis.

DATA AVAILABILITY

The data that support the findings of this study are available on request from the corresponding author, [KO]. The data, which contain information that could compromise the privacy of research participants, are not publicly available due to certain restrictions.

REFERENCES

[1] B. Nordén and H. Avery, “Global learning for sustainable development: a historical review,” *Sustainability*, vol. 13, no. 6, Mar. 2021, doi: 10.3390/su13063451.

[2] UNESCO, *Education for sustainable development: a roadmap*. Paris: UNESCO, 2020, doi: 10.54675/YFRE1448.

[3] M. Linkwitz and I. Eilks, “An action research teacher’s journey while integrating green chemistry into the high school chemistry curriculum,” *Sustainability (Switzerland)*, vol. 14, no. 17, 2022, doi: 10.3390/su141710621.

[4] Y. Osman, “Understanding how to develop an effective role-modelling character education programme in Saudi Arabia,” *Globalisation, Societies and Education*, 2024, doi: 10.1080/14767724.2024.2330363.

[5] X. Yuan, L. Yu, H. Wu, H. She, J. Luo, and X. Li, “Sustainable Development Goals (SDGs) priorities of senior high school students and global public: recommendations for implementing education for sustainable development (ESD),” *Education Research International*, vol. 2022, pp. 1–14, Mar. 2022, doi: 10.1155/2022/2555168.

[6] S. Bettencourt, D. N. Freitas, C. Lucas, S. Costa, and S. Caeiro, "Marine litter education: from awareness to action," *Marine Pollution Bulletin*, vol. 192, 2023, doi: 10.1016/j.marpolbul.2023.114963.

[7] L. Gutiérrez-García, J. Blanco-Salas, J. Sánchez-Martín, I. Corbacho-Cuello, and T. Ruiz-Téllez, "Assessment of botanical learning through an educational intervention based on aromatic plants and their uses in the immediate environment," *Environment, Development and Sustainability*, vol. 27, no. 10, pp. 25381–25402, May 2024, doi: 10.1007/s10668-024-04733-z.

[8] S. Syskowski, C. Lathwesen, C. Kanbur, A. Siol, I. Eilks, and J. Huwer, "Teaching with augmented reality using tablets, both as a tool and an object of learning," *Journal of Chemical Education*, vol. 101, no. 3, Mar. 2024, doi: 10.1021/acs.jchemed.3c00607.

[9] N. Karim *et al.*, "Climate change and environmental education: stance from science teachers," *Sustainability*, vol. 14, no. 24, p. 16618, Dec. 2022, doi: 10.3390/su142416618.

[10] D. Olsson, N. Gericke, and J. Boeve-de Pauw, "The effectiveness of education for sustainable development revisited–a longitudinal study on secondary students' action competence for sustainability," *Environmental Education Research*, vol. 28, no. 3, pp. 405–429, Mar. 2022, doi: 10.1080/13504622.2022.2033170.

[11] R. AlAli, K. Alsoud, and F. Athamneh, "Towards a sustainable future: evaluating the ability of STEM-based teaching in achieving sustainable development goals in learning," *Sustainability (Switzerland)*, vol. 15, no. 16, 2023, doi: 10.3390/su151612542.

[12] A. A. Yaki, "Fostering critical thinking skills using integrated STEM approach among secondary school biology students," *European Journal of STEM Education*, vol. 7, no. 1, 2022, doi: 10.20897/ejsteme/12481.

[13] O. A. Oyewo, S. Ramaila, and L. Mavuru, "Harnessing project-based learning to enhance STEM students' critical thinking skills using water treatment activity," *Education Sciences*, vol. 12, no. 11, 2022, doi: 10.3390/educsci12110780.

[14] A. Abdurrahman, H. Maulina, N. Nurulsari, I. Sukamto, A. N. Umam, and K. M. Mulyana, "Impacts of integrating engineering design process into STEM makerspace on renewable energy unit to foster students' system thinking skills," *Heliyon*, vol. 9, no. 4, 2023, doi: 10.1016/j.heliyon.2023.e15100.

[15] N. Budiarti, A. Widowati, and S. Nurohman, "Modules STEM-based science learning integrated with education for sustainable development materials on environmental pollution to improve science literacy and independent learning," *Jurnal Penelitian Pendidikan IPA*, vol. 11, no. 12, pp. 1249–1256, 2025, doi: 10.29303/jppipa.v11i12.13172.

[16] R. Idris, M. Faisal-E-alam, R. A. Castanho, and L. Loures, "Bridging the gender gap in STEM fields: empowering women for economic and social development in Malaysia," *WSEAS Transactions on Business and Economics*, vol. 21, pp. 617–629, 2024, doi: 10.37394/23207.2024.21.51.

[17] R. M. Saat and H. M. Fadzil, "Enhancing STEM education in malaysia through scientist–teacher–student partnerships (STSP)," *Concepts and Practices of STEM Education in Asia*, pp. 161–173, 2022.

[18] M. Batchelder *et al.*, "Experiences from a school–university partnership climate and sustainability education project in England: the value of citizen science and practical STEM approaches," *Sustainability*, vol. 15, no. 12, Jun. 2023, doi: 10.3390/su15129401.

[19] F. Li, J. Wu, J. Liu, Y. Ma, Y. Liu, and T. Zuo, "A study of STEM teaching and learning in IT industry innovation and practice programs," in *ICETM 2024 - Proceedings of the 2024 7th International Conference on Educational Technology Management*, pp. 515–519, 2025, doi: 10.1145/3711403.3711487.

[20] C. C. Hu, Y. F. Yang, Y. W. Cheng, and N. S. Chen, "Integrating educational robot and low-cost self-made toys to enhance STEM learning performance for primary school students," *Behaviour and Information Technology*, vol. 43, no. 8, pp. 1614–1635, 2024, doi: 10.1080/0144929X.2023.2222308.

[21] R. Chuliá-Jordán, A. Vilches Peña, and M. Calero Llinares, "The press as a resource for promoting sustainability competencies in teacher training: the case of SDG 7," *Sustainability*, vol. 14, no. 2, p. 857, Jan. 2022, doi: 10.3390/su14020857.

[22] Eliyawati, A. Widodo, I. Kaniawati, and H. Fujii, "The development and validation of an instrument for assessing science teacher competency to teach ESD," *Sustainability (Switzerland)*, vol. 15, no. 4, 2023, doi: 10.3390/su15043276.

[23] F. I. Raman, F. D. Hutagalung, and M. N. Abdul Rahman, "Preparing pre-service teachers for integration of education for sustainable development in school: a systematic review (2013-2022)," *Malaysian Journal of Society and Space*, vol. 18, no. 3, Aug. 2022, doi: 10.17576/geo-2022-1803-10.

[24] D. Hogan and J. O'Flaherty, "Exploring the nature and culture of science as an academic discipline: implications for the integration of education for sustainable development," *International Journal of Sustainability in Higher Education*, vol. 23, no. 8, 2022, doi: 10.1108/IJSHE-06-2021-0236.

[25] S. Yadav, "Education for sustainable awareness with integrating eco awareness into educational curricula," in *Exploring Pillars of Sustainability for Modern Age Improvements*, IGI Global Publication, 2024, pp. 103–122, doi: 10.4018/979-8-3693-5748-4.ch006.

[26] M. M. Isac *et al.*, "Differences in teachers' professional action competence in education for sustainable development: the importance of teacher co-learning," *Sustainability (Switzerland)*, vol. 14, no. 2, 2022, doi: 10.3390/su14020767.

[27] G. Espinoza-Ramos and A. Capucci-Polzin, "Embedding sustainability in curricula: a case study of an education for sustainable development (ESD) framework at the Westminster Business School," *CSR, Sustainability, Ethics and Governance*, vol. Part F325, pp. 279–299, 2025, doi: 10.1007/978-3-031-86337-0_16.

[28] M. S. Zainal Abidin, M. Mokhtar, and M. Arsat, "Unraveling the challenges of education for sustainable development: a compelling case study," *Qualitative Research Journal*, vol. 24, no. 4, pp. 408–424, 2024, doi: 10.1108/QRJ-05-2023-0090.

[29] P. Yadav and S. Singh, "Empowering educators: training and professional development for sustainability," in *Crafting a Sustainable Future Through Education and Sustainable Development*, IGI Global Publication, 2023, pp. 51–71, doi: 10.4018/978-1-6684-9601-5.ch003.

[30] E. Suryawati, Y. Yennita, S. R. Afwa, P. R. Dianti, and S. Syafrinal, "Real action based on search solve create and share (SSCS) model to improve sustainability awareness of junior high school students," *JPBI (Jurnal Pendidikan Biologi Indonesia)*, vol. 9, no. 3, pp. 271–281, Sep. 2023, doi: 10.22219/jpbi.v9i3.28940.

[31] K. Mongar, "Teachers' preparedness to teach environmental science in Bhutan," *Eurasia Journal of Mathematics, Science and Technology Education*, vol. 18, no. 10, 2022, doi: 10.29333/ejmste/12454.

[32] T. P. L. Nguyen, "Integrating circular economy into STEM education: a promising pathway toward circular citizenship development," *Frontiers in Education*, vol. 8, Mar. 2023, doi: 10.3389/feduc.2023.1063755.

[33] Z. H. W. Zeyu Han, Winnie Wing Mui So, "Challenges in assessing students' STEM-based problem solving," in *Ways of Thinking in STEM-based Problem Solving*, London: Routledge, 2024, pp. 250–262, doi: 10.4324/9781003404989.

[34] S. Hinterplattner, E. Schmidthaler, M. Schwinghammer, J. S. Skogø, and C. Hörmann, "The integration of digital education within an ozobot pilot project: Austrian teacher perspectives and practices," in *International Conference on Computer Supported Education, CSEDU - Proceedings*, vol. 1, pp. 60–71, 2025, doi: 10.5220/0013211400003932.

[35] F. A. Z. Bahari and S. Saleh, "Leveraging the ASSURE model: the integrated STEAM module development for year four geometry problem solving," *Jurnal Pendidikan Sains dan Matematik Malaysia*, vol. 14, no. 1, 2024, doi: 10.37134/jpsmm.vol14.1.1.2024.

[36] H. V. Akşab and M. Özyurt, "Use of ASSURE MODEL in ELT: reflections on the learning and teaching process," *International Journal of Assessment Tools in Education*, vol. 12, no. 4, pp. 1034–1054, 2025, doi: 10.21449/ijate.1571335.

[37] K. Eungoo and H.-J. Hwang, "The importance of anonymity and confidentiality for conducting survey research," *Journal of Research and Publication Ethics*, vol. 4, no. 1, pp. 1–7, 2023.
[38] S. E. Smaldino, D. L. Lowther, and C. Mims, *Instructional technology and media for learning*. London: Pearson, 2019.
[39] J. West, "Utilizing Bloom's taxonomy and authentic learning principles to promote preservice teachers' pedagogical content knowledge," *Social Sciences and Humanities Open*, vol. 8, no. 1, 2023, doi: 10.1016/j.ssaho.2023.100620.
[40] O. Almatrafi and A. Johri, "Leveraging generative AI for course learning outcome categorization using Bloom's taxonomy," *Computers and Education: Artificial Intelligence*, vol. 8, 2025, doi: 10.1016/j.caeai.2025.100404.
[41] R. W. Bybee *et al*., *The BSCS 5E instructional model: origins and effectiveness*. Washington, D.C.: The Office of Science Education National Institutes of Health, 2006.
[42] T. Kaewmanee, A. Srisenpila, and W. Worapun, "Integrating 5E inquiry-based learning and STEM education to enhance grade 5 students' science process skills and achievement in friction," *International Journal of Advanced and Applied Sciences*, vol. 11, no. 12, pp. 207–214, 2024, doi: 10.21833/ijaas.2024.12.023.
[43] N. Eliana, U. A. Wati, and S. Rahmadona, "Leveraging the ASSURE model for optimized information technology-based learning media," *AL-ISHLAH: Jurnal Pendidikan*, vol. 16, no. 3, 2024, doi: 10.35445/alishlah.v16i3.5639.
[44] X. Tang, S. R. B. M. Zainal, and Q. Li, "Multimedia use and its impact on the effectiveness of educators: a technology acceptance model perspective," *Humanities and Social Sciences Communications*, vol. 10, no. 1, 2023, doi: 10.1057/s41599-023-02458-4.
[45] F. H. Veiga, "Assessing student engagement in school: development and validation of a four-dimensional scale," *Procedia - Social and Behavioral Sciences*, vol. 217, pp. 813–819, 2016, doi: 10.1016/j.sbspro.2016.02.153.
[46] K. M. Surapaneni, "ABCs of providing constructive feedback to students during small group learning activities," *Advances in Physiology Education*, vol. 48, no. 4, pp. 752–755, 2024, doi: 10.1152/advan.00131.2024.
[47] M. S. Ahmad, N. A. Izhar, and Z. Hashim, "Integrating design thinking and blended learning in science education: development and expert validation of the Inno-BlenDT module," *Perspektif Jurnal Sains Sosial dan Kemanusiaan*, vol. 17, pp. 1–12, Dec. 2025, doi: 10.37134/perspektif.vol17.sp.1.2025.
[48] M. R. Lynn, "Determination and quantification of content validity," *Nursing Research*, vol. 35, no. 6, pp. 382–386, 1986.
[49] A. Narayanasamy, A. N. Mohamad Jaafar, and E. Kurniati, "Boosting preschool students reading skills: the validity of the I-SaBoBa module," *Semarak International Journal of Innovation in Learning and Education*, vol. 4, no. 1, pp. 13–26, 2024, doi: 10.37934/sijile.4.1.1326a.
[50] J. R. Fraenkel and N. E. Wallen, *How to design and evaluate research in education*. 6th ed, New York: McGraw-Hill, 2006.

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