SPEKTRA: Jurnal Kajian Pendidikan Sains
Vol. 12, No. 1, 2026, pp. 61-78
ISSN: 2548-642X, DOI: 10.32699/jcmvv894

EXPLORING TEACHER AND STUDENT NEEDS FOR AUGMENTED REALITY–BASED STEM EDUCATION FOR SUSTAINABLE DEVELOPMENT IN INTEGRATED SCIENCE LEARNING

Esti Susiloningsih[1], Apit Fathurohman[2], Nabilah Mansur[1]
[1]Primary School Teacher Education Study Program, Universitas Sriwijaya, Palembang, Indonesia
[2]Physics Education Study Program, Universitas Sriwijaya, Palembang, Indonesia

Article Info

Article history:
Received 08/12/2025
Accepted 28/04/2026
Published 30/04/2026

Keywords:
AR;
IPAS;
Learning Tools;
Need Analysis;
STEM-ESD

ABSTRACT

The integration of STEM and Education for Sustainable Development (ESD) in Integrated Science and Social Sciences learning remains limited due to conventional teaching methods, low interactivity, and inadequate learning resources, which hinder students' conceptual understanding and engagement. This study explores the needs of teachers and students in implementing Augmented Reality (AR)–based STEM–ESD learning as a basis for developing effective Integrated Science and Social Sciences learning tools. The study employed an explanatory sequential mixed-methods design, combining quantitative and qualitative data collection. Questionnaires were administered to 24 teachers and 92 students to identify general needs and perceptions, followed by semi-structured interviews with 16 students to obtain deeper insights into their learning experiences and expectations. The results indicate that teachers demonstrate partial readiness in integrating STEM–ESD and prefer AR learning tools that enhance conceptual clarity, provide structured instructional guidance, and align with curriculum competencies. Students reported limited engagement with existing learning materials, difficulties in understanding abstract concepts, and strong interest in AR-supported learning, emphasizing the need for accessible, interactive, and curriculum-relevant media. These findings suggest that AR-based learning tools should prioritize visual clarity, intuitive interfaces, and real-world contextualization to address current instructional gaps. The implications of this study highlight the importance of need-based AR learning design for supporting effective STEM–ESD integration, informing the development of innovative learning tools, and guiding teacher preparation and professional development in implementing technology-enhanced sustainable education.

Corresponding Author:
Esti Susiloningsih
Primary School Teacher Education Study Program, Universitas Sriwijaya, Palembang, Indonesia
Email: esti_susiloningsih@fkip.unsri.ac.id

1. INTRODUCTION

In recent decades, the rapid advancement of digital technologies has significantly transformed educational practices (Makarova & Makarova, 2018; Qureshi et al., 2021; Wang et al., 2024). Traditional teaching methods, which predominantly rely on textbooks and teacher-centered lectures, often fail to engage students effectively, particularly in science education where many concepts are abstract and difficult to visualize (Granger et al., 2012; Lasry et al., 2014;

Murphy et al., 2021). In elementary and secondary education, these challenges are even more pronounced because students often lack the prior knowledge and cognitive scaffolding required to understand phenomena occurring at microscopic, macroscopic, or system levels (A. Fathurohman et al., 2023; A. Fathurohman & Susiloningsih, 2022; Susiloningsih et al., 2023). These issues are particularly critical in Integrated Science and Social Sciences (IPAS) learning, where scientific, environmental, and sustainability concepts frequently intersect.

Educational research has highlighted the importance of interactive, student-centered, and multi-dimensional learning approaches to overcome these challenges (A. Fathurohman et al., 2024; Imam Rizaldi, Fahmi Surya Adikara, 2024). In practice, however, teachers still encounter several constraints in implementing innovative learning, including limited access to interactive instructional media, a lack of technological support, and insufficient guidance for integrating interdisciplinary concepts in classroom instruction. These conditions indicate that teachers need learning tools that are structured, easy to use, and capable of supporting the integration of science concepts with real-world contexts. From the students' perspective, conventional learning approaches often provide limited opportunities for active engagement and visualization of abstract scientific concepts. As a result, students tend to experience difficulties in understanding complex relationships between scientific phenomena and environmental issues. These conditions suggest that students need learning experiences that are more interactive, visual, and contextual to support better conceptual understanding and learning engagement.

The integration of Science, Technology, Engineering, and Mathematics (STEM) with Education for Sustainable Development (ESD) has become increasingly urgent in elementary education, not only to improve scientific literacy but also to cultivate early awareness, attitudes, and responsible behaviors toward environmental sustainability challenges. At the elementary level, students are in a critical developmental stage for forming values and habits; thus, the absence of contextual and sustainability-oriented science learning may result in fragmented understanding and low ecological awareness that persists into higher levels of education (I. Fathurohman et al., 2023). However, the implementation of STEM–ESD in classrooms remains limited due to several factors, including insufficient learning resources, varied teacher readiness, and the inherent complexity of science-environment interactions. For instance, a study by Agbor et al. (2025) showed that students' understanding of sustainability-related science topics remained superficial when learning relied solely on conventional teaching methods.

Augmented Reality (AR) has been recognized as a promising technological approach to enhance the visualization of abstract concepts and promote more engaging learning experiences (AlGerafi et al., 2023; Lampropoulos et al., 2022). For instance, a study by Septiani et al. (2025) showed that AR-based IPAS media significantly improved students' conceptual understanding and motivation by providing interactive and dynamic simulations of complex phenomena. Despite these benefits, the integration of AR in STEM–ESD-oriented IPAS learning remains limited in practice. This limitation is not merely a matter of topic coverage but reflects a deeper issue: the lack of alignment between technological innovation and the urgent need to support sustainability-oriented, interdisciplinary learning at the elementary level. Without such alignment, AR risks being used as a novelty tool rather than as a meaningful pedagogical intervention that fosters sustainability competencies. Most existing AR applications focus on narrow topics and are rarely aligned with curriculum requirements or contextualized to local learning environments (Iqbal et al., 2022). For instance, AR media in Indonesia have primarily addressed single-subject topics such as the circulatory system or solar system, with limited exploration of sustainability and interdisciplinary science concepts. Moreover, systematic needs assessments involving both teachers and students are seldom conducted prior to development, which often results in AR tools that are not fully relevant or effective for classroom use.

This gap highlights a critical issue in educational technology implementation: many innovations fail not due to lack of technological sophistication, but because they are not grounded in the real needs, readiness, and classroom contexts of end users. Therefore, conducting an exploratory needs analysis is not simply preliminary work, but a crucial foundation aligned with user-centered design principles to ensure that future AR-based learning tools are usable, relevant, and pedagogically meaningful. Such an approach helps prevent mismatches between design and practice, which have been widely reported as a major cause of unsuccessful technology integration in education. For instance, a study by Ramírez et al. (2025) highlighted the crucial role of user-centered needs assessments in designing effective educational interventions, demonstrating that understanding stakeholders' perspectives directly enhances the relevance and usability of instructional tools.

Therefore, this study aims to explore teacher and student needs in implementing AR-based STEM–ESD learning for IPAS. Specifically, it seeks to examine teachers' readiness and challenges in integrating STEM–ESD and AR, assess students' current learning experiences and difficulties, and gather qualitative insights regarding desired features for AR-based learning tools. By positioning needs analysis as a foundational step prior to product development, this study contributes a novel and essential perspective that bridges the gap between technological potential and practical classroom implementation. The findings are intended to provide empirical guidance for the development of AR-based IPAS media that are effective, engaging, and aligned with curriculum objectives.

2. METHOD

2.1 Research Method

This study employed a mixed-methods exploratory design, utilizing a sequential explanatory model, to systematically identify teacher and student needs related to the development of AR-based STEM–ESD learning tools for IPAS instruction. Quantitative data were collected first through questionnaires to capture the general profile of needs, followed by qualitative data through semi-structured interviews to deepen and clarify the quantitative results. To illustrate the sequence of the quantitative and qualitative phases employed in this study, the overall research procedure is presented in Figure 1.

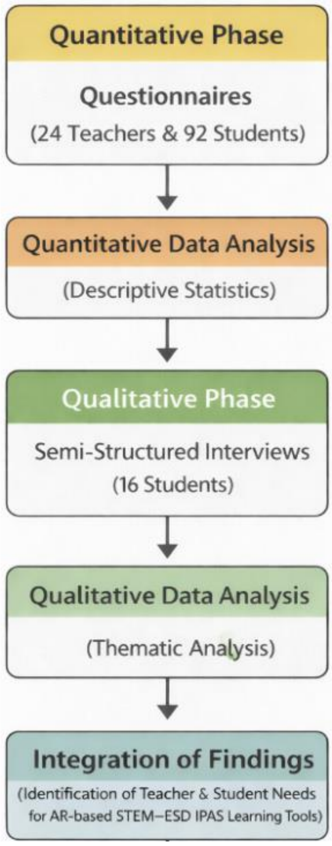

Figure 1. Research Procedure

2.2 Participants

The participants in this study consisted of IPAS teachers and Grade V students from SD Negeri 53 Palembang. Participants were selected using purposive sampling based on specific criteria to ensure their relevance to the research objectives. The teacher participants were selected if they: (1) actively teach IPAS in Grade V, (2) have experience delivering topics related to environmental sustainability and scientific inquiry, and (3) are involved in or open to the integration of technology in classroom instruction. Meanwhile, the student participants were selected based on their enrollment in Grade V IPAS classes and their direct involvement in ongoing learning activities, representing the primary users of the AR-supported STEM–ESD learning tools. SD Negeri 53 Palembang was deliberately chosen as the research site because it reflects the characteristics of a typical public elementary school implementing the Merdeka Curriculum, with diverse student backgrounds and initial exposure to technology-supported learning, although not yet optimally integrated. This context makes the school relevant for examining real classroom conditions, particularly in relation to the integration of sustainability-oriented IPAS learning and emerging digital technologies.

The teacher participants were those responsible for implementing IPAS curriculum components related to environmental sustainability, technological literacy, and scientific inquiry, while the student participants represented the target users of the AR-based learning tools. To provide a clearer overview of the participant characteristics, detailed demographic information is presented in Table 1.

Table 1. Participant Demographics

Category	Description	n
Teacher Participants		
Gender	Female	2
	Male	1
Age Range	31–40 years	2
	41–50 years	1
Teaching Experience	5–10 years	1
	> 10 years	2
Educational Background	Bachelor of Education (S.Pd.)	1
	Completed PPG (Teacher Professional Program)	2
Student Participants		
Gender	Female	17
	Male	15
Age	10	14
	11	15
	12	3

2.3 Data Collection Techniques

Data in this study were collected using three complementary techniques: a teacher needs analysis questionnaire, a student needs analysis questionnaire, and semi-structured interviews. Both questionnaires were designed using categorical response formats, including yes/no items, multiple-choice selections, multiple-response checklists, and short open-ended prompts. These formats were intentionally chosen to capture teachers' and students' concrete conditions, access, challenges, and expectations regarding the implementation of AR-based STEM–ESD learning tools without relying on scaled-rating responses. The teacher questionnaire consisted of 24 items organized into aspects such as current IPAS instructional practices, readiness for STEM and ESD integration, access and experience with AR technology, pedagogical and technological barriers, curriculum and infrastructure alignment, and expectations for AR-based learning tools.

Table 2. Blueprint of Teacher Needs Analysis Questionnaire

No	Aspects	Item Numbers	Number of Items
1	Current IPAS teaching practices	1, 2, 3, 4	4
2	Teacher understanding and readiness for STEM and ESD	5, 6, 7, 8	4
3	Technological readiness and teacher experience with AR	9, 10, 11, 12	4
4	Teaching barriers (pedagogical, technological, conceptual)	13, 14, 15, 16	4
5	Curriculum alignment and infrastructure support for AR–STEM–ESD implementation	17, 18, 19	3
6	Teacher expectations for AR-Based IPAS learning tools development	20, 21, 22, 23, 24	5
	Total		24

Based Table 2, the student questionnaire, containing 19 items, employed simple categorical formats suitable for elementary learners, capturing information on their IPAS learning experiences, difficulties in STEM–ESD topics, access to digital devices, familiarity with AR applications, environmental attitudes, and expectations toward AR-supported learning. The structure of this instrument is outlined in Table 3.

Table 3. Blueprint of Student Needs Analysis Questionnaire

No	Aspects	Item Numbers	Number of Items
1	Learning resources and IPAS learning experiences	1, 2, 3	3
2	Learning difficulties in IPAS topics	4, 5, 6	3
3	Student readiness and interest in using AR	7, 8, 9, 10	4
4	Student understanding of science, technology, environment, and sustainability	11, 12, 13	3
5	Environmental attitudes and concern (ESD competencies)	14, 15, 16	3
6	Student expectations for AR-Based IPAS learning tools	17, 18, 19	3
	Total		19

Based Table 3, to enrich and validate the questionnaire data, semi-structured interviews were conducted with selected students. The interview guide consisted of 16 open-ended questions exploring students' learning characteristics, conceptual understanding, technological readiness, motivation, and potential engagement with AR-based learning. The questionnaire instrument underwent an expert judgment validation process involving experts in science education and educational technology. The validation focused on content relevance, clarity of language, and alignment with the research constructs. The results indicated that the instrument was valid, with minor revisions made to improve wording clarity and item specificity based on expert feedback. This process ensured that the questionnaire was appropriate and reliable for capturing participants' perspectives on AR-based STEM–ESD learning. Details of the interview structure are provided in Table 4.

Table 4. Blueprint of Semi-Structured Interview Guide for Student Analysis

No	Aspects	Question Numbers	Number of Questions
1	General characteristics of students in IPAS learning	1, 2, 3	3
2	Academic and conceptual abilities related to STEM–ESD	4, 5, 6, 7	4
3	Technological readiness and support for AR use	8, 9, 10, 11	4
4	Motivation, interest, and response toward AR-Based learning	12, 13, 14	3
5	Implications for the development of AR-Based learning tools	15, 16	2
	Total		16

2.4 Data Analysis Techniques

The quantitative data obtained from the teacher and student questionnaires were analyzed using descriptive statistical techniques, including the calculation of frequencies, percentages, and measures of central tendency to identify dominant patterns of needs, readiness levels, and instructional gaps in the implementation of AR-based STEM–ESD learning. These numerical patterns were then interpreted to reveal emerging tendencies that characterized both teacher and student conditions. Meanwhile, the qualitative interview data were examined through a systematic thematic analysis process involving initial coding, categorization of meaning units, and the generation of overarching themes that reflected students' learning characteristics, technological readiness, and responses toward AR-supported learning. The findings from both data sources were subsequently triangulated to enhance the validity and coherence of the results. Through this integrated interpretation, a comprehensive needs profile was constructed to inform and guide the design of AR-based STEM–ESD learning tools for IPAS instruction.

3. RESULTS AND DISCUSSION

3.1. Teacher Needs Analysis Results

The teacher needs analysis indicates varied levels of readiness, challenges, and expectations across the six key aspects assessed in the questionnaire. To provide a clearer understanding of these patterns, the findings are presented through narrative explanations supported by visual summaries. The analysis first highlights how teachers currently conduct IPAS lessons. The majority continue to rely on conventional approaches, with limited integration of interactive or technology-supported strategies. These proportions represent teachers' actual classroom practices rather than their instructional preferences. Figure 2 illustrates the distribution of teaching methods used, highlighting the dominance of traditional lectures over digital or interactive approaches.

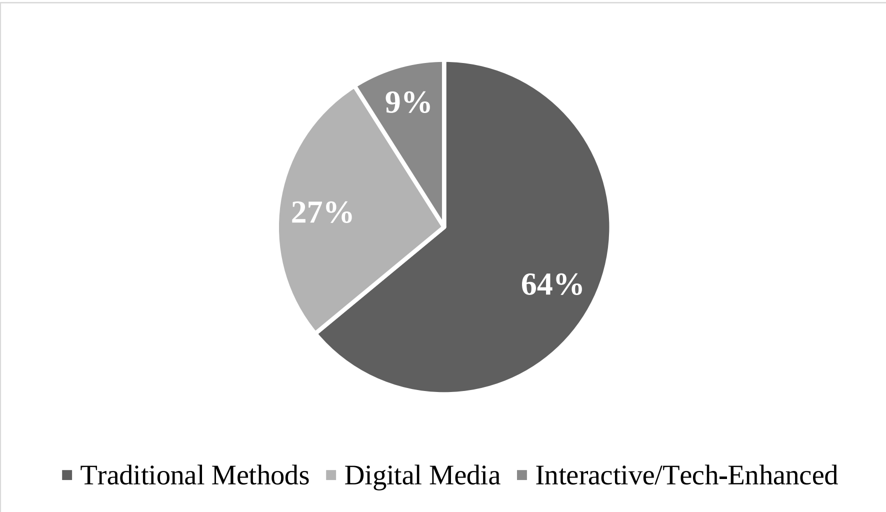

Figure 2. Current IPAS Teaching Practices

Moving forward from Figure 2, the findings reveal uneven levels of understanding and readiness for STEM–ESD integration. Although many teachers express familiarity with STEM–ESD concepts, only a portion feel fully prepared to apply them in practical classroom contexts. This indicates a partial readiness that requires further professional development to close the gap between conceptual understanding and implementation. Before examining teachers' technological readiness, it is essential to first understand their preparedness in adopting the STEM–ESD framework. This dimension reflects how comfortably teachers engage with interdisciplinary approaches and sustainability-oriented principles in their IPAS instruction. Figure 3 presents the distribution of teachers' readiness across these categories.

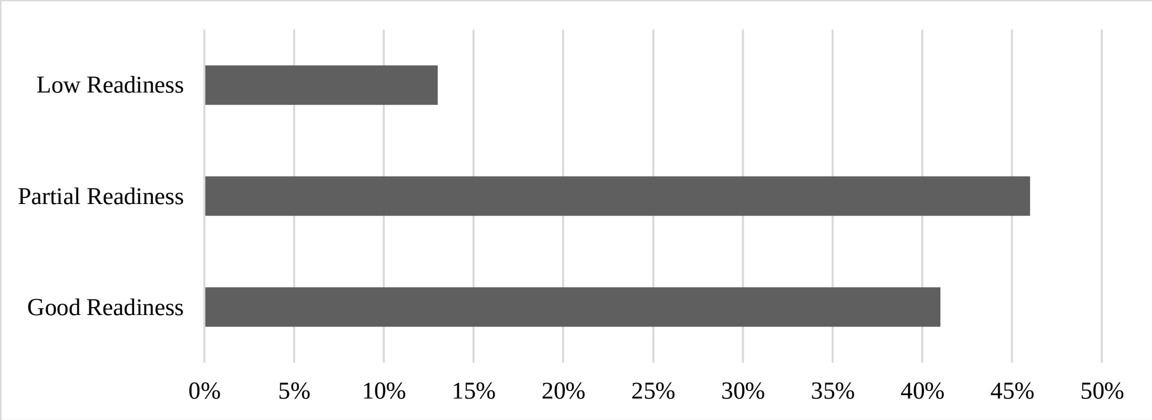

Figure 3. Teacher Readiness for STEM–ESD

Following Figure 3, the results show that most teachers exhibit partial readiness. While many are familiar with STEM–ESD concepts, fewer feel prepared to translate these ideas into effective classroom practice. This highlights a gap between conceptual understanding and real instructional application, pointing to the need for structured professional development. The next component of the analysis examines teachers' technological readiness, particularly their familiarity with augmented reality (AR) tools and their confidence in using technology to support IPAS learning. This section captures four dimensions that correspond to the questionnaire items: prior AR experience, digital device proficiency, confidence in integrating AR, and perceived usefulness of AR-based instruction. Figure 4 presents a visual summary of these indicators.

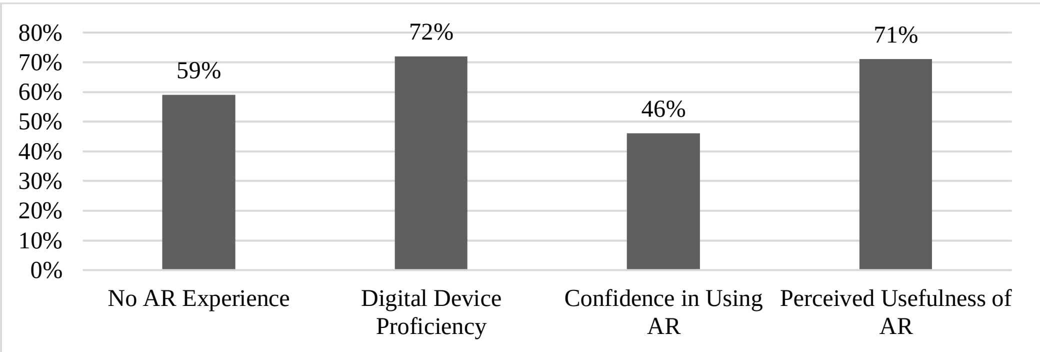

Figure 4. Teachers' AR Experience and Perceived Usefulness

Insights drawn from Figure 4 show that while most teachers have never used AR directly, their overall digital proficiency is relatively strong. Confidence in applying AR during instruction remains moderate, indicating a learning curve that teachers acknowledge but do not resist. The high perceived usefulness of AR-based learning highlights a strong motivational foundation: teachers believe AR can meaningfully support science concepts and are willing to adopt it when equipped with guided training and practical tools. The analysis then turns toward the contextual challenges that shape teachers' instructional practices. These barriers include infrastructural constraints, pedagogical limitations, and time availability, factors that significantly influence the feasibility of implementing STEM–ESD and AR-enhanced learning. Figure 5 illustrates the relative prominence of these barriers.

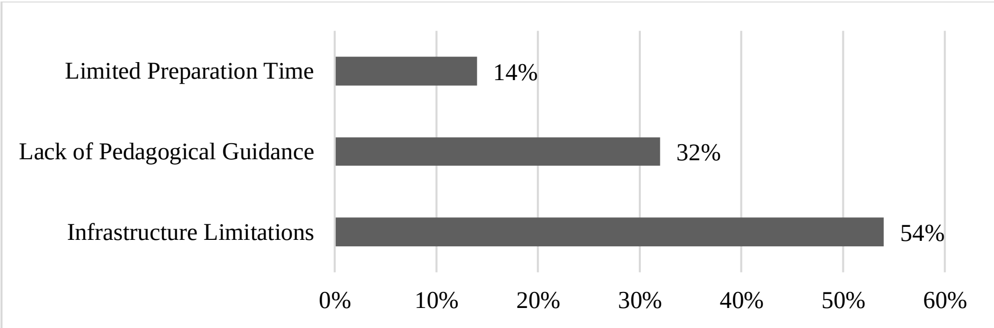

Figure 5. Teaching Barriers to STEM–ESD and AR Integration

The pattern in Figure 5 indicates that infrastructure remains the most substantial obstacle, especially in schools with limited device availability or unstable internet connectivity. Pedagogical barriers, such as the absence of clear instructional models for STEM–ESD and AR-based learning, further hinder adoption. Although time-related constraints appear less dominant, they still affect teachers' ability to prepare digital materials, reinforcing the importance of developing efficient, ready-to-use AR learning resources. As the analysis shifts toward teachers' expectations, the findings reveal a clear preference for AR tools that are not merely visually appealing but genuinely functional in supporting IPAS instruction. Teachers consistently emphasized the need for media that can simplify complex concepts through interactive representations, provide structured learning pathways, and remain aligned with curriculum demands.

Teachers also expressed clear expectations for AR-based tools that support learning in meaningful and practical ways. A recurring theme in their responses is the desire for AR features that can simplify complex IPAS concepts through interactive and dynamic representations. One teacher emphasized this need by stating, "If AR can show the movement or the process clearly, students will understand faster, especially for topics that are impossible to demonstrate in class." This perspective highlights how teachers see AR as a bridge between abstract content and students' conceptual understanding. In addition to visualization, teachers stressed the importance of structured guidance accompanying AR activities. Many noted that digital excitement alone is not enough to ensure effective learning. As one respondent explained, "Sometimes students get excited with technology but lose direction. A worksheet helps them stay on task while still enjoying the AR." This shows that teachers want AR tools that do more than capture attention; they must also provide clear learning pathways that maintain focus and support active engagement.

Curriculum relevance also emerged as a crucial expectation. Teachers consistently stated that AR tools must align with the existing IPAS competencies rather than operate as stand-alone or decorative media. One teacher clearly articulated this priority: "We don't want media that looks good but doesn't match the Kompetensi Dasar. It needs to fit what we actually teach." Their emphasis reflects a practical concern for efficiency, as teachers prefer tools that reduce preparation time, integrate smoothly with lesson plans, and directly correspond to required learning outcomes. Taken together, these comments reveal that teachers value practicality over novelty. They seek AR tools that enhance conceptual clarity through interactive visuals, maintain student focus through guided activities, and align closely with curriculum demands. Their expectations point toward a need for AR-based learning media that are pedagogically grounded, time-efficient, and directly supportive of classroom instruction.

3.2 Student Needs Analysis Results

The student needs analysis provides an initial picture of learners' experiences, challenges, and readiness related to current IPAS learning conditions, serving as a baseline prior to the development of AR-based STEM–ESD learning tools. Because students have not previously used AR-integrated materials, the analysis focuses on identifying existing gaps and limitations in the resources and activities they routinely encounter. To clearly highlight the emerging patterns, the findings are organized according to key dimensions of the questionnaire. The first dimension captures students' access to learning resources and their general experiences during IPAS lessons, describing how they perceive the availability, clarity, and engagement level of traditional classroom materials. Table 5 summarizes the distribution of student responses across these categories.

Table 5. Learning Resources and IPAS Learning Experiences

Aspect	Category	Percentage
Clarity of Learning Materials	Clear and easy to follow	18%
	Sometimes unclear or partially confusing	42%
	Too text-heavy and difficult to focus on	27%
	Hard to understand without teacher explanation	13%
Engagement Level of Learning Resources	Interesting and enjoyable	14%
	Neutral or average engagement	31%
	Boring or monotonous	34%
	Not engaging at all	21%
Availability and Accessibility of Resources	Adequate and easy to access	22%
	Available but not visually appealing	36%
	Limited or insufficient for some topics	29%
	Difficult to access due to device or format issues	13%
Student Perceptions of IPAS Learning Activities	Interactive and varied	12%
	Sometimes interactive, sometimes not	34%
	Mostly lecture-based	37%
	Almost entirely textbook-focused	17%

Table 5 presents students' baseline experiences with the conventional learning resources and IPAS activities that they currently use. Overall, the results indicate several areas of concern that may influence their readiness for more advanced instructional innovations such as AR-based STEM–ESD tools. First, the clarity of learning materials remains limited; only 18% of students find the materials easy to follow, while the majority describe them as unclear, overly text-heavy, or requiring teacher clarification to be understood. The perceived engagement level is also relatively low, with fewer than 15% rating the resources as enjoyable, and a substantial proportion viewing them as monotonous or not engaging. Accessibility is another area of challenge. Only about one-fifth of students report that the materials are easy to access, and many consider them visually unappealing or insufficient for certain IPAS topics. Students' experiences with learning activities also tend to be traditional in nature. Only a small portion of learners describe their lessons as interactive, whereas most characterize them as predominantly lecture-based or heavily dependent on textbooks. Taken together, these findings highlight that students are still primarily exposed to conventional, low-interactivity learning environments. Such conditions underscore the need for developing more engaging, accessible, and conceptually supportive IPAS learning tools, particularly those integrating AR and STEM–ESD elements, to address the gaps identified in the pre-implementation phase.

To further understand students' baseline readiness before introducing AR-based STEM–ESD tools, it is also important to examine the specific types of learning difficulties they encounter during current IPAS lessons. This dimension focuses on the kinds of conceptual and procedural challenges students face when engaging with existing materials and classroom activities. Figure 6 outlines the distribution of these difficulties as reported by the students.

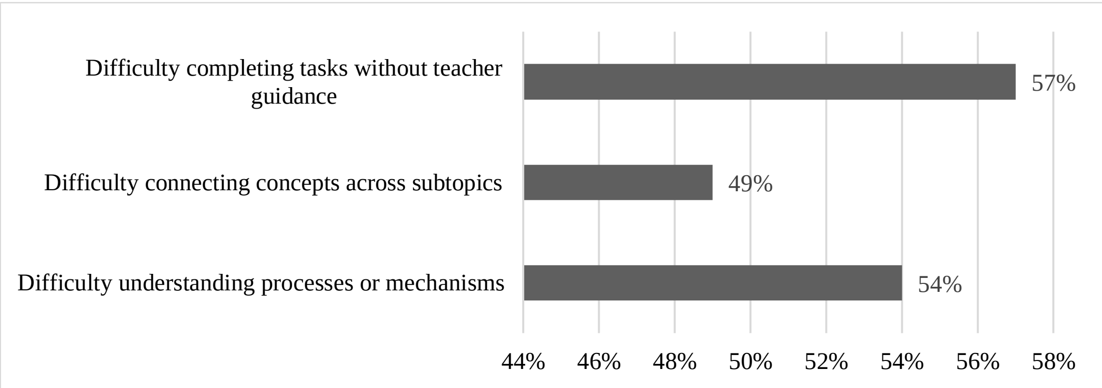

Figure 6. Learning Difficulties in Current IPAS Topics

The results in Figure 6 show that many students still struggle to grasp how IPAS concepts work, especially when lessons involve processes or multi-step explanations. Nearly half report difficulty linking ideas across different subtopics, which suggests that materials and activities used so far do not adequately support conceptual coherence. More than half also struggle to work independently without continuous teacher explanation, highlighting that their current resources are not sufficiently supportive or self-explanatory. These conditions justify the need for improved instructional media to strengthen clarity and facilitate more autonomous learning. In addition to identifying students' learning challenges, it is also essential to examine their baseline readiness and interest in adopting new learning technologies. This dimension provides insight into how well students might adapt to AR-based instructional tools and what kinds of support they may require during implementation. Figure 7 presents an overview of students' self-reported readiness and interest related to the potential use of AR in IPAS learning.

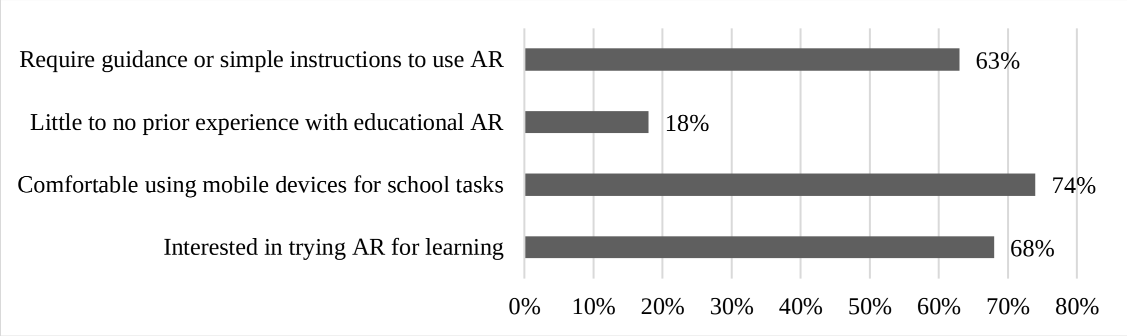

Figure 7. Student Readiness and Interest in AR

Figure 7 indicates that students show strong interest in AR and are already comfortable with mobile devices, which creates good initial conditions for implementation. However, very few have ever used AR for learning, meaning they would enter with limited familiarity and require onboarding. The high need for guidance reflects that AR tools must be designed with intuitive interfaces, clear steps, and teacher support. This gap between high interest and low experience further supports the urgency of developing accessible AR learning media. Beyond students' readiness for AR, it is also important to examine their current level of understanding of key science–technology–environment relationships, which form the conceptual basis of STEM–ESD learning. This dimension helps determine how well students grasp foundational ideas that will later be expanded through AR-supported instructional materials. Figure 8 presents an overview of students' existing understanding across these interconnected domains.

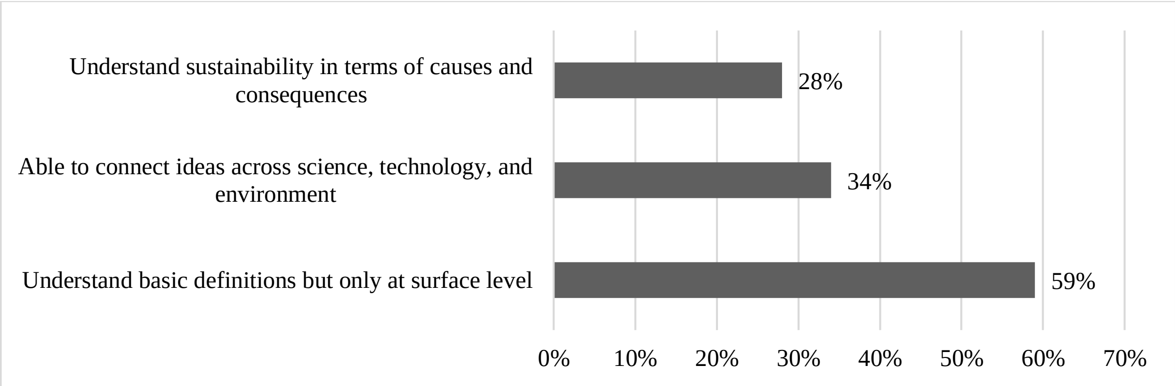

Figure 8. Student Understanding of Science–Technology–Environment Concepts

In Figure 8, most students report only surface-level understanding, with far fewer able to connect concepts across the science–technology–environment domains. Even fewer understand sustainability mechanisms or the relationships between human actions and environmental impact. These patterns confirm that the materials they currently use have not supported deeper comprehension, reinforcing the need for learning tools that can visually demonstrate relationships and encourage systems-level thinking. In addition to conceptual understanding, it is also important to examine students' environmental attitudes and the extent to which they apply sustainability-related behaviors in their daily lives. This dimension provides insight into how well students can connect IPAS learning with real-world environmental contexts, an essential foundation for STEM–ESD–oriented instruction. Figure 9 summarizes students' self-reported attitudes and their ability to act on environmental issues.

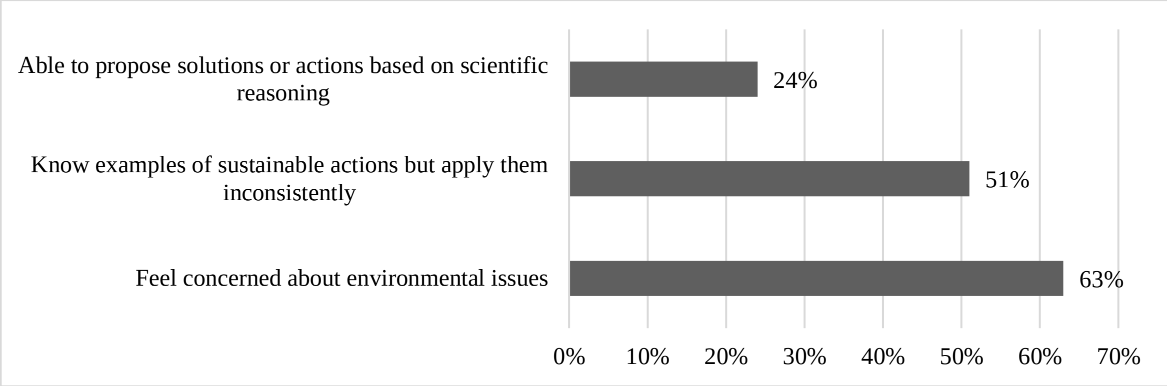

Figure 9. Environmental Attitudes and Concern

Figure 9 reveals that although students express environmental concern, their ability to translate that concern into consistent practice or science-based solutions is much lower. This gap between awareness and action indicates that current learning materials have not provided enough structured opportunities to apply IPAS concepts to real environmental contexts. The development of AR-supported tasks could help make these concepts more concrete and actionable.

To complement the quantitative findings, it is also important to explore students' qualitative input regarding the types of AR features they consider useful for future IPAS learning. This dimension provides deeper insight into the specific characteristics and user-experience elements that students believe would support their learning most effectively. Students described clear expectations for AR tools they would like to use in future IPAS lessons. Many expressed the need for media that makes difficult content more visible, with one student noting, "If the picture can move and show how it really works, it will be easier for us to understand." Others emphasized the importance of simple guidance: "If it is too complicated, we will get confused. It must be easy to follow." Some students highlighted relevance to the curriculum, stating that the material should match what they study in class rather than unrelated content. Several also raised practical concerns about accessibility, particularly the need for tools that function well on basic mobile devices. Overall, these expectations show that students want AR tools that are clear, intuitive, aligned with classroom materials, and feasible to use even with limited technological resources. This alignment of expectations further strengthens the rationale for developing accessible and pedagogically supportive AR-based IPAS learning tools.

3.3 Semi-Structured Student Interviews Results

The semi-structured interviews with sixteen students revealed diverse experiences, abilities, and expectations related to IPAS learning and the potential integration of Augmented Reality (AR). Across all responses, students demonstrated varied levels of readiness, conceptual understanding, and motivation, which directly inform the design of AR-based learning tools. In terms of general characteristics in IPAS learning, most students described IPAS as a subject that is "interesting but sometimes confusing," especially when dealing with abstract or cross-disciplinary concepts. One student noted, "*Kalau topik IPAS itu kadang nyambung ke fisika, kadang ke biologi, jadi saya suka bingung harus mulai dari mana*" (S03). Another added, "*Guru biasanya pakai video, tapi tetap saja ada bagian yang sulit dibayangin*" (S01). These responses indicate that while engagement exists, clarity and visualization remain challenges.

Regarding academic and conceptual abilities in STEM–ESD, several students expressed difficulty understanding the interconnectedness between science, technology, engineering, and sustainability. Student S07 mentioned, "*Kalau kaitan sains sama lingkungan masih oke, tapi kalau sudah ngomong rekayasa atau teknologi, saya agak nggak paham perannya apa*". Others struggled with systems thinking, as reflected by S05: "*Saya tahu sampah itu merusak lingkungan, tapi belum ngerti proses lengkapnya kenapa bisa parah begitu*." However, a few students demonstrated stronger integration skills, such as S04 who said, "*Kalau kita pakai energi terbarukan, berarti teknologinya harus ramah lingkungan dan efisien, baru bisa dibilang berkelanjutan.*" These varied abilities highlight the need for scaffolding and clearer conceptual linking in learning materials. Technological readiness for AR use also varied. Many students reported being familiar with AR from games or social media filters, although not specifically for learning. S10 explained, "*Aku pernah pakai AR buat filter Instagram, tapi belum pernah buat pelajaran*." Despite this, students expressed enthusiasm for AR-enabled learning because it could help visualize complex IPAS phenomena. However, some limitations emerged, particularly device constraints or internet stability. For instance, S08 stated, "*HP aku kadang lemot kalau aplikasi berat, takutnya AR itu butuh HP yang bagus*." These findings suggest a generally positive readiness, with attention needed for accessibility and device compatibility.

Students also showed strong motivation and interest toward AR-based learning. Many described AR as "*lebih nyata*," "*lebih seru*," and "*tidak membosankan*," compared to traditional methods. S12 stated, "*Kalau ada AR, kayaknya saya bisa langsung lihat bendanya tanpa harus ngebayangin. Jadi lebih cepat ngerti*." Similarly, S14 expressed, "*Aku jadi lebih semangat kalau ada teknologi baru, soalnya beda dari biasanya*." Nonetheless, motivation was tied to perceived usefulness; as S13 noted, "*Asal AR-nya nggak ribet dipakai, pasti aku suka*." This highlights that usability will play an important role in maintaining student engagement. Finally, the interviews revealed several implications for developing AR-Based IPAS learning tools. Students consistently emphasized the importance of visual clarity, ease of navigation, and contextual examples. S15 advised, "*Kalau bisa objek AR-nya jangan cuma 3D, tapi ada penjelasan langkah-langkahnya juga*." Another student highlighted the need for interactivity: "*Aku mau AR yang bisa diputar, dizoom, terus ada simulasi singkat biar ngerti prosesnya*" (S16). Additionally, students requested alignment with curriculum content to ensure relevance. These insights collectively indicate that the AR tool should prioritize accessibility, interactivity, conceptual scaffolding, and real-world contextualization.

Overall, student responses demonstrate high potential for AR integration in IPAS learning but also reveal critical design considerations, particularly related to device readiness, conceptual support, and intuitive interface design. The interview data strongly supports the development of an AR-based learning tool that is interactive, curriculum-aligned, and optimized for varying levels of student technological capability.

3.4 Discussion

The results of the teacher and student needs analyses provide a comprehensive understanding of the gaps in IPAS learning while revealing critical nuances in both teacher readiness and student learning experiences. Although teachers demonstrated relatively good digital literacy and were familiar with the use of basic educational technologies, their confidence in integrating Augmented Reality (AR) into classroom practice remained low. This discrepancy suggests that the challenge is not primarily technical competence, but rather pedagogical readiness and perceived complexity of AR implementation. Interview findings further revealed that teachers associate AR with high technical demands, limited infrastructure, and uncertainty in aligning AR features with curriculum objectives. These perceptions explain why infrastructure is viewed as a major barrier, not merely due to physical limitations, but also due to a lack of structured guidance and institutional support for integrating emerging technologies into teaching practice.

This pattern resonates with the observations made by Siller et al. (2023), who found that teachers' conceptual familiarity with STEM frameworks does not automatically translate into classroom practice without targeted scaffolding. Similar trends were reported by Marouli (2021), revealing that educators frequently face challenges in operationalizing sustainability concepts due to limited pedagogical models. The convergence between current findings and earlier studies underscores the importance of providing educators with concrete, ready-to-use tools and professional development. From the students' perspective, the analysis highlights persistent learning difficulties, particularly in visualizing scientific processes, connecting interdisciplinary concepts, and maintaining engagement with conventional instructional materials. These findings are consistent with Mas'ula et al. (2025), who reported that students struggle with abstract science concepts when learning lacks interactive and visual elements.

Qualitative interview data further revealed that students often rely on memorization rather than conceptual understanding, especially when learning materials fail to provide concrete representations of invisible or complex processes. This reinforces the argument that AR can function as a cognitive bridge by transforming abstract concepts into interactive and observable experiences. Students' strong interest in technology and their positive attitudes toward AR-supported learning further support its feasibility as an engaging instructional medium, as also highlighted by Hung et al. (2023). A particularly important finding of this study is the gap between students' high environmental awareness and their limited ability to translate that awareness into concrete actions. While students expressed concern about environmental issues, many were unable to explain cause–effect relationships or predict the consequences of human actions on ecosystems. This indicates that awareness alone is insufficient without experiential understanding.

In this context, AR-based simulations become highly relevant, as they can visually and dynamically demonstrate the real impact of environmental actions, such as pollution, deforestation, or resource overuse, allowing students to observe consequences in a safe and controlled virtual environment. Such features can support not only conceptual understanding but also the development of action-oriented sustainability competencies. This finding is consistent with Kurup et al. (2021) who noted that environmental concern often lacks depth when not supported by scientifically grounded learning experiences. Teacher expectations regarding AR tools further emphasize the need for practical, curriculum-aligned, and user-friendly learning media. Teachers expressed a preference for clear visualizations, structured instructional guidance, and direct alignment with IPAS competencies. This indicates that successful AR implementation requires not only technological innovation but also careful instructional design that reduces cognitive load for teachers while enhancing usability in real classroom settings. Taken together, the findings demonstrate that AR-based STEM–ESD tools have the potential to address multiple interconnected needs.

Rather than functioning solely as a visualization tool, AR can serve as an integrative platform that supports teachers' pedagogical transition, enhances students' conceptual understanding, and bridges the gap between environmental awareness and actionable knowledge through simulation-based learning experiences. The consistency between quantitative trends and qualitative insights strengthens the validity of these conclusions and highlights the importance of designing AR tools that are contextually grounded and responsive to actual classroom challenges. As a preliminary study, these insights provide a strong foundation for the next stage of research and development. The findings underscore that effective AR-based learning tools must be designed through a user-centered approach, taking into account teacher confidence, infrastructure constraints, and students' need for interactive and experiential learning. Future studies should therefore focus on the design, validation, and implementation of AR-based STEM–ESD learning tools, particularly emphasizing simulation features and teacher support systems to ensure meaningful and sustainable integration in IPAS learning contexts.

4. CONCLUSION

The needs analysis of teachers and students highlights critical gaps in current IPAS learning practices, particularly regarding conceptual clarity, engagement, and the integration of STEM–ESD principles. Teachers exhibit partial readiness to implement interdisciplinary and sustainability-oriented approaches, while students show interest in technology but lack prior experience with AR tools. Both groups emphasize the necessity for instructional media that are clear, interactive, curriculum-aligned, and accessible. These findings confirm that existing learning resources are insufficient to fully support autonomous and meaningful learning, underscoring the importance of developing AR-based STEM–ESD tools to enhance IPAS learning experiences.Based on these insights, the study suggests that AR-based learning tools should prioritize intuitive design, interactive visualizations, structured guidance, and alignment with classroom content to maximize usability and pedagogical impact. Developers and educators should consider integrating features that facilitate conceptual understanding, encourage active learning, and provide opportunities for applying sustainability concepts in real-world contexts. Implementing such tools has the potential to improve both teacher preparedness and student engagement, forming a foundation for more effective and scalable STEM–ESD instruction in IPAS learning.

ACKNOWLEDGEMENTS

We would like to express our sincere gratitude to Universitas Sriwijaya for the funding provided. This research was funded by the Universitas Sriwijaya Budget for the 2025 Fiscal Year, in accordance with Rector's Decree Number 0028/UN9/LPPM.PT/2025 dated 17 September 2025.

REFERENCES

Agbor, C. N., Etan, M. ., Akuji, R. ., & Ogbor, C. . (2025). Methods of Teaching Environmental Education for Sustainability. *International Journal of Economics, Environmental Development and Society*, *2025*(2), 209–233. https://orcid.org/0000-0003-3298-1053

AlGerafi, M. A. M., Zhou, Y., Oubibi, M., & Wijaya, T. T. (2023). Unlocking the Potential: A

Comprehensive Evaluation of Augmented Reality and Virtual Reality in Education. *Electronics*, *12*(18), 3953. https://doi.org/10.3390/electronics12183953

Fathurohman, A., Oklilas, A. F., Marlina, L., Kurdiati, L. A., Susiloningsih, E., Azhar, A., & Samsuryadi, S. (2023). Effectiveness of Using the Mobile Learning App for STEM-Based High School Physics Materials as Indonesian Student Learning Resources on Learning Outcomes. *Jurnal Penelitian Pendidikan IPA*, *9*(3), 1018–1023. https://doi.org/10.29303/jppipa.v9i3.2991

Fathurohman, A., Seira, E. A., Susiloningsih, E., Kurdiati, L. A., Azhar, & Fatiatun. (2024). *NEO cypher learning: The new e-learning platform based learning management system for education*. 020005. https://doi.org/10.1063/5.0201099

Fathurohman, A., & Susiloningsih, E. (2022). The Effectiveness of MPI BeWe to Improve the Learning Quality of Prospective Elementary School Teachers in the Elementary Teacher Education Study Program (PGSD) FKIP Unsri. *Formatif: Jurnal Ilmiah Pendidikan MIPA*, *12*(2). https://doi.org/10.30998/formatif.v12i2.13838

Fathurohman, I., Amri, M. F., Septiyanto, A., & Riandi. (2023). Integrating STEM based Education for Sustainable Development (ESD) to Promote Quality Education: A Systematic Literature Review. *Jurnal Penelitian Pendidikan IPA*, *9*(11), 1052–1059. https://doi.org/10.29303/jppipa.v9i11.4430

Granger, E. M., Bevis, T. H., Saka, Y., Southerland, S. A., Sampson, V., & Tate, R. L. (2012). The Efficacy of Student-Centered Instruction in Supporting Science Learning. *Science*, *338*(6103), 105–108. https://doi.org/10.1126/science.1223709

Hung, C., Lin, Y., Yu, S., & Sun, J. C. (2023). Effects of <scp>AR</scp> - and <scp>VR</scp> -based wearables in teaching <scp>English</scp> : The application of an <scp>ARCS</scp> model-based learning design to improve elementary school students' learning motivation and performance. *Journal of Computer Assisted Learning*, *39*(5), 1510–1527. https://doi.org/10.1111/jcal.12814

Imam Rizaldi, Fahmi Surya Adikara, E. S. (2024). Penggunaan Gadget Terhadap Konsentrasi Belajar Anak Analysis of Parents Strategies in Overcoming the Impact of Gadget Use on Primary School Children ' S Learning. *Analisis Strategi Orang Tua Dalam Mengatasi Dampak Penggunaan Gadget Terhadap Konsentrasi Belajar Anak Sekolah Dasar*, *4*(3), 175.

Iqbal, M. Z., Mangina, E., & Campbell, A. G. (2022). Current Challenges and Future Research Directions in Augmented Reality for Education. *Multimodal Technologies and Interaction*, *6*(9), 75. https://doi.org/10.3390/mti6090075

Kurup, P. M., Levinson, R., & Li, X. (2021). Informed-Decision Regarding Global Warming and Climate Change Among High School Students in the United Kingdom. *Canadian Journal of Science, Mathematics and Technology Education*, *21*(1), 166–185. https://doi.org/10.1007/s42330-020-00123-5

Lampropoulos, G., Keramopoulos, E., Diamantaras, K., & Evangelidis, G. (2022). Augmented Reality and Gamification in Education: A Systematic Literature Review of Research, Applications, and Empirical Studies. *Applied Sciences*, *12*(13), 6809. https://doi.org/10.3390/app12136809

Lasry, N., Charles, E., & Whittaker, C. (2014). When teacher-centered instructors are assigned to student-centered classrooms. *Physical Review Special Topics - Physics Education Research*, *10*(1), 010116. https://doi.org/10.1103/PhysRevSTPER.10.010116

Makarova, E., & Makarova, E. (2018). Blending pedagogy and digital technology to transform educational environment. *International Journal of Cognitive Research in Science Engineering and Education*, *6*(2), 57–65. https://doi.org/10.5937/ijcrsee1802057M

Marouli, C. (2021). Sustainability Education for the Future? Challenges and Implications for Education and Pedagogy in the 21st Century. *Sustainability*, *13*(5), 2901. https://doi.org/10.3390/su13052901

Mas'ula, F., Putri, R. A., Asrofi, A. J., Murni, A. W., & Syväjärvi, M. (2025). Development of

Interactive Learning Media Based on Powerpoint on Learning IPAS Material Elementary School Plant Body Parts. *Islamic Journal of Integrated Science Education (IJISE)*, *4*(1), 45–54. https://doi.org/10.30762/ijise.v4i1.4661

Murphy, L., Eduljee, N. B., & Croteau, K. (2021). Teacher-Centered versus Student-Centered Teaching. *Journal of Effective Teaching in Higher Education*, *4*(1), 18–39. https://doi.org/10.36021/jethe.v4i1.156

Qureshi, M. I., Khan, N., Raza, H., Imran, A., & Ismail, F. (2021). Digital Technologies in Education 4.0. Does it Enhance the Effectiveness of Learning? A Systematic Literature Review. *International Journal of Interactive Mobile Technologies (IJIM)*, *15*(04), 31. https://doi.org/10.3991/ijim.v15i04.20291

Ramírez, A. S., Ayala, G. X., Murillo, M., Glik, D. C., & Guerrero, A. D. (2025). Integrating Theory With a User-Centered Design Approach to Maximize mHealth Acceptability and Usability. *Health Education & Behavior*, *52*(3), 329–339. https://doi.org/10.1177/10901981241311232

Septiani, E. Y., Soliha, I. A., & Fadilah, Y. (2025). Strategies for using augmented reality-based interactive learning media to improve the understanding of ipas concepts. *Al-Mubin; Islamic Scientific Journal*, *8*(2). https://doi.org/https://doi.org/10.51192/almubin.v8i2.2040

Siller, H.-S., Nitzan-Tamar, O., & Kohen, Z. (2023). Scaffolding practices for modelling instruction in STEM-related contexts: insights from expert and novice teachers. *ZDM – Mathematics Education*, *55*(7), 1351–1364. https://doi.org/10.1007/s11858-023-01529-9

Susiloningsih, E., Tahir, A., Setiono, A., Vanda, Y., Sriwijaya Palembang, U., Teknik Soroako Luwu Timur, A., Tinggi Ilmu Manajemen Sukma Medan, S., & Negeri Sultan Aji Muhammad Idris Samarinda, I. (2023). The Effectiveness Analysis Of The Implementation Of Class Active Learning On Students Character In Two Ways Learning Process. *(Jurnal Manajemen Pendidikan)*, *5*(1), 195–199. https://doi.org/10.55352/mudir

Wang, C., Chen, X., Yu, T., Liu, Y., & Jing, Y. (2024). Education reform and change driven by digital technology: a bibliometric study from a global perspective. *Humanities and Social Sciences Communications*, *11*(1), 256. https://doi.org/10.1057/s41599-024-02717-y