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Bibliometric analysis of cognitive regulation models in science education: Trends, key contributors, and research impact

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ABSTRACT
This study presents a bibliometric analysis of cognitive regulation models in science education, focusing on STEM (Science, Technology, Engineering and Mathematics) contexts between 2004 and 2024. Using the Scopus database and VOSviewer (version 1.6.17) and Bibliometrix (RStudio version 4.4.1), we identified Self-Regulated Learning (SRL) as a key theme, strongly linked to motivation, self-efficacy and academic performance. Emerging areas—such as emotional regulation and digital learning environments—highlight the field's response to challenges such as the COVID-19 pandemic. Key findings emphasise that integrating learning analytics, blended instruction, and formative assessments can enhance SRL outcomes in both traditional and online settings. However, emotional regulation and SRL application in large-scale online platforms remain underexplored. We conclude that personalised feedback and metacognitive strategies are vital for improving learners' self-regulation. Future studies should focus on emotional regulation, technology-driven interventions, and interdisciplinary approaches to foster student success in STEM.

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Introduction

Background and Rationale

Cognitive regulation models play a crucial role in educational research (Azevedo, 2020; Schunk & Zimmerman, 2007; Wirth et al., 2020) due to their significant impact on learning outcomes, especially in science education. These frameworks explain how learners regulate their cognitive, emotional, and metacognitive processes—vital for academic performance and critical thinking. In STEM disciplines such as biology, chemistry and physics, effective cognitive regulation is essential for tackling abstract concepts and developing self-directed learning skills (Suryawati et al., 2024). Therefore, examining these models helps optimise academic outcomes by addressing both cognitive and emotional demands.

Self-Regulated Learning (SRL), rooted in Bandura's social cognitive theory, is a core cognitive regulation model emphasising independent learning through self-assessment, planning, and reflection

(Schunk & Zimmerman, 2007). Learners employing SRL strategies (e.g., goal-setting, self-monitoring, reflection) often demonstrate higher academic success, particularly in science contexts that demand mastery of complex, abstract material (Dağgöl, 2023). Its relevance in science education, through goal-setting and progress evaluation, highlights how SRL guides focused and critical thinking (Fitriani et al., 2024; Fatmawati et al. 2025).

Other models, such as Metacognitive Awareness and Cognitive Emotion Regulation (CER), complement SRL by enhancing learning. Metacognitive Awareness involves the ability to monitor and regulate cognition, improving academic performance through the adjustment of learning strategies (Muhali et al., 2019; Wirzal et al., 2022). Learners with high metacognitive awareness tend to perform better by recognising knowledge gaps and modifying their approaches (Abdelrahman, 2020; Asy'ari et al., 2019; Azevedo, 2020). In science education, fostering metacognitive skills leads to deeper understanding and improved problem-solving (Taşçi & Yurdugül, 2017).

CER emphasises managing emotional responses to learning challenges, which can significantly affect academic performance. Adaptive strategies, such as cognitive reappraisal, reduce anxiety and enhance learning, while maladaptive strategies, like rumination, can exacerbate stress (Sun et al., 2020). Addressing both cognitive and emotional aspects of learning, particularly in science education, helps learners persevere through challenges.

These models collectively illustrate the need for holistic educational approaches. By integrating SRL, Metacognitive Awareness, and CER into instructional strategies, educators can create environments that support both cognitive and emotional regulation, fostering resilience and enhancing problem-solving skills (Wirth et al., 2020).

Bibliometric analysis offers a powerful tool for mapping the evolution of cognitive regulation models in STEM. Such analysis is particularly needed to unify fragmented research and identify emerging trends, key contributors, and interdisciplinary collaborations (Djeki et al., 2022). By examining publication volume, citation networks, and keyword clusters, VOSviewer and Bibliometrix highlight how cognitive regulation studies intersect psychology, education, and neuroscience, thus enriching our holistic understanding of the field.

However, bibliometric studies face limitations in data completeness and representativeness. Exclusive reliance on databases such as Scopus or Web of Science can overlook significant contributions from broader sources such as Google Scholar, and citation counts may not fully reflect the quality or impact of research (Polat, 2022). Therefore, it is important to supplement bibliometric data with qualitative insights for a comprehensive view.

Cognitive regulation models remain vital for enhancing learning outcomes in science education, addressing both cognitive and emotional learning dimensions. By fostering SRL, metacognition, and emotional regulation, these models equip learners to thrive in demanding academic environments. Bibliometric analysis will continue to be a critical tool in guiding future research and understanding the evolving impact of cognitive regulation.

Research Gaps

Despite the growing interest, research on cognitive regulation models in science education remains inconsistently integrated. This fragmentation makes it difficult to compare studies and develop a unified framework for categorising key strategies (Nakhostin-Khayyat et al., 2024; Yusupov et al., 2020). While SRL and metacognitive approaches are well-documented, standardised definitions and operationalisations are lacking, impeding cohesive progress in science education contexts.

A major gap is the absence of consensus on defining and operationalising cognitive regulation models. Researchers vary in their approaches, some emphasising self-regulation's role in enhancing cognitive flexibility, while others highlight the interplay between metacognition and emotional regulation. This variation creates a fragmented research landscape, making comparisons and standardisation difficult, especially in science education (Nakhostin-Khayyat et al., 2024; Yusupov et al., 2020).

Furthermore, many studies fail to address the specific demands of science education. Critical thinking, problem-solving, and managing complex information are often overlooked in favour of general educational contexts. Existing research shows SRL promotes autonomy and motivation (Balashov et al., 2021), but strategies tailored for science disciplines such as biology, chemistry and physics remain underexplored (Eker & İnce, 2018).

Another challenge lies in the lack of methodological consistency. Many studies rely on self-reported data, which can introduce biases and may not accurately reflect learners' cognitive processes (Dang et al., 2020; Fan et al., 2022; Van Der Ham et al., 2021; Villegas & Panoy, 2023). Additionally, diverse assessment tools and frameworks complicate meaningful comparisons and limit evidence-based interventions in science education (Eker & İnce, 2018).

The interaction between cognitive regulation and factors such as motivation, emotional intelligence, and social dynamics remains insufficiently explored. For example, emotional intelligence's role in facilitating cognitive regulation could provide insights into how learners manage stress and the cognitive demands of science learning (Amponsah et al., 2024; Mukhametzyanova, 2021). Moreover, understanding the contributions of key researchers, institutions and countries in cognitive regulation research is needed. Mapping collaboration networks can enhance knowledge-sharing and interdisciplinary research (Muñoz et al., 2016).

The integration of technology into science education presents additional opportunities and challenges. While digital tools and online platforms have transformed engagement with content, gaps remain in leveraging these tools to support SRL, metacognitive awareness, and emotional regulation in remote and hybrid learning environments (Hung & Young, 2021). Research needs to explore how technology can enhance these processes, particularly in large-scale online contexts.

Finally, the evolution of cognitive regulation models across different contexts remains underexplored. Bibliometric analysis, as applied by Wang and Hasim (2024) in technology-enhanced learning, has yet to be fully applied to science education. This approach could identify emerging themes, key contributors, and research gaps, providing a clearer picture of the models' development over time.

Addressing these gaps—unified frameworks, context-specific research, methodological rigor, and interdisciplinary exploration—through advanced methodologies like bibliometric analysis will be crucial for advancing the study of cognitive regulation in science education.

Research Objectives

The primary objective of this bibliometric study was to investigate cognitive regulation models in STEM education, focusing on trends, key contributors, and research impact between 2004 and 2024. More specifically, we aimed to identify publication trends and geographical distribution, examine collaboration networks and top contributors, and elucidate how cognitive regulation research has developed over time. These goals offer insights into emerging themes and pave the way for future research directions.

The research sought to identify key contributors—authors, institutions and countries—that played a pivotal role in advancing the study of cognitive regulation in science education. By examining influential publications and journals, the study highlighted the most impactful research and clarified where academic efforts had been concentrated. We formulated the following research questions to guide our analysis:

1. RQ1: What are the main publication trends and key journals in cognitive regulation for STEM education?
2. RQ2: Who are the top authors, institutions, and countries contributing to this field, and how do they collaborate?
3. RQ3: Which themes and topics have emerged over time, and what gaps or future directions can be identified?

Literature Review

Theoretical Foundation of Cognitive Regulation Models

Cognitive regulation, Self-Regulated Learning (SRL), and metacognitive strategies are central in educational psychology, particularly in science education where learners face complex concepts and must develop autonomy and critical thinking (Prayogi et al., 2025). These interdependent constructs enable learners to plan, monitor, and adjust their study approaches, leading to improved academic success in disciplines such as biology, chemistry and physics. Cognitive regulation involves managing cognitive processes (e.g., planning, monitoring, evaluating learning strategies) to achieve effective outcomes (Nguyen & Ikeda, 2015). In science education, this is vital for tackling abstract concepts in physics, biolofy or chemistry, prompting strategy adaptation through self-assessment. Strong cognitive regulation supports critical thinking, elaboration, and synthesis—skills essential for mastering scientific material. SRL integrates cognitive regulation with motivation and emotion, allowing learners to take control of their education via goal-setting, strategy selection, and reflection (Cassidy, 2011; Lavi et al., 2019). In science courses, SRL is critical for managing both cognitive tasks and emotional demands. Evidence shows SRL strategies (e.g., setting goals, monitoring progress) enhance academic performance, motivation and problem-solving abilities (Radović et al., 2024; Theobald, 2021; Jansen et al., 2019).

Metacognitive strategies, a core element of SRL, encompass awareness and control of one's cognitive processes (Muhali et al., 2019). In science education, where higher-order thinking is frequently required, metacognitive approaches (e.g., self-questioning, reflective thinking) enable learners to evaluate understanding and adjust study techniques (Ulfatun et al., 2021). This is particularly beneficial for grasping complex concepts such as chemical reactions. Combining cognitive regulation, SRL, and metacognition is key for science curricula involving abstract concepts and inquiry-based tasks. Methods like problem-based learning and inquiry-based learning strengthen student engagement, prompting goal-setting and reflection (Jaramillo et al., 2022). Nonetheless, implementing these models can be challenging in online or hybrid settings, where lack of external structures and limited teacher scaffolding may hinder self-regulation (Calamlam et al., 2022). Educators often require professional development to effectively teach these strategies and create environments conducive to SRL (Stephen & Rockinson-Szapkiw, 2021).

Collaborative learning in science also benefits from cognitive regulation, requiring "socially shared regulation," where group members jointly plan and monitor learning (Isohätälä et al., 2017). Such collaboration can boost feedback and peer support, enhancing learning outcomes in science classrooms (Anderson et al., 2023). In summary, cognitive regulation, SRL, and metacognition are critical to effective science learning. They empower learners to self-manage, stay motivated, and master complex content. However, barriers remain in virtual and collaborative settings, making targeted teacher training and instructional interventions vital for maximising the impact of these strategies on outcomes.

Previous Studies Using Bibliometric Analysis

Bibliometric analysis is frequently employed to uncover research trends, key contributors, and emerging themes in education. It has been used in fields such as SRL, mobile-assisted language learning (MALL), and emergency remote teaching (ERT), providing useful comparisons for our focus on cognitive regulation in science (Wang & Hasim, 2024; Tonbuloğlu & Avcı Akbel, 2023). SRL is extensively studied, with bibliometric work (e.g., Sulistiawati et al., 2023) revealing key trends from 1990–2022 across 2,106 documents. This underscores SRL's importance in digital settings and performance outcomes—insights that parallel our examination of cognitive regulation in science. Similarly, Turmuzi et al. (2023) focused on MALL, illustrating how mobile tools support self-regulation. Although language-focused, their findings about technology's role in self-regulation are relevant for science contexts, reinforcing the theme of tech-enhanced cognitive regulation. With emergency remote teaching (ERT), researchers (e.g., Mäkipää et al., 2022; Chan & Daigle, 2022) highlighted the importance of flexible cognitive regulation amid rapid shifts to online learning. These findings inform how external factors (crises, tech changes) influence self-regulation, paralleling science education’s need for adaptable strategies in dynamic settings.

Unlike studies on language or COVID-related topics, our work centres on cognitive regulation in science education. This approach reveals how learners handle complex scientific content through self-directed learning and enhanced academic achievement. While SRL and MALL analyses provide foundational insights, our focus on STEM brings fresh perspectives on applying these theories in discipline-specific contexts. Wang and Hasim (2024) also examined self-regulated language learning in mobile contexts, illustrating the role of technology in bolstering self-regulation. Their methods (e.g., co-occurrence and burstness analyses) are transferable to cognitive regulation research in science education. Tonbuloğlu and Avcı Akbel’s (2023) analysis of ERT trends exemplifies how global crises influence educational practices and collaborations. Our study parallels their approach by examining publication patterns and networks, but focuses on long-term theoretical shifts in cognitive regulation for science. In conclusion, SRL, MALL, and ERT bibliometric studies underline the value of mapping research trends, contributors, and themes. Our study extends these methodologies, revealing how cognitive regulation models shape science education, thus informing future practices and theoretical progress.

Method

Research Design

This study employed a bibliometric analysis guided by the PRISMA protocol (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) to examine trends, contributors, and research impact in cognitive regulation for science education. Bibliometric analysis quantitatively maps scientific literature, revealing trends, key publications, co-occurring keywords, and citation networks (Farooq et al., 2024; Prahani et al., 2022). Our goal was to offer a comprehensive overview of existing literature on cognitive regulation (focusing on SRL and metacognitive strategies) and their use in STEM contexts.

Data Source and Search Strategy

The literature originated from Scopus, selected for its broad coverage of peer-reviewed journals. We used ("cognitive regulation" OR "self-regulated learning" OR "metacognitive strategies") AND ("science education" OR "STEM education" OR "higher education" OR "university") as our query, conducted in June 2024. A 20-year range (2004–2024) was chosen to capture two decades of evolving research in a maturing field. We limited the results to English articles to maintain consistency and focus on widely cited, high-impact publications.

PRISMA Protocol

A systematic PRISMA-based approach helped us identify, screen, and include relevant documents. Table 1 outlines the stepwise method, ensuring transparency and reproducibility in our selection process.

Table 1

PRISMA protocol utilised.

Step	Details
Database	Scopus
Time span	2004-2024
Document type	Peer-reviewed articles
Language	English
Identification	2,511 articles identified through the search query
Screening	789 irrelevant publications removed; 60 review articles excluded
Final inclusion	1,662 articles included in the final analysis

During the screening phase, publications were excluded based on relevance, resulting in a dataset of 1,662 original research articles focused on cognitive regulation in science education or STEM fields.

Data Analysis

The analysis comprised three components. First, a keyword co-occurrence analysis used VOSviewer (version 1.6.17) to visualise relationships among key topics. Frequent terms—such as self-regulated learning, motivation, and self-efficacy—emerged as dominant, while emotion regulation and blended learning were less explored but showcased emerging interests.

Second, a citation network analysis was performed via Bibliometrix in RStudio (version 4.4.1), mapping relationships and calculating metrics (e.g., centrality, impact). Prominent clusters revolved around self-regulated learning and learning analytics, while a cluster on academic procrastination also exhibited noteworthy influence in higher education.

Lastly, thematic evolution analysis examined research shifts in five periods (2004–2014, 2015–2017, 2018–2019, 2020–2021, 2022–2024). Earlier studies emphasised e-learning and academic performance, while recent works highlighted metacognitive strategies and COVID-19 impacts, indicating growing attention to emotional and social dimensions of self-regulation.

Tools and Software

We utilised VOSviewer (version 1.6.17) to create keyword co-occurrence maps and Bibliometrix in RStudio (version 4.4.1) for citation and thematic analysis, leveraging their robust capabilities to uncover trends and collaborations in the dataset.

Validity and Reliability

The Scopus database provided a high-quality, peer-reviewed source pool (Fatawi et al., 2024). VOSviewer and Bibliometrix are established, validated bibliometric tools, ensuring reliable outcomes. Multiple researchers verified the analyses to maintain consistency. To further enhance reliability, two independent researchers applied our inclusion/exclusion criteria to a randomly selected subset of 200 articles from the total dataset. Each researcher independently coded articles for inclusion or exclusion. Afterward, we compared their decisions using Cohen’s kappa (K) to measure inter-rater agreement beyond chance (Landis & Koch, 1977). Our analysis yielded a K value of 0.85, indicating strong inter-rater reliability. Discrepancies on the remaining articles were resolved through discussion, ensuring all final decisions aligned with the study’s scope and quality standards.

Ethical Considerations

As this study used secondary data from the Scopus database, all information was publicly available and ethically sourced. No human subjects or sensitive data were involved, so ethical approval was not required.

Method Limitations

A key limitation is our exclusive use of Scopus, potentially excluding relevant works from other databases. Moreover, bibliometric methods highlight quantitative patterns, possibly overlooking depth in individual studies. Future work could incorporate qualitative content analysis for a broader view of cognitive regulation in science education.

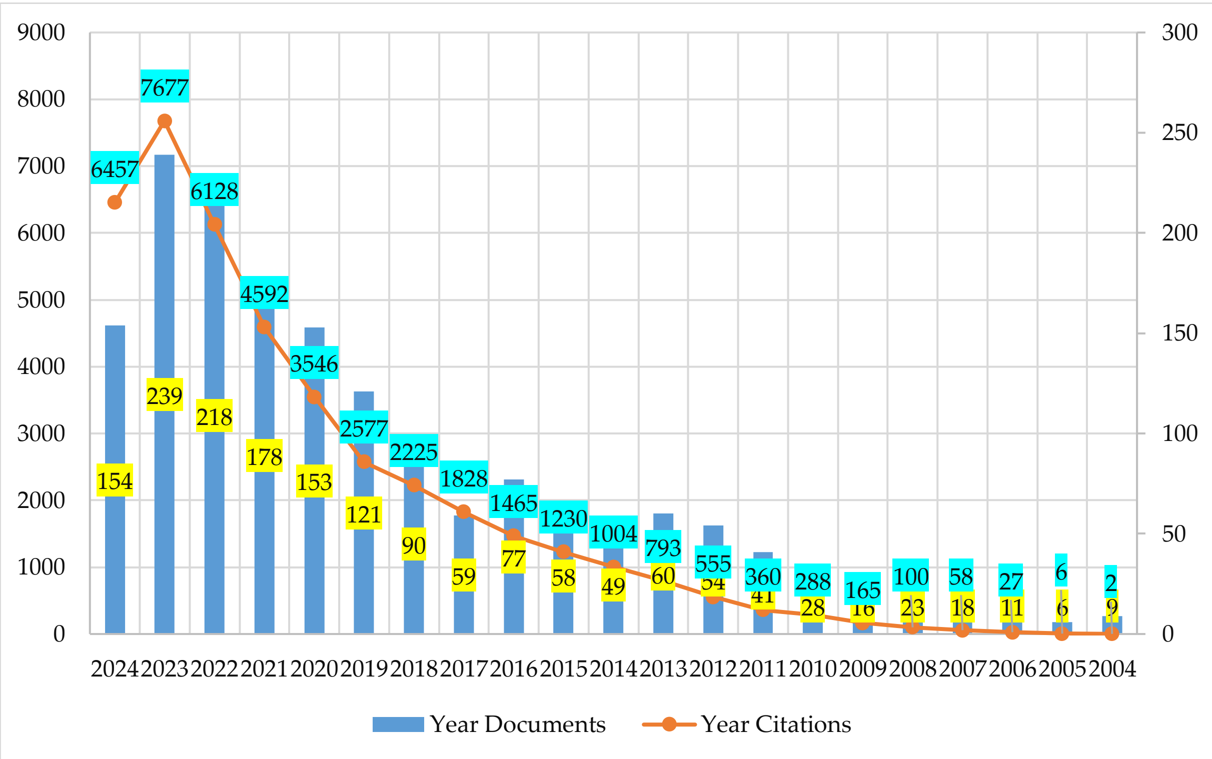
Results

Publication Trends in Cognitive Regulation Models

Research on cognitive regulation in science education has grown markedly over the past two decades. Figure 1 displays annual publication and citation counts (2004–2024), showing increased academic interest. While publication volume has risen, citation data indicate a gradual impact uptake, suggesting the field is still maturing in terms of scholarly influence.

Figure 1

Publication trends of cognitive regulation models in science education



From 2020 onward, publications rose sharply (e.g., 239 in 2023 vs. 9 in 2004). This jump aligns with a wider trend in education, emphasising cognitive processes (e.g., metacognition, emotional regulation) and their impact on learning. Although publication numbers soared, citation growth lagged (peaking at ~7,677 in 2023). Early years (e.g., only 2 citations in 2004) illustrate how recognition of new studies takes time, exhibiting a delayed academic impact. The lag reflects the field's novelty, competition from a large volume of publications, and its interdisciplinary nature, which can dilute immediate visibility within specific domains. A key emerging theme is Self-Regulated Learning (SRL), crucial for independent inquiry and problem-solving in science. Research (Lin et al., 2019) observed an SRL surge (2013–2017), reflecting its foundational role in cognitive regulation. Embodied cognition has also grown in relevance, tying learning to physical experiences. In science education, hands-on methods (Kersting et al., 2021) are used to reinforce cognitive regulation, enabling deeper conceptual understanding. Technology (VR, AI, intelligent systems) has further propelled research on cognitive regulation. Tools like VR (Li et al., 2024) offer real-time feedback, aiding visualisation of abstract concepts and supporting enhanced regulation. Collaborative learning and socially shared regulation are gaining prominence, with group settings fostering mutual monitoring and strategy adjustment. Such social interactions bolster problem-solving and highlight the collective aspect of cognitive regulation. Despite expansion, citation growth remains gradual. As recent studies mature, their impact may increase. Interdisciplinarity also disperses citations across fields, slowing accumulation in a single domain. In summary, publication trends show a rapidly growing field, underscoring the importance of SRL, metacognition, and emotional regulation in science education. Citation impact, however, lags, likely due to field novelty and interdisciplinary breadth. Nonetheless, as research matures, impact should strengthen, deepening our understanding of cognitive regulation in STEM.

Key Contributors

Research on cognitive regulation in science education has been driven by several prolific scholars and institutions over the last two decades. Tables 2 and 3, plus Figure 2, highlight leading contributors and collaborations in the field. Table 2 shows the top 10 authors, based on number of articles and AF (Article Fractionalized-indicate each author's individual contribution to their publications) scores. Lawrence Jun Zhang (AF 4.75) stands out for significant work (based on N of documents) on metacognitive strategies and SRL.

Table 2

Top 10 most prolific authors

Authors	Articles	AF	Affiliation	Country
Gašević, Dragan	11	1.81	Monash University	Australia
Panadero, Ernesto	11	2.90	Dublin City University	Ireland
Zhang, Lawrence Jun	11	4.75	The University of Auckland	New Zealand
De La Fuente, Jesús	10	2.33	University of Navarra Pamplona	Spain
Bellhäuser, Henrik	9	2.68	Johannes Gutenberg-Universität Mainz	Germany
Bernacki, Matthew L.	9	2.45	The University of North Carolina	United States
Dresel, Markus	9	1.93	Universität Augsburg	Germany
Tsai, Chin-Chung	9	2.67	National Taiwan Normal University	Taiwan
Broadbent, Jaclyn	8	3.67	Deakin University	Australia
Tsai, Chia-Wen	8	6.17	Ming Chuan University	Taiwan

Chia-Wen Tsai has the highest AF (6.17), reflecting strong individual contributions in tech-enhanced contexts, while Jaclyn Broadbent (AF 3.67) focuses on blended and online learning. Ernesto Panadero (AF 2.90), despite 11 publications, has collaborative work on SRL and formative assessment, showing diverse influence. Table 3 and Table 4 shows top affiliations and countries in cognitive regulation research. The University of Granada (40 articles) and Maastricht University (38) highlight Europe's prominence, while the USA (657) and China (485) lead globally, reflecting the field's international nature.

Figure 2 (co-authorship network) illustrates collaboration clusters among key researchers, each node sized by number of co-authored papers. Lines indicate collaboration strength, revealing regional or institution-based partnerships.

One cluster features Bellhäuser, Dresel, and Schmitz (Germany), focusing on motivation and cognitive regulation. Gašević collaborates with van der Graaf and Fan Yijun on learning analytics and SRL, demonstrating the role of technology in cognitive regulation. Another group is led by Zhang, focusing on metacognitive strategies in higher education, while Panadero's cluster highlights SRL and assessment practices across European contexts. Overall, the co-authorship network reveals both close collaborations and isolated research hubs, with regional ties (notably in Europe) facilitating partnerships and interdisciplinary efforts.

Table 3

Top 10 most prolific affiliations

Affiliation	Articles
University of Granada	40
Maastricht University	38
Islamic Azad University	31
McGill University	30
University of North Carolina	30
University of Vienna	29
Utrecht University	28
Newcastle University	25
The Education University of Hong Kong	25
University of Macau	25

Table 4

Top 10 most prolific countries

Country	Articles
USA	657
China	485
Spain	417
Germany	344
UK	300
Netherlands	258
Australia	257
Indonesia	233
Malaysia	175
Iran	160

Interdisciplinary collaboration (e.g., psychology, neuroscience, ed tech) and strong institutional support (e.g., Monash, Auckland) enrich research depth and citation impact, as seen with Gašević and Zhang. Active networking (e.g., conferences, professional groups) boosts collaboration and visibility, fueling influential work and methodological innovation. Despite advances, a lack of longitudinal studies persists, limiting understanding of how cognitive regulation evolves over time. Future work should include extended tracking of these strategies' long-term impact. Additionally, a higher education focus restricts generalisability. Including K–12 and informal contexts would broaden the applicability of cognitive regulation models. In summary, leading figures like Gašević, Panadero, and Zhang significantly shape cognitive regulation research, especially in tech-enhanced and science-focused environments. Collaborative networks span the globe, with USA, China and Spain leading in publication counts. Such partnerships will continue driving innovation and broadening the impact of cognitive regulation in diverse educational contexts.

Figure 2

Co-authorship network

Influential Publications and Journals

Over the past two decades, cognitive regulation in science education has seen substantial growth, with key journals and publications shaping its evolution. Identifying influential outlets and articles reveals major research trends, top contributors, and emerging directions. Such analysis helps researchers pinpoint advancements and anticipate future needs in cognitive regulation scholarship. The leading journals demonstrate the field’s interdisciplinary scope. Table 5 shows Computers and Education having the highest h-index (20) and g-index (23). Since 2008, it has published 23 highly cited papers (1,865 citations), focusing on technological tools for SRL and metacognition—a key trend in educational research. Frontiers in Psychology has emerged quickly, holding the highest g-index (29) and most publications (64). Its psychological orientation—especially on emotional regulation and motivation—positions it as a crucial source for understanding how cognitive and affective factors intersect in learning.

Table 5

Top 10 most influential journals

Source	h_index	g_index	m_index	*TC	*NP	*PY_start
Computers and Education	20	23	1.176	1865	23	2008
Learning and Individual Differences	18	19	1.059	901	19	2008
Frontiers in Psychology	17	29	1.7	1027	64	2015
Computers in Human Behavior	16	16	0.889	1716	16	2007
Internet and Higher Education	16	18	1	3241	18	2009
Studies in Higher Education	14	16	1	1082	16	2011
Education and Information Technologies	12	21	1.333	647	21	2016
Metacognition and Learning	12	17	0.8	584	17	2010
Sustainability (Switzerland)	11	19	2.2	395	29	2020
System	11	23	0.579	683	23	2006

Note. *TC: Total Citations; *NP: Number of Publication; *PY: Publication Year

A notable journal, The Internet and Higher Education, with 3,241 citations (18 publications since 2009), examines how digital environments shape cognitive regulation. As online learning grows, this resource offers relevant perspectives on virtual classroom demands. Among newer outlets, Sustainability (Switzerland) shows notable impact (m-index 2.2) since 2020, with 395 citations. Its focus on sustainability in education underscores the rising theme of merging environmental and educational concerns, including sustainable learning's role in cognitive regulation. Influence also derives from landmark articles. Table 6 shows Pekrun et al. (2011) as top-cited (1,373 total; 98.07/year). Their Achievement Emotions Questionnaire (AEQ) study illuminates how emotions (e.g., anxiety, joy) shape learning, influencing instructional design and pedagogy.

Table 6

Top 10 most influential articles

Authors	Title	*TC	*TCY	*NTC
(Pekrun et al., 2011)	Measuring emotions in learners' learning and performance: The Achievement Emotions Questionnaire (AEQ)	1373	98.07	13.85
(Dabbagh & Kitsantas, 2012)	Personal Learning Environments, social media, and self-regulated learning: A natural formula for connecting formal and informal learning	1065	81.92	19.60
(Schraw et al., 2006)	Promoting self-regulation in science education: Metacognition as part of a broader perspective on learning	786	41.37	5.25
(Blair & Diamond, 2008)	Biological processes in prevention and intervention: The promotion of self-regulation as a means of preventing school failure	756	44.47	8.01
(Rosen et al., 2013)	Facebook and texting made me do it: Media-induced task-switching while studying	511	42.58	16.11
(Carless et al., 2011)	Developing sustainable feedback practices	508	36.29	5.13
(Broadbent, 2017)	Comparing online and blended learner's self-regulated learning strategies and academic performance	438	54.75	10.97
(Littlejohn et al., 2016)	Learning in MOOCs: Motivations and self-regulated learning in MOOCs	421	46.78	11.10
(Tai et al., 2018)	Developing evaluative judgement: enabling learners to make decisions about the quality of work	406	58.00	14.53
(Hadwin & Oshige, 2011)	Self-regulation, coregulation, and socially shared regulation: Exploring perspectives of social in self-regulated learning theory	371	26.50	3.74

Note *TC: Total Citations; *TCY: TC per Year; *NTC: Normalized TC

Blair and Diamond (2008) examined biological underpinnings of self-regulation to prevent school failure. With 756 citations, they broadened the field to developmental and neurological aspects, underscoring how biology affects long-term learning regulation. Rosen et al. (2013) address media multitasking (511 citations) and its cognitive toll, linking digital distractions to reduced engagement in learning. With technology's growing role, media usage and its effects on cognitive regulation remain crucial research areas. Carless et al. (2011) (508 citations) highlight sustainable feedback practices that foster SRL. Their work emphasizes actionable, reflective feedback, aligning with formative assessment trends and learner autonomy.

Overall, these journals and publications underscore major themes: emotional regulation, technology integration, media influence, and feedback. Metrics (h-index, g-index, m-index) clarify their impact, while interdisciplinary work is key for broadening the field. As research advances, emotional regulation, digital tools, and effective feedback will stay central, guided by collaborative efforts and innovative technologies.

Keyword Co-Occurrence and Emerging Themes

A keyword co-occurrence analysis uncovers major themes in cognitive regulation research within science education. Figure 3 depicts frequent keywords and their interrelationships, grouped into clusters like self-regulated learning, cognitive strategies, digital literacy, and feedback. These clusters illustrate the field's varied focal points and indicate emerging directions in both traditional and technology-driven learning.

The green cluster centres on Self-Regulated Learning (SRL) and Performance. Self-regulated learning dominates, indicating its pivotal place in cognitive regulation. Keywords such as motivation, self-efficacy, and academic achievement underscore how SRL drives better outcomes (Broadbent, 2017; Uçar, 2018). Intrinsic motivation also matters, as emotions (anxiety, joy) deeply shape learning (Pekrun et al., 2011).

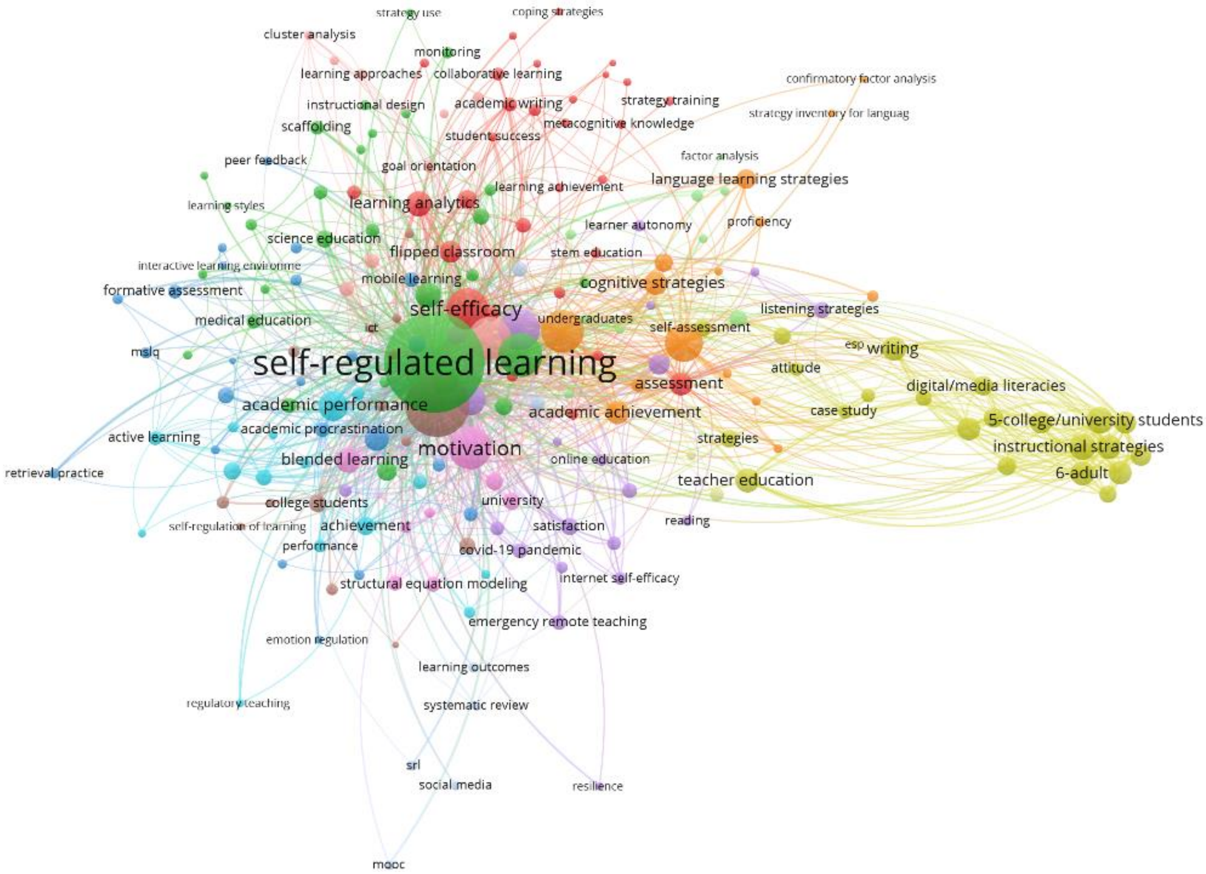
The red cluster highlights Cognitive and Learning Strategies, including learner autonomy and language strategies. Studies (Leopold & Leutner, 2015; Hattie & Donoghue, 2016) confirm that organisational tools, rehearsal, and elaboration boost comprehension and complex concept mastery. Educators' roles in teaching these strategies are essential, as collaborative learning and teacher training help foster autonomy (Arthur & Akwetey, 2021; Schraw et al., 2006).

The blue cluster focuses on Active Learning and Feedback, featuring keywords like peer feedback and flipped classroom. Carless et al. (2011) show how ongoing feedback enhances reflection and adjustment. With learning analytics and formative assessment (Tai et al., 2018), data-driven support for self-regulation is increasing. Peer feedback also promotes self-regulation by developing evaluative skills (Er et al., 2021).

The yellow cluster underscores Digital Literacy and Instructional Strategies. Digital literacies (Khlaisang & Yoshida, 2022) empower learners to find, evaluate, and apply resources for better self-regulation. Tools like online platforms and interactive multimedia (Rini et al., 2022) facilitate goal-setting, tracking, and strategy adjustments. Consequently, instructional methods focusing on digital skill development are increasingly common to foster SRL and academic performance.

Figure 3

Research trends based on keyword co-occurrence



The purple cluster addresses Learning Outcomes and Remote Teaching, showing how COVID-19 reshaped self-regulation demands. Remote settings require higher autonomy, with keywords like emotion regulation, self-efficacy, and digital literacy (Sukirman et al., 2022). Time management, motivation and feedback become critical (Alqahtani & Rajkhan, 2020). Emotional strain (Mahyoob, 2020) can compound self-regulation challenges, although supportive digital platforms (Liu et al., 2022) can alleviate isolation and boost collaboration.

Lastly, the orange cluster highlights Language Learning and Strategies, where self-regulation theories support goal-setting and monitoring (Dabbagh & Kitsantas, 2012). L2 learners rely on autonomy beyond formal instruction, prompting instructional designs that embed SRL for grammar, vocabulary and communication skills (Schraw et al., 2006).

Overall, the co-occurrence map underscores emerging themes: SRL, cognitive/metacognitive strategies, digital literacy, active learning, and COVID-19 impacts. Collectively, they signal the field's emphasis on strengthening student agency in both classroom and online settings. As digital technologies grow, these themes will further influence future research and educational practice.

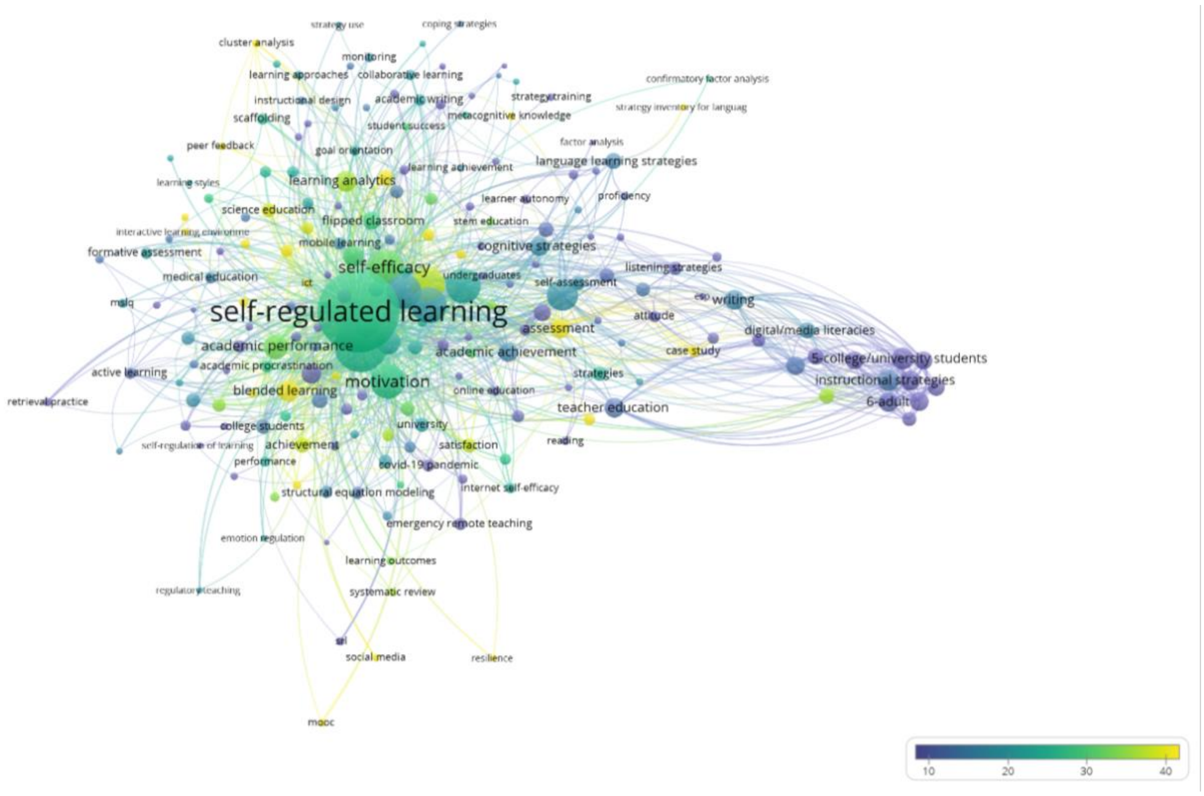
Citation Networks

In bibliometric analysis, citation networks help uncover a field's intellectual structure, connectivity, and impact. Figure 4 depicts keywords in cognitive regulation for science education, sized by occurrence and color-coded by citation count. Green nodes signal frequently cited themes (e.g., SRL, motivation), while blue nodes show newer but growing research areas. Such networks reveal key study directions, foundational works, and emerging subfields.

At the network's centre, green nodes reflect the importance of Self-Regulated Learning (SRL) and motivation, indicating their foundational role. Terms such as self-efficacy, academic performance, and blended learning further demonstrate focus on how self-regulatory strategies shape academic results. For instance, Pekrun et al. (2011) showed how emotions affect SRL, establishing links between motivation, emotion, and performance. Within this green cluster, key terms like goal orientation, scaffolding, and learning analytics illustrate the instructional focus on supporting SRL. Scaffolding research examines phased withdrawal of external supports, while learning analytics provides real-time data to inform self-regulation interventions.

Figure 4

Average citations



Next, the yellow cluster centres on Cognitive and Learning Strategies—keywords such as collaborative learning, monitoring, and rehearsal show how cognitive regulation is used in practical settings (Broadbent, 2017). This cluster also features learner autonomy and assessment, pointing to the application of self-regulation in contexts such as language acquisition, where learners self-manage and evaluate progress.

The blue cluster highlights digital/media literacies and instructional strategies—emerging focus areas. With online platforms becoming mainstream, media literacy has proven vital for self-regulation (Muthupoltotage & Gardner, 2018). High digital literacy enables learners to set goals, monitor progress, and collaborate effectively (Khlaisang & Yoshida, 2022). Moreover, the blue cluster underscores instructional strategies in digital settings, where media literacy merges with design methods. Such research gained traction during COVID-19, when online learning demanded self-directed approaches and flexible pedagogies.

The purple cluster reflects pandemic-driven themes such as remote learning and emotion regulation, highlighting the global shift to online education. Alqahtani and Rajkhan (2020) underscore the criticality of emotion regulation when traditional supports are absent, while Mahyoob (2020) details the psychological challenges (anxiety, isolation) amplified in remote contexts.

Keywords such as emergency remote teaching and self-efficacy also appear here, underlining the concerns about learner self-regulation amid pandemic disruptions. Liu et al. (2022) demonstrate how blended environments, fostering collaboration and peer feedback, can bolster SRL even under crisis conditions. Emerging terms on the network's edges—MOOCs, social media, resilience—point to new applications of cognitive regulation. MOOCs often demand self-management without strong instructor presence (Broadbent, 2017), and resilience is becoming crucial given global disruptions. As education adapts, research on maintaining motivation and SRL in these contexts is expected to increase.

In summary, the citation network spotlights both core themes (SRL, motivation, self-efficacy) and emerging areas (digital literacy, pandemic-driven remote learning, resilience). Clusters highlight the adaptability of cognitive regulation to various contexts—language learning, online tools, emergency teaching. Future studies will likely expand on digital integration, social media, and informal learning, underscoring the field's dynamic evolution.

Theme Centrality and Evaluation

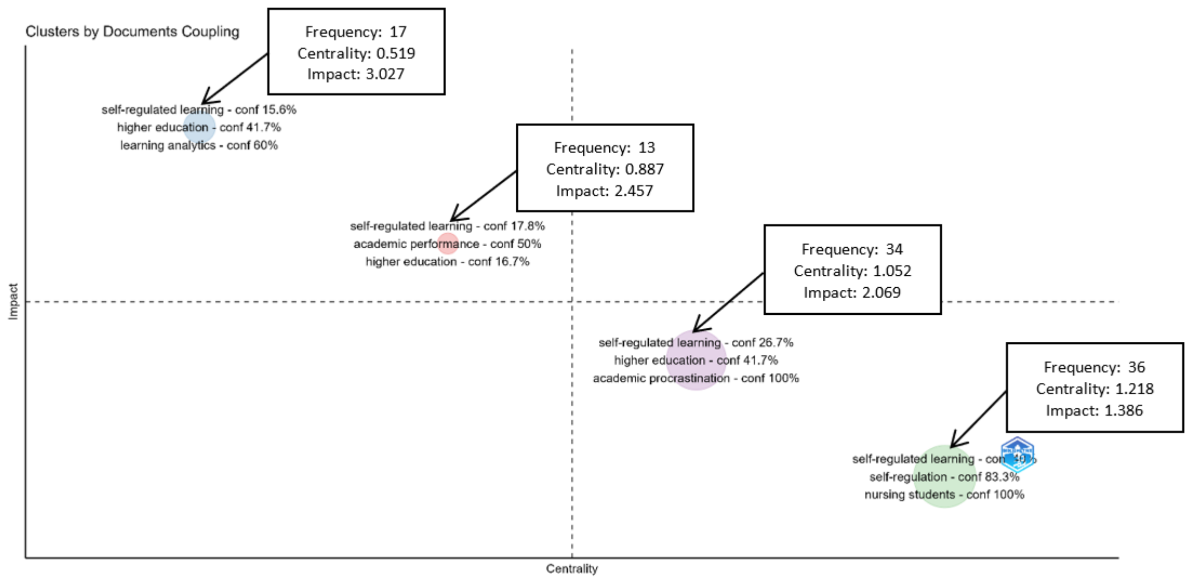
The theme centrality and evolution (Figures 5 & 6) offer key insights into the development of cognitive regulation in science education over time. Figure 5 (document coupling) reveals cluster centrality and impact, while Figure 6 (Sankey) shows how themes evolve (2004–2024), highlighting shifts in focus and breadth.

In Figure 5, centrality (connectivity) and impact (citation strength) determine each cluster's role in the broader landscape. Clusters span niche, high-impact topics to broadly integrated yet less influential areas, reflecting diverse self-regulation focuses in education.

The top-left cluster features SRL, higher education, and learning analytics. Though centrality is low (0.519), impact is high (3.027), indicating influential yet niche work. Focus on learning analytics reveals a cutting-edge, data-driven approach to monitoring and enhancing SRL, especially in online or hybrid environments where behavior tracking fosters self-regulation.

Figure 5

The centrality and impact of key publications



In contrast, the top-right cluster focuses on SRL and academic procrastination, showing high centrality (1.052) and impact (2.069). Procrastination in higher education (100% overlap) signals a major concern, as it undermines self-regulation. High connectivity and strong influence highlight the need to tackle procrastination to boost academic performance and SRL.

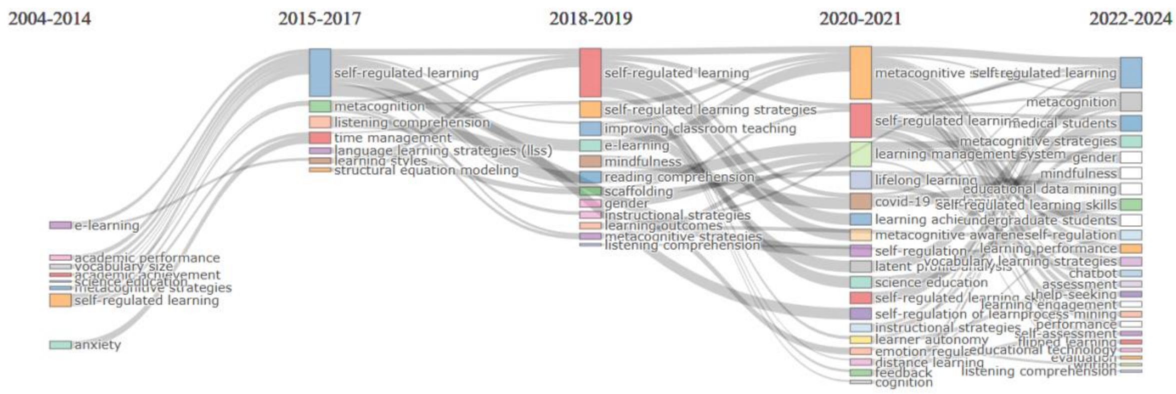
The bottom-right cluster addresses SRL in nursing education, boasting the highest centrality (1.218). Although its impact (1.386) is modest, the high connectivity bridges multiple subfields, pointing to self-regulation in professional contexts. Nursing demands autonomy and self-regulatory competencies, drawing increased focus to professional education settings (Hecke et al., 2024; Assolari et al., 2024), compared to non-STEM disciplines, which may emphasize interpersonal dynamics more prominently (Coluccio et al., 2024; Fei et al., 2024).

The middle cluster, with moderate centrality (0.887) yet high impact (2.457), merges SRL, academic performance, and higher education. This balance of connectivity and influence underscores the importance of understanding how SRL drives academic success. A 50% overlap with higher education reaffirms the practical link between self-regulation and learner performance, guiding interventions to enhance outcomes.

Figure 6 provides a longitudinal perspective (2004–2014, etc.), showing early focus on e-learning, academic performance, and SRL. This established how self-regulation functions in digital environments. Topics such as vocabulary size and anxiety also reveal interest in language acquisition and emotional aspects, reflecting motivation challenges in e-learning.

Figure 6

Theme evolutions in cognitive regulation in science education



From 2015 to 2017, themes such as metacognition, time management, and learning styles gained prominence, signaling a deeper interest in how learners manage cognition for better outcomes. Ongoing emphasis on SRL, combined with listening comprehension and structural equation modeling, demonstrates more granular examinations of how they monitor, evaluate, and adapt learning strategies. During 2018–2019, research broadened again, integrating instructional strategies and emotional factors, such as mindfulness, gender, and scaffolding. This shift underscores the growing importance of social and emotional aspects in self-regulation, with mindfulness emerging as a notable avenue for supporting cognitive regulation in high-autonomy, self-directed settings.

In 2020–2021, a significant expansion occurred, influenced by COVID-19. Themes such as lifelong learning, data mining, and pandemic-related education point to how self-regulation helps learners tackle remote and emergency teaching. The rise of data mining and learning analytics reflects the growing reliance on technology to study and support SRL in online contexts, while lifelong learning emphasises the broader, continuing value of SRL. By 2022–2024, attention turned to metacognitive strategies in specialised fields such as medical education, with renewed interest in gender issues and data mining/feedback. This reveals the continued fusion of social and technological aspects of SRL. The spotlight on medical learners emphasises self-regulation in professional training, demanding high autonomy and cognitive regulation.

Overall, foundational SRL remains central, but the field has broadened to embrace emotional, social and technological factors. The ongoing interest in academic performance, metacognition, and instructional strategies points to a commitment to refining interventions. Meanwhile, data-driven methods and professional education settings highlight an evolving emphasis on meeting 21st-century learner demands in increasingly digital contexts.

Discussion

The findings of this bibliometric analysis reveal that SRL, motivation and self-efficacy form the most frequently studied cluster, with a marked emphasis on academic performance across STEM contexts. Notably, we identified five main research themes—SRL, metacognition, emotional regulation, blended/online learning, and feedback/assessment—which align with existing literature but also underscore where science education research diverges from other fields. This comparative lens highlights the unique focus in science education on practical, inquiry-based activities that demand self-regulatory competencies, whereas other fields may concentrate more on skills development and linguistic proficiency.

Our co-occurrence analysis further revealed that Self-Regulated Learning (SRL) remained central across diverse fields, mirroring findings in language and online education (Broadbent, 2017; Pitenoee et al., 2017). However, the emphasis on motivation and performance in science suggests that interventions such as blended learning and scaffolding are pivotal for supporting inquiry-based tasks. This focus diverges from language education's primary attention on metacognitive awareness for proficiency gains. Hence, a practical outcome of our analysis is that science educators may adapt successful SRL interventions used in language learning—particularly those that strengthen goal-setting and monitoring—to bolster student mastery of complex STEM concepts.

Our findings also underscore a difference in how technology is leveraged: while online education research often places digital platforms (e.g., learning analytics) at the forefront (Khlaisang & Yoshida, 2022), science education tends to view technology as a complementary tool rather than the primary driver of SRL. Specifically, our citation network analysis shows that technology in science education predominantly aims to improve academic achievement via blended instruction and data-driven feedback, reflecting an outcome-oriented approach. This aligns with prior studies highlighting that, in STEM settings, technology is frequently integrated to enhance hands-on or inquiry-based learning rather than to replace it.

From a theoretical standpoint, the prevalence of SRL, motivation, and self-efficacy in STEM research (Uçar, 2018) confirms the strong link between self-regulatory processes and achievement. As indicated by our analysis of the most-cited publications, real-time data from learning analytics (Muthupoltotage & Gardner, 2018) is gradually becoming integral to science curricula, allowing instructors and learners to identify misconceptions and adjust study habits promptly. This finding aligns with broader SRL frameworks, suggesting that the timely availability of performance data is particularly beneficial in abstract STEM domains that demand iterative practice and problem-solving.

Although emotional regulation emerged as an emerging cluster in our keyword co-occurrence map, it received fewer citations and appeared in fewer documents compared to SRL and motivation. This gap is critical, as emotional regulation strongly influences learning persistence and stress management (Menggo et al., 2022). Our results suggest that science education researchers could benefit from integrating emotional regulation strategies (e.g., mindfulness, reflective journaling) into SRL-focused interventions, thereby fostering a more holistic approach that addresses both cognitive and affective dimensions of learning.

Moreover, our findings reveal that large-scale online platforms (e.g., MOOCs) and social media remain under-represented within cognitive regulation research. Consistent with Rini et al. (2022), this highlights a critical need to investigate how structured feedback mechanisms, peer interactions, and digital badges or gamification might bolster SRL within MOOCs. Similarly, examining social media platforms as informal learning spaces could provide insights into how everyday digital practices influence learners' self-regulation, motivation, and collaboration—an area ripe for exploration given the ubiquitous nature of social networking among learners.

Our thematic evolution analysis shows a clear uptick in pandemic-related studies post-2020, demonstrating an urgent demand for research on how learners adapted their SRL strategies amid emergency remote teaching (Ma'rufa & Mustofa, 2021). While immediate solutions often involved makeshift digital tools, few studies have examined long-term adaptability and institutional support structures needed to sustain effective SRL in ongoing hybrid or remote environments. Future investigations should thus consider longitudinal designs to capture how learners evolve and refine their SRL capacities over successive semesters of disrupted learning.

In summary, although our bibliometric analysis reveals robust emphasis on SRL, motivation, and self-efficacy, it also pinpoints critical gaps in emotional regulation, digital platform usage (e.g., MOOCs, social media), and crisis-driven adaptations (e.g., pandemic response). Bridging these gaps will likely require interdisciplinary efforts, integrating psychological frameworks of emotion with educational technology innovations. Such comprehensive approaches could enhance the efficacy of self-regulatory strategies, especially in complex STEM contexts where learning demands are both cognitively and emotionally challenging.

Conclusion and Implications

Our bibliometric findings reveal that SRL, motivation and self-efficacy collectively define the cornerstone of cognitive regulation research in STEM (2004–2024). While emotional regulation, mindfulness, and digital learning show promising growth, they remain comparatively underexplored. By analysing co-occurrence clusters and thematic evolution, we conclude that science education has responded to modern challenges—particularly COVID-19—by increasingly integrating technology and acknowledging learners' emotional needs, although more empirical work is needed to operationalize these insights effectively.

Our evidence supports a trajectory where technology (learning analytics, blended learning, and formative assessment) increasingly underpins SRL-driven instruction. Nevertheless, the relative scarcity of emotional regulation research suggests a need for interventions that address stress, anxiety, and resilience—factors critical to sustaining deep engagement in STEM fields. Hence, we recommend that educators and researchers develop and evaluate emotional-regulation-inclusive strategies to complement the strong focus on cognitive skill-building.

Future research should systematically integrate emotional regulation constructs—such as mindfulness or resilience training—into SRL frameworks for STEM education, particularly in high-stress domains such as the biomedical or nursing fields. Additionally, exploring innovative feedback models (e.g., peer review, automated analytics) in MOOCs or social media-based learning communities can clarify how learners develop and sustain SRL beyond the traditional classroom. Interdisciplinary collaborations (e.g., involving psychologists, technologists, domain specialists) are essential to build robust, evidence-based interventions that produce resilient, self-directed learners in complex STEM environments.

Limitations

First, although our dataset provides a broad overview, the focus on Scopus-indexed articles may omit relevant studies from other databases or in non-English languages. Second, emotional factors (e.g., stress, anxiety) and digital SRL remain less developed, limiting the generalizability of current findings to large-scale or informal online contexts. Finally, the reliance on cross-sectional bibliometric methods restricts our ability to determine the long-term effectiveness of SRL interventions in dynamic educational settings.

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Declaration of Interest

All authors declared no conflict of interest.

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Impact of active learner involvement in a contextual and relevant environmental education programme on learning effectiveness

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ABSTRACT

This research aimed, among other things, to reveal the methods used and the pedagogical approaches preferred by teachers to address courses related to the environment and environmental education. We targeted teachers from three subjects: Life and Earth Sciences (LES), History-Geography (HG), and Islamic Education (IE). One of the research objectives is to characterise the impact of adopting active approaches combined with the contextualisation of environmental education on the acquisition of environmental knowledge and on the development of the willingness to adopt pro-environmental behaviours. To achieve this objective, we conducted a pedagogical intervention within the school's environmental club (Club created by the teachers). The data collection tool consisted of two questionnaires; the first was addressed to a sample of 362 teachers, and the second was intended for a sample of 60 learners (30 learners representing the experimental group, and 30 learners forming the control group). We adopted a descriptive correlational design for the part concerning teachers and a quasi-experimental design for the section reserved for learners. The results allowed us to confirm that the active engagement of learners in contextual, relevant and motivating environmental education programs leads to a significant improvement in the acquisition of environmental knowledge, as well as the development of willingness to act in favour of the environment and adopt pro-environmental behaviours.

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Introduction

Environmental education (EE) is an integral aspect of the development of individuals and social groups, which relates to their relationship to the environment (El Batri, 2020). It aims to develop useful knowledge, practical skills and behaviours imbued with environmental ethics. This allows acting individually and collectively in favour of the environment (Baysura & Alcı, 2024). EE is a field of reflection and interdisciplinary action par excellence. It allows the integration of various types of interdisciplinary cognitive resources (Affolter & Varga, 2018; Tan & So, 2019).

A pedagogical approach is a way of understanding the different elements involved - the learner, the content, the teacher, and the relationships between them, such as through the organisation of communication, the teaching/learning environment, etc.) through strategies, predetermined methods, and techniques to form a coherent system" (El Batri, 2020b). Within a particular framework of EE, we can distinguish two typologies of approaches: one relating to the learning object and the other relates to the learning process (EL Batri et al., 2022).

Concerning the approaches relating to the learning object, EL Batri et al., 2022 and Fraser et al., 2015 distinguished the following approaches: cognitive, affective, spiritual (religious) , moral, behaviourist, pragmatic and praxis. For the approaches relating to the learning process, these same authors specified the following approaches: experiential, systemic, holistic, interdisciplinary, cooperative, critical and problem-based approach (problem-solving pedagogy). It should be noted that these approaches are not mutually exclusive. In fact, they are complementary. The behaviourist approach, for instance, aims to instil specific behaviours that promote environmental protection through positive or negative reinforcement. The problem-solving approach engages learners in identifying and analysing real environmental issues, encouraging them to develop well-informed and appropriate solutions. Both approaches can be combined to maximise their impact on environmental education.

In the literature, we find a plurality of definitions of the term 'pedagogical method', but almost all converge towards the same meaning, being It's the process that leads to the goal set. In other words, it is the set of activities and procedures organised by the teacher that guides the learner to achieve well-defined objectives. Generally, teaching methods are classified into two large groups: traditional transmissive methods and active methods (El Batri et al., 2019a; Freeman et al., 2014).

The so-called traditional methods are essentially centred on the transmission of knowledge and the authority of the teacher. The latter mainly uses a vertical dialogue in the form of question/ answer, or presents and explains the lesson with an almost total passivity of the learner. Evaluation is essentially based on memorisation and repetition of the same content. For example, the dogmatic method and the interrogative method (El Batri et al., 2019a).

Active learning is generally defined as any teaching method that engages learners in the learning process (El Batri, 2020b; Ülger and Çepni, 2020). This type of learning requires learners to engage with meaningful learning activities and think about what they are doing. The key element of this type of learning is the active involvement of the learner. Active learning is among the best pedagogical practices that enhance learners' performance, according to several researchers (Bram, 2016; Freeman et al., 2014; Wallace et al., 2021).

Among the active learning methods widely studied and recognised as having a positive effect on student outcomes, we can cite working in small groups (Johnson, D. W., & Johnson, R. T., 2018; Gillies et al., 2023; UNESCO, 2017 and others), based on problem solving (Jonassen & Hung, 2015; Loyens et al., 2015). Problem-based learning is often associated with another active method, which is discovery learning (Abrahamson & Kapur, 2018; Hanafi, 2016). Discovery learning can be defined as an educational method that encourages pupils to learn through their own exploration, experience and research. Learning generally involves identifying a problem, developing, and testing hypotheses, to draw a conclusion (Collins & O'Brien, 2011, p. 160). In this process, the teacher is a facilitator rather than an instructor. Its role is to organise a rich appropriately resourced learning environment and to encourage the learner's self-directed curiosity and problem-solving skills 'guided discovery', rather than demonstrating or providing "correct" answers (Wallace, 2015).

Other active learning methods can be found in the literature, including the dialogue method (Karakaş, 2022: Muhonen et al., 2016). It was introduced by Paulo Freire, in which teachers engage learners in discussions to understand their perceptions and experiences (Collins & O'Brien, 2011). Dialogue teaching harnesses the power of speech to stimulate and develop learner thinking, learning, and understanding (Muhonen et al., 2016). The demonstrative method (Bouchut, 2022; Ekeyi, 2013) refers to the type of teaching method in which the teacher is the main actor while the learners observe with the intention of acting later. Here, the teacher does everything the learners are supposed to do at the end of the lesson (demonstration) by showing them how to do it and explaining the process step by step (Quoted by Ekeyi, 2013).

The area of EE is largely influenced by active learning methods. This is why we find more or less the same methods recommended in EE (El Batri et al., 2019a; Genc, 2015; Özalemdar, 2021). This is to improve knowledge, values, attitudes and behaviour towards the environment. Genc (2015) stressed that active learning methods must be implemented to achieve effective EE. Other researchers (Boeve-de Pauw & Van Petegem, 2018; El Batri et al., 2019a) have reported that teaching methods that encourage more active learner engagement improve environmental attitudes and conceptual understanding. In addition to the methods already mentioned, studies in EE stress the importance of visits and field trips on the cognitive, emotional, physical and ethical level (El Batri et al., 2019a, 2019b, 2020a; Lee et al., 2020; Saribas et al., 2017; Sothmann & Menzel, 2017). Pro-environmental behaviour refers to actions and practices that contribute to the protection and preservation of the environment. These behaviours can range from individual actions, such as recycling and conserving energy, to collective efforts, such as participating in environmental advocacy or community clean-up projects.

In addition to the impact of active learner engagement, it is very important to contextualise environmental knowledge and activities. Contextualisation in education is a pedagogical action that involves linking science to society and to the learner's local environment (Kitheka, 2024; Latip & Kadarohman, 2024; Parker & Roumell, 2020; Zimmerman & Weible, 2017). It is an operationalisation and concretisation of broad and ambiguous scientific concepts. It is another aspect of didactic transposition that aims to make scientific knowledge more meaningful for the learner. Some authors have expressed this contextualisation by referring to "the local approach" (Villemagne, 2005, p. 338). According to El Batri (2020b), this approach is based on anchoring educational activities in the learners' living environment and the socio-ecological issues that characterise it. Several authors have emphasised the positive impact of addressing local and tangible environmental issues on improving learning outcomes and the learner's pro-environmental behaviour (Chanse et al., 2017; Higde et al., 2017; Saribas, Kucuk & Ertepinar, 2017; Sauvé, 2014; Tugurian & Carrier, 2017 and others). These studies, along with many others on environmental education and learning psychology, support the idea that contextualising environmental education, combined with active learner engagement, generally leads to a significant improvement in the acquisition of environmental knowledge and the development of a willingness to adopt pro-environmental behaviours.

In addition, to instil original, relevant and effective environmental education, we have utilised certain Islamic principles. It is well known in many communities that religious influence runs deep in people's lives and sometimes determines the type of relationship an individual can have with oneself, with others, and with the environment. Some environmental education specialists (Athayde, 2017; Avis, 2021; Kim et al., 2017; Parker, 2017) advocate for the consideration of religion and indigenous cultures in environmental education programmes. Among the Islamic principles that can be utilised within the framework of environmental education, we can mention the following:

• Principle of shared vital resources

Islam considers essential environmental resources for life, such as water, to be shared among all people, and no one is allowed to exclusively appropriate such resources and deprive others of them (Surah Al-Qamar (the Moon), verse 28).

• Man as a responsible steward of the environment, not an absolute owner

In the Islamic perspective, man is not the absolute owner of his environment, and he is not allowed to do whatever he wants, even with what he possesses. Indeed, he is considered a steward (caliph), meaning a responsible manager who should properly manage and utilize his possessions, without causing harm or wastefulness (Surah Al-A'raf, verse 56; Surah Al-Baqarah (the Cow), verse 205).

• Principle of moderation and prohibition of waste

Islam highly praises those who adopt the principle of moderation in the consumption of resources. Several verses and Hadiths recommend that consumption should be reasonable (the middle path), avoiding any waste and excess. This values God's gifts on one hand and prevents falling into deficiencies and shortages on the other hand, ensuring sustainable consumption.

• Principle of environmental preservation and prohibition of pollution

Islam highly values the preservation of the environment and prohibits any irresponsible harm to the lives of beings, whether human, animal, or plant.

• The call to clear and cultivate the land for the benefit of humanity and living beings.

Many Quranic verses and Hadiths of the Prophet (PBUH) encourage Muslims to clear and cultivate the land for their own benefit and for the benefit of all living beings.

Research Questions

This study aims to answer three research questions:

1) What are the methods and the pedagogical approaches used by teachers to tackle courses in environmental education?
2) Are there significant correlations between the adoption of behavioural and/or problem-solving approaches and the development of pro-environmental behaviours?
3) Does the contextualisation of environmental education combined with active learner engagement lead to a significant improvement in the acquisition of environmental knowledge and the development of the willingness to adopt pro-environmental behaviours?

The uniqueness of this study lies in considering the local context in its environmental and socio-cultural dimensions. In the literature, we did not find similar studies that address these two dimensions of contextualisation together. This action research was not limited to making the learner aware of the specificities of their local environment and identifying its main issues. Indeed, the activities of the environmental club promoted active learner engagement and participation in solving certain local environmental problems.

Methods

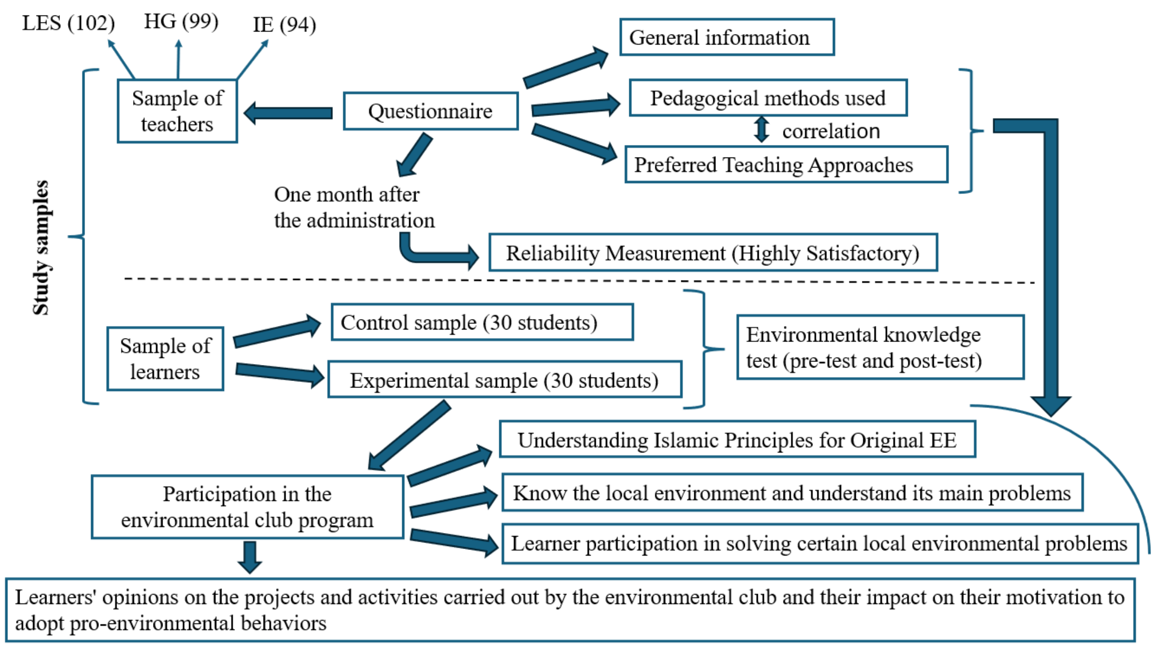
Research Design

For this research, we adopted a quasi-experimental design. This design is often used to measure the impact of implementing a programme or an educational intervention (Güvenir & Türkmen, 2024; Karpudewan & Mohd Ali Khan, 2017; Miller, Smith & Pugatch, 2020). In the field of education, when testing the effect of a pedagogical intervention, it is not possible to perfectly control all the other variables that may come into play. Additionally, there is a lack of random assignment. In this case, we rather speak of a 'quasi-experimental' design (Falk & Heckman, 2009).

Figure 1 presents a general summary diagram of the entire methodological process adopted in this research.

Figure 1

General diagram of the methodological process



Samples

Sample of teachers

We used stratified sampling to represent both urban and rural areas. This is because we have taken into account the significant educational differences between the two environments which have been revealed by previous studies (CSEFRS, 2018; El Batri et al., 2019a, 2019b, 2020a). The sample of teachers concerns middle school teachers of three subjects: Life and Earth Sciences (LES), History-Geography (HG) and Islamic Education (IE). Indeed, the syllabi of these three subjects contain units relating to the environment and environmental education (EE). The "LES" particularly with its units relating to ecology, and the "HG" convey the notions of environmental education through certain units relating to geography and citizenship education. And finally, the "IE" syllabus with the unit entitled "environmental education" taught in the 3 years of middle school. All teachers interviewed belong to the Regional Academy of Fez-Meknes. With the aim of obtaining valid results from a representative sample, we collected exhaustive samples from the Fez Directorate (urban) and the Moulay Yacoub Directorate (rural). Table 1 shows quantitative data on the sample of teachers selected.

Table 1

Sample of teachers

Environment	LES			HG			IE			Total
	N total teachers	Sample		N total teachers	Sample		N total teachers	Sample		$N_1+N_2+N_3$
		N_1	%		N_2	%		N_3	%	
Urban	112	102	91	160	99	62	145	94	65	295 (70%)
Rural	26	23	88	27	23	85	25	21	84	67 (86%)
Total	138	125	91	187	122	65	170	115	68	362 (73%)

Note that some teachers did not indicate their gender in the questionnaire. We mentioned them in the genre table as well (no answer). Tables 2 and 3 respectively represent gender / subject and gender / environment cross tables. LES is taught mostly by female teachers (Table 2). Table 3 shows that female teachers represent 61% in urban areas and only 45% in rural areas.

Table 2

Teacher gender /subject cross-tabulation*

		Subject			Total
		IE	HG	LES	
Gender of the Teacher	No answer	9	7	6	22
	Male teachers	50	61	34	145
	Female teachers	56	54	85	195
	Total	115	122	125	362

Table 3

*Environment * teacher gender cross-tabulation*

		Gender of the Teacher			Total
		No answer	Male teachers	Female teachers	
Environment	Urban	21	109	165	295
	Rural	1	36	30	67
Total		22	145	195	362

Sample of Learners

To participate in the environmental club projects, we randomly selected pupil members (15 boys and 15 girls) from many students who expressed their willingness to join the club. The selected pupils represent leaders in their classes (two per class, one boy and one girl) in terms of environmental awareness. They may not necessarily be the top-performing pupils in their classes. They participate in the management of the club with the teachers and coordinate between the club and their classes. However, the environmental club is open and everyone can participate in certain activities offered. To measure the impact of our intervention within the environmental club, we randomly selected another class of 30 as a control group. Table 4 summarises the data from both samples.

Table 4

Sample of Learners

	Boys	Girls	Total
Experimental Sample (Environmental Club Members)	15	15	30
Control Sample	17	13	30
Total	32	28	60

Data Collection Tool

The tool used to collect data from teachers was a three-part questionnaire. The first part was reserved for general information concerning the teachers taking part in the study - their age, gender, establishment, municipality and delegation. The second part of the questionnaire is an exploration of the different methods used by teachers of the three subjects (IE, HG and LES) to deal with the units relating to the environment in their programmes. We defined the different methods that could be used (12 items) and the teachers were invited to tick the appropriate box according to their degree of use of each method. We used the four-point scale. 0 points were awarded to "Not used", 1 to "Rarely", 2 to "Occasionally" and 3 points to "Often". The percentages of teachers have been counted for each subject separately. However, each teacher can claim to have used more than one method. Note that these same methods have been mentioned in other studies (El Batri et al., 2019a).

Table 5

Extract of the teaching methods proposed to teachers

1) The teacher explains the lesson and the students listen without participation (dogmatic).
2) Partial participation of students by answering some questions asked by the teacher (interrogative method).
3) Dialogue method with active participation of students at all stages of the lesson.
4) Group work method for performing works and assignments either inside or outside the classroom.
5) Realization of laboratory experiments.
6) Performing school outings to supplement and support environmental knowledge.

The third part of the questionnaire aimed at teachers explores the different pedagogical approaches preferred by teachers to tackle courses related to the environment and environmental education. We used approaches adapted to EE as proposed by Agusalim and Karim (2024); Bloom and Fuentes (2019); Miseliunaite et al. (2022); Rechberger, (2024); Walshe, (2017) and others. The five-point Likert scale identified the level of agreement or disagreement of teachers for each type of approach. We assigned 0 points to “Strongly disagree”, 1 to “Disagree”, 2 to “Indifferent”, 3 to “Somewhat agree” and 4 points to “Strongly agree”. It should be noted that the teacher can respond favourably or unfavourably to several types of approaches, especially since certain approaches are more or less correlated with each other.

Table 6

Extract from the proposed teaching approaches

1) The cognitive approach: it aims to transmit to learners a set of environmental knowledge.
2) The religious approach: centred on the development of attitudes and values consistent with a religion.
3) The behaviourist approach: aims to instil an appropriate behaviour with respect to the environment.
4) The experiential approach aims at direct contact with real situations, the realisation of experiences and interaction with the living environment to develop handling skills, on the one hand, and, on the other hand, to understand natural phenomena.
5) The holistic approach: takes into account all the dimensions of the subject and allows the development of a global vision of socio-environmental and educational realities.
6) The systemic approach: takes into account the networks of interrelations and interdependencies within the environment (ecosystems).
7) The interdisciplinary approach: integrates knowledge from different disciplines for better understanding and informed action.

Regarding the validity of the tool used, in addition to our professional experience as a teacher of LES, we explored the literature to look for the different teaching methods and approaches likely to be used in courses relating to the environment as well than EE. The methods that we have proposed to have been validated and already used in other studies (El Batri et al., 2019a). The pedagogical approaches appropriate to the EA that we have proposed to have been mentioned in several other studies (Bloom and Fuentes, 2019; Miseliunaite et al., 2022; Rechberger, 2024; Walshe, 2017). The responses collected giving a very small proportion to the items "other methods" and "other approaches" show that the main methods and pedagogical approaches are indeed those that we have proposed.

One month after the end of data collection, we carried out a post-test with 12 teachers who were chosen at random from the teachers already interviewed. The responses which were similar to those collected during the first data collection were of the order of 92% as an average percentage. This indicates that the reliability of the instrument is very satisfactory. The reliability index (Cronbach's alpha) applied to the questionnaire components gave 0.695 for the approaches and 0.714 for the teaching methods. This shows that the internal consistency of the instrument is satisfactory.

In addition to the questionnaire addressed to teachers regarding preferred approaches and methods, we formulated another questionnaire, this time for the pupil members of the environmental club. In this questionnaire, we sought the opinions of the pupils regarding the projects and activities carried out by the club and their impact on their relationship with the environment. In addition to the questionnaires, we conducted an environmental knowledge test for both the experimental and control groups. This test aimed to measure the impact of the implemented projects on the acquisition of environmental knowledge, especially at the local level. We administered a pre-test before the implementation of club activities and a post-test upon completion of the environmental club program.

Environmental Knowledge Test

The questions in the environmental knowledge test targeted some of the key environmental issues at both local and international levels, such as biodiversity, natural imbalances, water resources, and air pollution. It is worth noting that two questions have already been studied by the pupils as part of their Life and Earth Sciences curriculum. The other five questions are related to the projects and activities carried out by the environmental club. These activities primarily focus on the local environment.

Questionnaire for Environmental Club Member Pupils

This questionnaire aimed to evaluate the projects and activities carried out within the environmental club and their impact on pupils' relationship with the environment, particularly their willingness to adopt pro-environmental behaviours. Among the questions asked in this questionnaire, we note:

1) Do you feel that the activities carried out as part of the environmental club are important and relevant? Answers to this question were collected using a five-point Likert scale: 0 points for "strongly disagree", 1 point for "disagree", 2 points for "indifferent", 3 points for "somewhat agree" and 4 points for "strongly agree".
2) How would you describe your involvement in the activities of the environment club. We offered three choices as an answer to this question: “very well engaged”, “moderately engaged” and “weakly engaged”.
3) Do you intend to eventually participate in the activities of the environment club? We gave five choices as an answer to this question: 1 “Surely yes”, 2 “rather yes”, 3 “not sure”, 4 “no”, 5 “not at all”.
4) Have the activities of the environment club had a positive impact on your future relationship with the environment and particularly your adoption of pro-environmental behaviours? The answer either yes or no.
5) What are your suggestions for improving the programmes and activities of the environment club.

Data Collection

Data collection was face-to-face (through questionnaires) for both teachers and learners. As far as the environmental club is concerned, given that we carried out many practical activities, we cannot measure in detail all the repercussions of these activities on learners' attitudes and pro-environmental behaviour in the short and medium term. However, we have collected indicators on the impact of the environmental club's intervention on improving both learners' environmental knowledge and their relationship with their environment, as well as their predisposition and willingness to adopt pro-environmental behaviours. To ensure the most used methods, we only kept at the results level the proportions of the methods which were declared often used. Data entry and digital coding were carried out using IBM SPSS20 statistical software.

Pedagogical Intervention within the Framework of the Environmental Club

In light of the teaching methods and approaches most appreciated by teachers, as well as those recommended in the literature, particularly those emphasising active learner involvement through problem-solving, experiential, cooperative, and pragmatic approaches, and starting from contextual and meaningful environmental problems for the learners, we have adopted a programme that is simple in its overall structure, rich and diverse in its content, but effective in addressing the challenges of an original, context-based environmental education that interacts with the local environment and its specific issues. We have set three essential objectives for the activities of the environmental club:

Objectives of the Environment Club Programme

1) The understanding of Islamic principles for an original education relating to the environment.
2) In-depth knowledge of the local environment and understanding of its main problems.
3) The commitment of the learners and their participation in the resolution of certain local environmental problems.

Conduct of Activities Related to the 3 Objectives of the Environmental Club Program

The environmental club in our school consisted of 30 pupil members**,** with three volunteer teachers who supervised the club activities. We had a Lfe and Earth Sciences teacher, an Islamic education teacher, and a French language teacher. The club activities were intense and took place over a period of six weeks between February and March 2023, with 2 hours per week (Wednesday afternoons).

Regarding the first objective, the Islamic education teacher supervised three research projects carried out by three groups of learners on the "Islamic principles for an original education relating to the environment." The outcome of this project was presented in a plenary conference attended by all club members and students from the school. The principles presented and discussed in the conference are as follows:

- Principle of shared vital resources
- Man as a responsible caretaker of the environment and not its absolute owner
- Principle of moderation and prohibition of any waste
- Principle of environmental preservation and prohibition of pollution
- The call to clear and cultivate the land for the benefit of humans and living beings.

For the second objective, “The more or less in-depth knowledge of the local environment and the understanding of its main problems”, we planned several activities to deepen the learners' knowledge about their local environment. This knowledge pertains to both the natural environment (mountains, rivers, forests, local biodiversity, endemic species, etc.) and the human-created environment (the main monuments that constitute the heritage of the region). This was achieved through active methods involving learners in research related to their environment. As for the studied environmental issues, we focused on the main environmental problems that characterise the region, such as pollution of the "Oued Sebou" river, the erosion of local biodiversity through the extinction of certain fish species, urban waste, deforestation, and the overexploitation of certain resources. Within this framework, among the activities carried out, we can mention the following:

• We organised a photography contest regarding local environmental pollution.

• We highlighted the learner's local environment by preparing information sheets about each tree in the school. We asked club members to prepare sheets for each tree, including its name (scientific, French and Arabic), main characteristics, and habitat.

• The life and earth sciences teacher supervised research and a plenary conference on the fish species that have disappeared from the "Sebou" river, the causes of their extinction, and the efforts made to overcome the challenges of water pollution.

• A group of three volunteer club members prepared a presentation supervised by the life and earth sciences teacher on the evolution of forest cover in Morocco and the measures taken to halt forest degradation.

Regarding the third objective "Learner engagement and participation in solving certain local environmental problems". After knowing the essential of his/her local environment and its problems, the learner was put in a situation of action to participate in the resolution of some of the problems of his region. Among the activities carried out are:

• Tree planting: Areas behind certain classrooms in the school were filled with litter and waste. In collaboration with the parents' association, we cleaned up the trash, prepared the area, and planted olive and date palm trees.

• Waste collection in the "Ain Chkef" forest, along with several gardening and waste collection activities within our school. These activities were carried out through collaboration between the environmental club and the parents' association.

• Recycling activities: The French language teacher conducted recycling workshops with club members. They created beautiful artwork and useful items (decorations, pencil cases, baskets, etc.) from commonly discarded materials. We organised an exhibition of the products made.

Data Analysis

Data analysis was based mainly on descriptive statistics and enabled us to identify correlations between the variables studied. The descriptive statistics focus on the teaching methods used and the approaches favoured by the teachers of the three subjects studied. We also assessed learners' opinions on the activities carried out as part of the environmental club, and their impact on the evolution of their relationship with the environment. Exploring the different correlations between dependent and independent variables allowed us to detect highly significant correlations and weaker or non-significant ones. Indeed, we found correlations with gender, others between certain methods and between certain pedagogical approaches.

For the environmental knowledge test (learners), we carried out comparisons between the experimental sample and the control sample before and after the environmental club activities had been carried out (pre-test and post-test). Such comparisons provided us with reliable indicators of the effectiveness of the activities carried out by the environmental club.

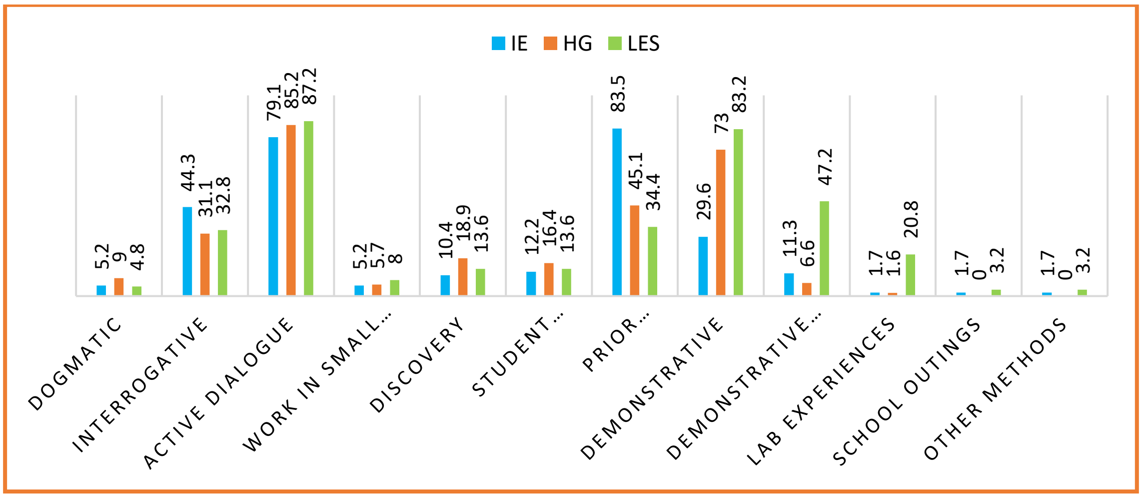
Results

Pedagogical Methods

Figure 2 shows that active dialogue is the most used teaching method in the three subjects. The demonstrative method is often used mainly for teachers of life and earth sciences (LES) and history-geography (HG) while the teachers of Islamic education (IE) made extensive use of pupils' advance preparations, in addition to the active dialogue and, to a lesser extent, the interrogative method. The demonstration by means of ICT is only used significantly at the level of LES courses. The other methods are very poorly represented in the three subjects, namely the dogmatic method, the work in small groups, the discovery method, and pupil presentations. School trips are almost non-existent.

Figure 2

Percentage of teachers in each subject who often use the mentioned teaching methods

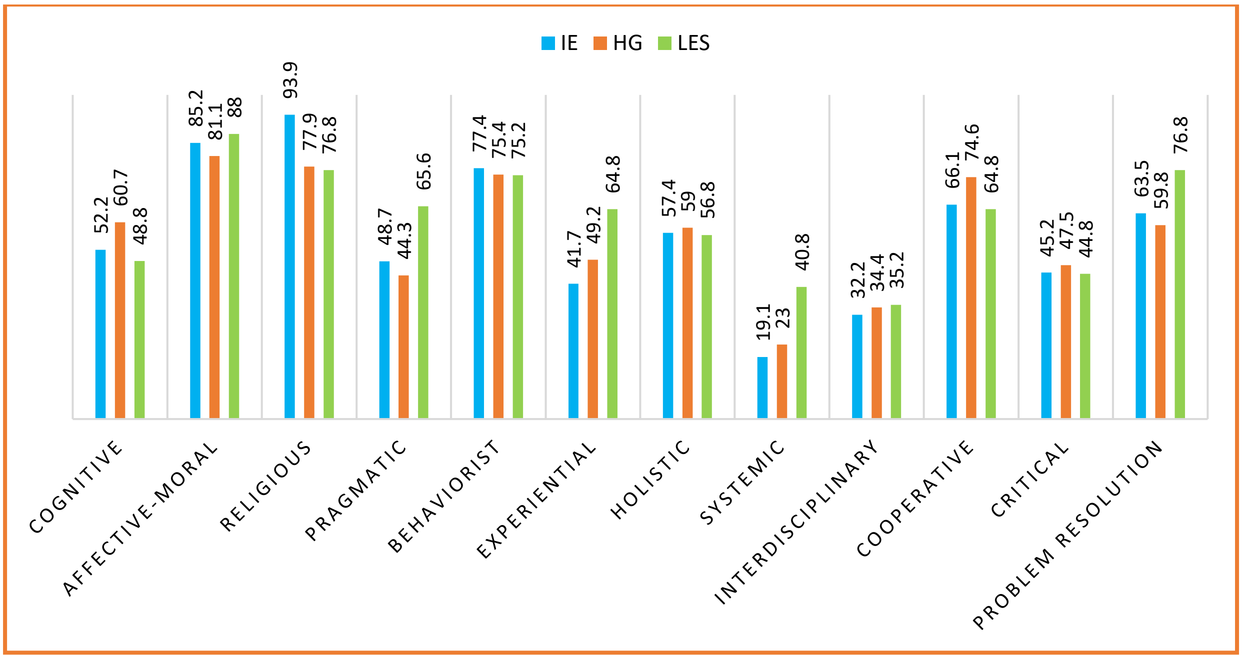


Pedagogical Approaches

Most teachers are in favour of adopting several approaches in environmental education (EE) (eclectic position). The preferred approaches are the affective-moral approach, the religious approach, the behaviourist approach, the cooperative approach, and problem-solving approach (Figure 3).

Figure 3

Percentage of "strongly agree" opinions for each type of pedagogical approach



Correlations with the Teacher's Gender

Regarding LES, we found a significant positive correlation between the gender of the teacher of LES and the use of ICT. In fact, female teachers use ICT more compared to their male colleagues (Table 7).

Table 7

Correlation gender/use of ICT in life and earth sciences

			Demonstration by ICT
Spearman's Rho	Teacher Gender	Correlation coefficient	.260**
		Sig. (2-tailed)	.003
		N	125

Note. **. Correlation is significant at the 0.01 level (2-tailed).

Table 8

Comparison of the number of LES teachers who often use ICT according to gender

	Gender			Total
	No answer	Male teachers	Female teachers	
Teachers who often use ICT	2	9 (26%)	48 (56%)	59
Total	6	34	85	125

Correlations between Approaches and Active Methods

Some approaches and active methods have shown very significant correlations between them. First, the problem-solving approach is closely linked to three other approaches which are the experiential approach, the cooperative approach, and the pragmatic approach (Table 9). On the other hand, the method of discovery is strongly correlated with the students' presentations (Table 10).

Table 9

Correlations with the Problem-solving Approach

			Experiential Approach	Cooperative Approach	Pragmatic Approach
Spearman's Rho	Problem Solving Approach	Correlation coefficient	.304**	.265**	.189**
		Sig. (2-tailed)	.000	.000	.000
		N	362	362	362

Note. **. Correlation is significant at the 0.01 level (2-tailed).

We also recorded a highly significant correlation between the behaviourist approach and the pragmatic approach (correlation coefficient = 0.318 with a significance level of 0.01). In addition to another significant correlation between the religious approach and the affective-moral approach (correlation coefficient = 0.150 with a significance level of 0.01).

Table 10

Correlation between discovery method and student presentations

			Discovery method
Spearman's Rho	Student Presentations	Correlation coefficient	.476**
		Sig. (2-tailed)	.000
		N	362

Note. **. Correlation is significant at the 0.01 level (2-tailed).

Environmental Knowledge Test

An environmental knowledge test was administered to both groups (experimental and control) before starting the club activities and another was administered immediately after the completion of all club activities. Table 11 presents the percentages of students in both groups who obtained their average (grade ≥ 10/20) in the pre-test and post-test.

Table 11

Learners who achieved their average score (10/20) in the environmental knowledge test before (pre-test) and after (post-test) participating in the environmental club activities

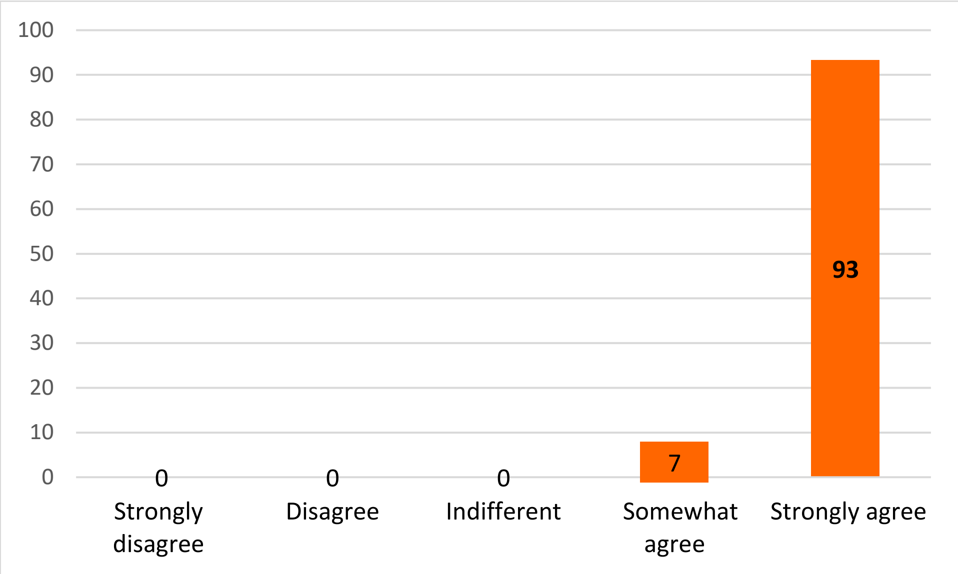
	N (Learners)	Learners who achieved their average in the environmental knowledge test			
		Pre-test		Post-test	
		N1	%	N2	%
Control Sample	30	2	7	6	20
Experimental Sample	30	3	10	29	97

In the pretest, which was conducted before the initiation of the environmental club activities, both types of samples (experimental and control) obtained low scores in the environmental knowledge test. We counted less than 10% of students who were able to obtain the average in this test. Prior to the intervention of the environmental club, we did not observe any significant difference between the control and experimental samples in terms of test results. However, after the completion of the club activities, the same test administered to the same samples yielded significantly different results compared to the initial administration (pretest). Indeed, the percentage of learners who succeeded in this test increased from 7% to 20% for the control sample and from 10% to over 96% for the experimental sample (Table 11).

Learners' Interaction with Environmental Club Activities

Figure 4

Learners' opinions on the importance and relevance of activities carried out within the environmental club

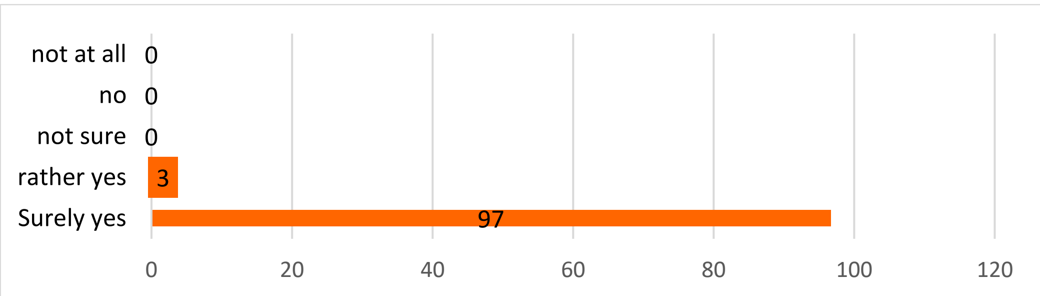


Regarding the first question of the questionnaire aimed at learner members of the environmental club regarding their opinions on the activities carried out, "Do you think the activities conducted within the environmental club are important and relevant?" Figure 4 shows that most surveyed learners (28, or 93%) strongly agree that the activities conducted are important and relevant.

All learner members of the club have stated that they have been highly engaged in club activities. In other words, none of them rated their own engagement as "average" or "low." Furthermore, most surveyed learners expressed their willingness to potentially participate in club activities. In fact, 96.66% responded to question 3 with "Surely yes," while only 3% responded with "Rather yes" (Figure 5).

Figure 5

Learner members of the environmental club who expressed their willingness to potentially participate in the activities of the club



For question 4 of the questionnaire, all learner members of the club (100%) admitted that the activities of the environmental club will have a positive impact on their potential relationship with the environment, particularly their adoption of pro-environmental behaviours.

For the last question regarding suggestions from club members to improve the programmes and activities of the environmental club, the first proposal stated by 18 members (60%) is the organisation of environmental excursions. They propose organising trips to natural sites, reserves, national parks, etc., to learn about the environment in a hands-on manner. In second place, we have two proposals: tree planting (15 members) and environmental awareness activities (50%). As for other suggestions, we have cleaning (10 members) either inside the school or in certain local environmental sites, and finally, some club member learners (6) have proposed organising waste recycling workshops (Figure 6).

Figure 6

Suggestions from club members to improve the programmes and activities of the environmental club

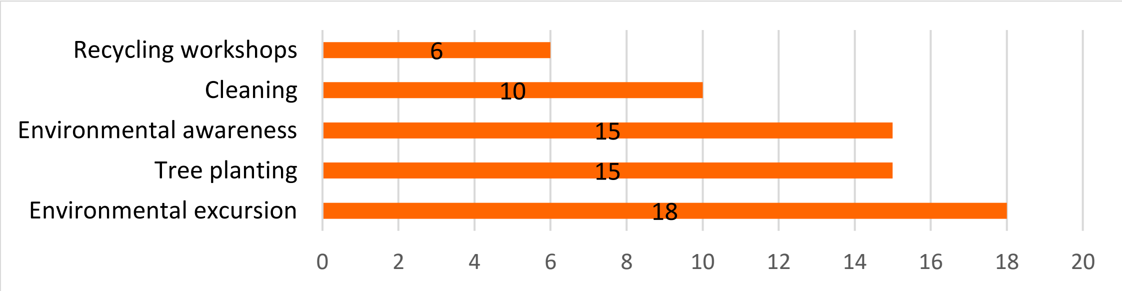


Figure 7

Selected photos from the photography contest regarding local environmental pollution

The learners conducted research supervised by the life and earth science teacher on fish species that have disappeared from the "Sebou" river and the causes of their extinction. They discovered a fish species (the Allis shad: Alosa alosa) that vanished from the river over 20 years ago due to industrial pollution.

Figure 8

The fish species that has disappeared from the "Sebou" river due to industrial pollution is the Allis shad (Alosa alosa)

Figure 9

Excerpts from the sheets prepared by learner members of the club about the trees in the school

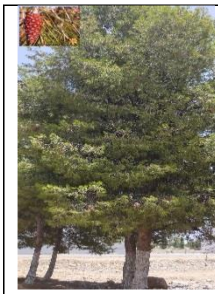
				
Pinus halepensis (Pin d'Alep) الصنوبر الحلبي	Ceratonia siliqua (Caroubier) شجرة الخروب	Olea europaea (Olivier) شجرة الزيتون	Citrus aurantium (Bigaradier) شجرة النارنج	Ficus carica (Figuier) شجرة التين

Figure 10

Gardening and cleaning activities carried out by club members within the school

		
10.1. Gardening activities carried out by student members of the environmental club under our supervision	10.2. Gardening activities carried out by student members of the environmental club under our supervision	10.3. Cleaning of the school's grounds carried out by student members of the environmental club
		
10.4. Beautification of the school's green spaces	10.5. Cleaning of the school's green spaces under our supervision	10.6. Cleaning of all surfaces of the school

Discussion

There are significant differences between the three subjects studied (LES, HG and IE) in terms of the methods often used. This is logical since each subject has its own particularities. We found that the teaching of the three subjects relies mainly on verbal methods centred on the teacher (dialogue, demonstrative method, and interrogative method). This with a remarkable insufficiency about the use of active methods centred on the active involvement of the learner in his own learning (work in small groups, discovery method, student presentations and scientific outings). Such methods are likely to develop learners' autonomy (Feyzioğlu & Demirci, 2021) and their practical skills related to manipulation. In addition to the development of certain social skills linked to interactions and cooperation between students during group work and school outings.

The predominance of the use of verbal methods and the notable lack of implemented active methods have been well confirmed by a recent study that surveyed primary school teachers in the same region (Fes-Meknes) (El Batri et al., 2022). It appears that teachers at the primary and secondary levels work with similar methods. Other research has also confirmed the absence of school outings in Moroccan public schools (El Batri et al., 2019a, 2019b, and 2020a). The methodological shortcomings recorded may be due, according to research that has evoked EE in the same region of Morocco, to a lack of the necessary teaching materials (El Batri et al., 2019b), a lack of motivation (Sayad et al., 2015), and the lack of any formal programme relative to training and continuing education, relating to EE, intended for the benefit of teachers (El Batri et al., 2019b).

The significant increase in the method of prior preparations at the level of the IE subject is not explained by activities (outside the classroom) that encourage research and reflection on the part of the learners. On the contrary, it is about the simple writing of certain contents of the lessons. Teachers of IE systematically ask pupils to write the Qur'anic verses and hadiths of the prophet that relate to each lesson by copying them from the IE textbook. This is to save time in the classroom and to focus on explaining and writing the rest of the lesson. Figure 2 also shows that science subjects (LES) have priority in the use of ICT. This is due because the LES laboratories are the best equipped with digital equipment (PC, data show, digital resources).

Basically, we can say that the pedagogical methods often used are mainly characterised by oral explanation and demonstration. With a very notable lack concerning the active methods arousing the commitment of the learner through personal explorations, experiences, and research activities (discovery method, presentations, work in small groups, outings). Note in this regard that the method of work by small groups has been requested by many researchers to improve the effectiveness of learning (El Batri et al., 2019a; UNESCO, 2017; Polat et al., 2022; Wilson & Varma-Nelson, 2016 and others). School trips, which were absent in the sample studied, proved to be extremely important in EE (El Batri et al., 2019a, 2019b, 2020a; Hoover, 2021; Saribas et al., 2017; Sothmann and Menzel, 2017). The importance of school outings has been confirmed by these researchers concerning several integral dimensions of a person's development (cognitive, socio-emotional, physical and moral). Some authors (El Batri et al., 2019a) have shown that frequent use of several active methods (eclecticism) is an indicator of more effective learning. Along the same lines, de-Oliveira et al (2022) pointed out that teachers need to diversify methodologies in theoretical and practical lessons to foster learning. This, according to the authors, can be achieved by diversifying the teaching process in different ways. Among which, there is the development of practical activities that promote interaction. In this sense, Jeronen et al. (2016) also indicate the group work method and thus appreciated the teaching methods involving the active participation of learners and interactivity.

Regarding the preferred approaches in EE, most teachers are in favour of adopting several approaches (religious, affective-moral, behaviourist, cooperative, problem-solving, etc.). We can say that teachers appreciate an eclectic position regarding the use of pedagogical approaches. We have found this same position in several research studies that have addressed environmental education and sustainable development. In this context, Kopnina (2018) emphasised that the diversity of issues, topics and problems related to sustainability require an eclectic approach to environmental education.

In other research, (Ahmad, 2024; Clark et al., 2017; Pisters et al., 2019) concluded that there are several avenues of research and analysis to reconstruct education for and also in/through, with and about the environment. In addition, Kopina (2018) recognised that plural perspectives of education for sustainable development are promoted by both practitioners and researchers in environmental education.

However, the research that impressed us the most is the one that focused on a sample of Moroccan primary school teachers (El Batri et al., 2022). In this study, they found the same pedagogical approaches most appreciated by teachers as those found in our research (Affective-moral, religious, behaviourist, cooperative, and problem-solving approaches). This means that environmental education should be built, according to the conception of the surveyed teachers, on five essential approaches. For this, it is preferable to start with contextual and relevant environmental issues (problem-solving approach). The contextualisation of environmental education stipulates, among other things, the consideration of indigenous cultures and the religion of the target population. We know that religious grounding is deeply embedded in people's lives in many communities and sometimes determines the type of relationship a person can have with oneself, others, and their environment. Thus, experts in environmental education (Agusalim & Karim, 2024; Parker, 2017) have called for the consideration of religion and indigenous cultures in environmental education programmes.

The religious approach is closely linked to the affective-moral approach (both are correlated at a significance level of 0.01). The affective-moral approach in environmental education aims to evoke positive emotions towards the environment and to develop ethical and responsible values and attitudes regarding nature and environmental issues. According to Cao et al. (2022) and Torsney & Matewos (2022), the affective aspect and the sense of connection are essential for environmental protection and responsibility leading to informed action. Moreover, the behaviourist approach gains its legitimacy from the fact that promoting sustainable pro-environmental behaviours is among the essential goals of environmental education. Therefore, the behaviourist approach can be an effective tool in environmental education (Schneider & Sanguinetti, 2021; Amiri et al., 2024). However, it is essential to combine the behaviourist approach with other approaches that foster a deeper understanding of environmental issues. Finally, the cooperative approach is likely to address several challenges related to environmental education (Arslan, 2025; Colomer et al., 2021). Indeed, the cooperative approach promotes active engagement of learners, the implementation of practical activities, projects, awareness-raising actions, and more. Thus, this approach provides a dynamic and participatory learning framework that allows learners to develop essential skills to address current and future environmental challenges.

In LES, we detected a significant positive correlation between the gender of the teacher and the use of ICT. In fact, female teachers use ICT significantly more than their male colleagues. We have already mentioned that LESs, unlike other subjects, constitute a female subject (77% are women). However, by looking further into the specifics of the samples studied, we found that the vast majority of older teachers (age over 49) are men. Indeed, female teachers with ages below 49 years represent 64% of all female teachers. Whereas men with ages below 49 represent only 26% of all male teachers. That is, the majority of female teachers are younger, and the majority of male teachers (68) are older. We can then link the massive use of ICT by women to the age factor rather than the gender factor.

We have found very significant correlations between certain active approaches and methods. The problem-solving approach is correlated with three other approaches: the experiential, cooperative and pragmatic approach. By synthesizing the definitions given by the researchers who have discussed these approaches (Arslan, 2025; Bloom & Fuentes, 2019; Saleem & Dare, 2023), we found very close rational links between these approaches. The experiential approach aims at direct contact with real situations, the realisation of experiences and interaction with the living environment to develop handling skills, on the one hand, and, on the other hand, to understand natural phenomena. In other words, the experiential approach makes it possible to develop the skills necessary to be able to solve environmental problems. The cooperative approach also aims, among other things, to effectively solve environmental problems, and the pragmatic approach aims by definition at developing problem-solving skills and eco-management. Therefore, we can say that this is a family of closely related approaches. Even if the researchers cited have evoked these approaches separately, we can say that the experiential, cooperative and pragmatic approaches are only details of the problem-solving approach. This one being the all-encompassing approach of the other three. Consequently, the logical links between these approaches explain and confirm their statistical correlations. Therefore, it is desirable to jointly adopt these approaches. We can say the same thing about the very significant correlation between the discovery method and the students' presentations (Table 10). In fact, the method of discovery underpins the carrying out of research, exploration and investigation by pupils (El Batri et al. 2019a, p. 371). This may involve presentations which can constitute a detail of the method of discovery and can be more general and encompassing. This explains the very significant correlation between the two methods.

The activities carried out within the framework of the environmental club address certain deficiencies observed in the methods used by teachers in the three subjects studied. In particular, there is a notable lack in the use of active methods based on student engagement and exploration. Furthermore, the preferred approaches by the teachers have been effectively implemented by the environmental club through various activities. These approaches include religious, behaviourist, cooperative, and problem-solving approaches. All of these are implemented with the aim of significantly improving the acquisition of environmental knowledge and fostering the willingness to adopt pro-environmental behaviours.

Table 11 demonstrates that the activities carried out by the environmental club have had a highly positive impact on improving the learners' environmental knowledge. This can be attributed to the fact that all the areas covered in the knowledge test were well addressed in the activities conducted by the environmental club. These knowledge areas mainly pertain to the local environment and the contextualization of environmental education. We also incorporated cultural contextualization by referring to the Islamic principles of environmental education. Therefore, this type of knowledge is meaningful and motivating for the learners. Additionally, we employed active methods that actively involved the learners in all the activities conducted by the environmental club. These activities included research work and presentations on the local environment and its specific issues, carrying out meaningful activities in support of the local environment, and participating in resolving certain problems (such as creating fact sheets about the school's trees, tree planting, cleaning, recycling activities, and awareness campaigns).

Furthermore, active learner engagement promotes better knowledge retention. This was clearly demonstrated in the results of the environmental knowledge test (Table 11). When learners are actively involved in hands-on activities, they are more likely to remember the information learned and apply it in real-world contexts. This fosters a true understanding and adoption of ecological concepts and values. We can say that the significant improvement in environmental learning is greatly facilitated when two essential ideas are put into practice: the utilisation of the local environment and its specific issues, along with the active engagement of learners in meaningful environmental education programs. The slight increase in the proportions of learners in the control group who were able to achieve the passing score in the post-test (compared to the pre-test results) (Table 11) can be explained as follows: during the 6-week period between the pre-test and the post-test, some learners were able to gather information on certain questions posed in the test. This may have been accomplished either through the plenary sessions presented by club members or through their independent explorations outside of club activities.

We believe that the experiences undergone by the learners during the activities conducted within the framework of the environmental club will have significant consequences on their knowledge, attitudes, and potential relationship with the environment. They thoroughly enjoyed the activities carried out. Over 93% of the club members perceive the activities as important and relevant. Consequently, they were all highly engaged in the implemented activities. The strong appreciation shown by the learners towards the club's activities is also evident in the expressed willingness of almost all members to participate in future club activities. This can be considered a success of the club program, as active learner engagement is crucial for the success of any environmental education program. Another indicator of the program's success is that all club members believe that the activities conducted will have a positive impact on their potential relationship with the environment, particularly in adopting pro-environmental behaviours.

Many authors stress the role of personal involvement and the importance of prioritizing local environmental topics. In this regard, Saribas et al. (2017) stated that "Environmental education courses should include presentations, reflections, and discussions on authentic, local, and specific environmental issues." Higde et al. (2017) also highlighted that a closer look into local, tangible and actionable aspects of climate change education result in individual favourable behaviours that support the march towards climate change mitigation. According to Jones and Davison (2021), childhood learning experiences about climate change can have lasting effects. Similarly, Tugurian and Carrier (2017) specified that children possess an environmental identity. This identity can be leveraged, according to the same authors, to enhance the learner's environmental behaviour and strengthen their interest in natural sciences.

To address current environmental issues, it is necessary to reconnect individuals with nature. Nature attachment is a crucial predictive factor for pro-environmental behaviour (Braun and Dierkes, 2017). By focusing on specific problems present in their immediate environment, students can develop a deep understanding of the interconnectedness between their actions and the environment. A key advantage of addressing local environmental issues is the relevance it brings to the educational experience. When learners can directly observe and interact with the environmental challenges in their own community, they develop a personal connection and a sense of responsibility towards seeking solutions (Hastuti et al., 2024; Heiskanen, Thidell & Rodhe, 2016). This hands-on approach fosters a sense of ownership and empowerment, motivating students to act and make a positive impact.

Studies demonstrate that active learner engagement in environmental learning promotes deeper understanding, increased motivation, and lasting behavioural change (Chen & Martin, 2015; El Batri et al., 2019b). Active engagement encourages learners to take an active role in their own learning. When involved in hands-on activities, research projects, field trips, and problem-solving initiatives, learners are more likely to develop natural curiosity, intrinsic motivation, and a sense of personal accomplishment. This approach helps develop essential skills such as critical thinking, problem-solving, collaboration, and informed decision-making.

Research also shows that exposure to nature and active learner engagement in environmental education can have positive effects on their mental and emotional well-being (Passmore & Holder, 2017; Schaubroeck & Rugani, 2017). When engaged in outdoor activities, conservation projects, and community actions, learners develop an emotional connection with nature, which can reduce stress, improve mental health, and foster a sense of connection with their environment.

The proposals put forward to enhance the programs and activities of the environmental club accurately reflect the appreciated activities, whether they have been effectively implemented or requested and desired by the learners. In fact, except for field trips, all the other proposals (Figure 6) have been effectively implemented within the framework of the environmental club program. The inclusion of environmental excursions remains a potential addition. Indeed, several researchers have found that excursions have multiple positive impacts on learners, particularly in cognitive and affective aspects, as well as a significant improvement in motivation and willingness to act in favour of the environment (Behrendt & Franklin, 2014; El Batri et al., 2019a).

Conclusions

This research aimed mainly to achieve three objectives; the first is to reveal the methods used and the pedagogical approaches appreciated by teachers to approach courses related to the environment and environmental education. The second objective was the identification and explanation of certain significant correlations between the pedagogical approaches adopted. As for the third objective, it was to study, using action research, the impact of the active engagement of learners in a contextualized environmental education program both on the improvement of the acquisition of environmental knowledge and on the willingness to adopt pro-environmental behaviour.

For the first objective, the pedagogical methods often used by the teachers under study are largely dominated by verbal methods centred on the teacher's activity (dialogue, demonstrative method, and interrogative method). Teachers appreciate the adoption of several pedagogical approaches to address environmental issues (the religious, behaviourist, cooperative, and problem-solving approaches). Some of these approaches are closely logically linked and strongly correlated statistically with each other. These include the experiential, cooperative and pragmatic approaches, which, along with the problem-solving approach, constitute a family of closely linked approaches.

The action research related to the third research objective was characterized by an active engagement of learners in a double-contextualized environmental education program. The first contextualization was cultural, integrating Islamic principles of environmental education into the activities carried out, and the second contextualisation involved conducting practical activities targeting the local environment and its specific issues. Overall, we can affirm that the active engagement of learners in contextualised and relevant environmental education programs promotes a significant improvement in the acquisition of environmental knowledge in addition to the development of the willingness to adopt pro-environmental behaviours.

Recommendations

This research is, of course, limited in time and space. The highly beneficial effects of contextualising environmental education at various cognitive and behavioural levels can be confirmed or refuted by further research conducted in other countries and cultures. We recommend that future researchers and practitioners from different regions of the world study the impact of this dual contextualization (cultural and environmental) on the quality of learning related to environmental education and on the resolution of local environmental problems in the short, medium, and even long term.

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Enhancing critical thinking in Indonesian high school physics with physbook-powered problem-based learning

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ABSTRACT

To align with Assessment and Teaching of 21st-Century Skills (ATC21S), especially in the area of Critical Thinking Skills (CTS), it is crucial to embrace educational innovations that depart from traditional approaches and to incorporate technological advancements into the educational process. This study seeks to (1) elucidate how the PBL model, with the support of PHysBook, is employed to enhance students' CTS, (2) delineate the enhancements in students' CTS resulting from the implementation of the PBL model with PHysBook assistance, and (3) characterize the student responses following the adoption of the PBL model supported by PHysBook to boost learners' CTS. This research follows a true experimental design with randomly assigned subject control groups and pre-test and post-test evaluations. The study encompassed 140 tenth-grade high school students, with a sample size of 104 students. The assessment of student activity in the control class has sufficient categories—the value of observation of student activities on CTS in the high category. There is a difference between O1 and O2 in class with the PBL model assisted by PHysBook in improving CTS with an increased rate in the high category with strong effect scores. The incorporation of PBL learning with PHysBook assistance to enhance CTS garnered positive feedback from students, making it a valuable innovation in the realm of education. In light of the study's limitations, it is recommended that future researchers explore similar investigations in different educational institutions or at various academic levels to compare the outcomes of CTS improvement.

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Introduction

In the pursuit of meeting the demands of The Assessment and Teaching of 21st-Century Skills (ATC21S), there is a realization of a modernized learning approach. This contemporary learning process necessitates the development of critical thinking (CT), creativity, effective communication, collaboration abilities, and innovative and scientific thinking (Astuti et al., 2019; Hastuti et al., 2019; Miras et al., 2023). In the twenty-first century, critical thinking skills (CTS) is crucial to allows students to be considerably more precise about what happens (Wafa & Jatmiko, 2022).

According to information from the Organization for Economic Co-operation and Development (OECD), the CTS of Indonesian schoolchildren remains quite low, science performance scores are nine from the bottom (71) from 79 countries (Lentika & Admoko, 2022). They were then, based on preliminary study data conducted in two Senior High Schools (SHS) in Surabaya, with a total of 190 students. A total of 171 learners fell into the category of low CTS, 19 learners fell into the category of medium CTS, and none fell into the high CTS. Thus, it can be seen that students' CTS level is still in the low category in physics subjects (Saphira & Prahani, 2022). Other findings, in research by Saphira & Prahani (2022), learning is still carried out with conventional learning models and learning media based on physical books and work on boards. As a result, poor CTS is now a critical issue that requires quick attention.

One subject that has many aspects related to the flow of CT is physics. Physics is based on experimental observations and quantitative measurements. The process of acquiring knowledge physics gives students the opportunity to hone their critical, creative, collaborative, and communication skills (the 4C's) (Estuhono et al., 2019; Khoiri et al., 2021a; Sarwi et al., 2019; Yuli et al., 2022). Physics learning strongly supports integrating technology to motivate students to provide interest, convenience, and exploration space for users. In order to get significant education, physics has to prioritize higher-order thinking skills (HOTs), mainly CT (Lestari & Winarto, 2022). For instance, Susetyarini et al. (2022) state that students' collaborative, critical thinking, creative thinking, and communication skills were in the good category. There was an increase in the first and second cycles through problem-based learning. The findings of this study are problem-solving-oriented learning can improve classical 4C skills.

Previous research by Wijayanto et al. (2021) shows that using PBL models is very good for physics learning. Educators have demonstrated for the past 50 years that PBL successfully enhances students' cognitive and social learning skills. Furthermore, Samadun & Dwikoranto (2022) concluded that applying the PBL model could improve students' CTS. Research by Prahani et al. (2022) shows that the utilization of Android-based educational tools for physics instruction is on the rise, and the ongoing digitization of physics learning is a gradual and continuous trend (Jatmiko et al., 2021). In line with research by Saphira (2022), mobile-based learning has increased publication trends over the past ten years. Thus, research on mobile-based learning is in demand by researchers, and there needs to be development and implementation in schools. Research by Bakri et al. (2021), Develop an Android-based Pocket Book application on physics learning. The resulting development shows that the product can be used effectively and efficiently. As well as research by Bani & Masruddin (2021) also developed research on Android-Pocket Book on harmonic oscillation material. The results show that android-pocket book learning media is effective for improving learners' cognitive learning outcomes (Rahmasari & Kuswanto, 2023), and learners tend to respond positively to android-based learning media. Based on the description above, in order to meet ATC21S, especially CTS, it is necessary to have learning innovations that are different from traditional learning and apply technological digitalization in the learning process (Negoro et al., 2024; Ristanto et al., 2022). Only now, previous research has been limited to the development and implementation of ability indicators or even no previous research at related high schools that implement e-pocket book-assisted PBL to improve CTS. Utilizing PHysBook to support the implementation of the PBL model offers the following benefits: 1) Can be accessed offline (without being connected to the internet); 2) The development can be adjusted to the material to be applied; 3) High compatibility and easy to operate;

4) No privacy data is stored; 5) In accordance with the problems and needs of students. However, to its initial development, PHysBook is still limited to Android operating systems and still in Indonesian Language. To further development its is will be upgrading to more variety operating systems and languages. Moreover, to its feasibility of PHysBook it is will be uploading to Google Playstore.

Research Questions

To meet the needs of schools and become the latest in this research, an e-pocket book-assisted learning innovation was prepared using the PBL model for high school students. Hence, this research raises the following inquiry:

(1) How to implement the PBL learning model assisted by PHysBook to improve students' CTS?

(2) How to improve students' CTS with the PBL learning model assisted by PHysBook?

(3) How do students respond after implementing PBL assisted by PHysBook to improve students' CTS?

Literature Review

The Rational Between Learning Theory, PBL Models, and CTS Indicators

One of the abilities that supports each of these 3 HOTs is CT. It follows that mastering CT is a prerequisite to learning the remaining 3 HOTs processes (Satriawan et al., 2020). CTS have been integrated into the Indonesian school curriculum since the introduction of the 2013 National Curriculum and continue to be part of the Curriculum Merdeka (Afdareza et al., 2020; Pahrudin et al., 2021; Tyas et al., 2019). CTS students will make an effort to use logical thinking to comprehend and make difficult decisions, as well as to see how various systems are interconnected (Saputri et al., 2019). Physics lessons provide pupils the opportunity to build the 4C’s (Aliftika & Utari, 2019; Khotijah et al., 2019).

The four indicators in CT and problem taking process are interpretation, analysis, evaluation, and inference (Facione, 2020; Seventika et al., 2018). Using present-day technology as an instructional tool in conjunction with real-world difficulties experienced in daily life is one method of enhancing CTS, according to established educational theories (Antón-Sancho et al., 2023; Damayanti & Kuswanto, 2021; Wibowo, 2023; Wijayanto et al., 2023). Based on research by Ardianti et al. (2022) states that the the PBL model is supported by several foundational learning and developmental theories. Piaget's Individual Constructivism Theory emphasizes that learners build knowledge through personal experiences, while Vygotsky's Constructivist Social Learning Theory highlights the importance of social interactions and cultural context. PBL aligns with Bruner's Discovery Learning Theory by encouraging exploration and inquiry, and with Ausubel's Theory of Meaningful Learning by integrating new knowledge with existing cognitive structures. John Dewey's Theory of experiential learning is reflected in PBL's emphasis on engaging students in real-world problems and active participation. The relationship between learning theory, PBL syntax, and indicators of CTS is as in Table 1.

Table 1

The relationship of learning theory, PBL syntax, and CT indicators

<table>
<tr><th colspan="2">Learning Theory</th><th>Syntax of PBL</th><th>CT Indicators</th></tr>
<tr><td rowspan="2">Piaget
Piaget saw that the process of constructing knowledge is carried out through assimilation and accommodation.</td><td rowspan="6">Dewey
Teachers should provide assignments with a problem-solving focus and assist students in researching social justice and intellectual significance.

Bruner
Encourage students to select, retain and change information effectively by encouraging students to have hands-on learning experiences and conduct their own experiments for them to discover principles for themselves.</td><td>Phase 1
Orient students to problems.</td><td>Interpretation
In this case, giving impressions, opinions, or views on something is a problem given to learners.</td></tr>
<tr><td>Phase 2
Organizing learners on problems.</td><td rowspan="3">Analyze
Linking the information obtained with concepts and solving strategies.</td></tr>
<tr><td rowspan="4">Vygotsky
Although students are still involved in active learning, educators must actively guide every student's activity.

Ausubel
Assimilate new knowledge into learners' preexisting cognitive systems.</td><td>Phase 3
Support instructors' individual or group research projects.</td></tr>
<tr><td>Phase 4
Learners create and showcase demonstrations and artifacts.</td></tr>
<tr><td rowspan="2">Phase 5
Examine and assess the process of solving problems.</td><td>Evaluation
Review or review each troubleshooting step or identified information.</td></tr>
<tr><td>Inference
Make conclusions by attaching supporting evidence and explaining reasoning with logic.</td></tr>
</table>

PHysBook (Pocket Physics E-Book)

In this study, a media was implemented that helped in the process of implementing PBL in the classroom. The media is in the form of an application-based computer program with the name PHysBook or stands for Pocket Physics E-Book. The specifications of PHysBook development are as in Table 2.

Table 2

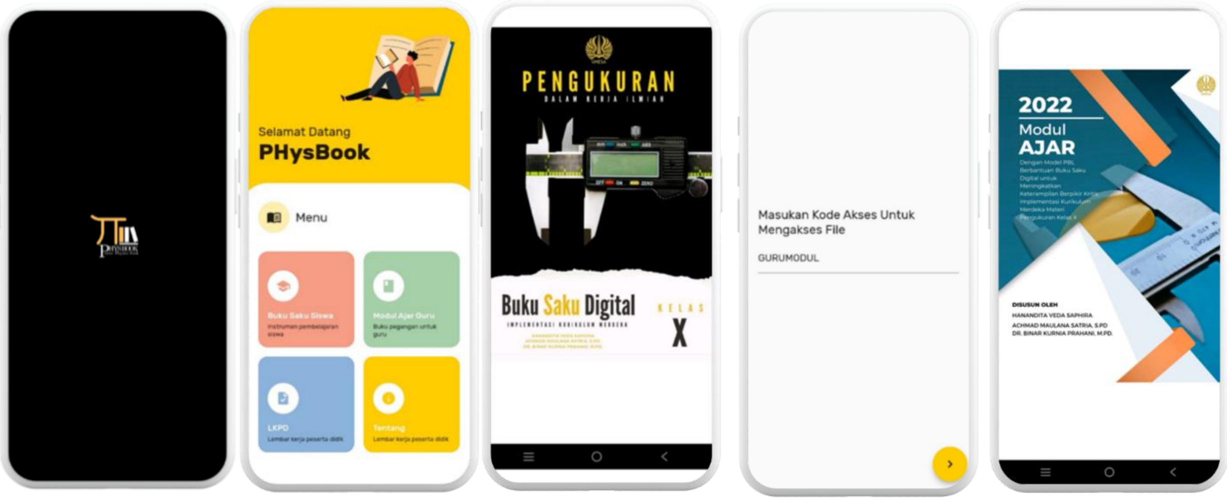
Specification of PHysBook

App Name	PHysBook	Language	:	Indonesia
File Size	< 100 MB	Operating systems	:	Android
Link Download	unesa.me/PHysBookApk	Minimum Version	:	*Nougat* (Android 7.0)
Application features	1. Home start 2. A pocket book of materials 3. Teaching modules for teachers 4. Students Worksheet 5. Developer info			

The use of mobile-based Android as a learning medium has become one future technology with high flexibility (Prahani et al., 2022). Moreover, research by Hidayatulloh et al. (2020) the development of STEM-based textbook has a validity score of 3.70, categorizing it as very valid. Additionally, the increase in students' classical problem-solving skills was 0.75, placing it in the high category. Furthermore, the percentage of students achieving completeness in problem-solving skills tests is 90%, indicating that STEM-based textbooks are effective in enhancing students' problem-solving skills. In line with this, Kaukaba et al. (2022) developing "ABC - Acid & Base Chemistry" android mobile learning media that is valid, practical, and effective in improving students' learning outcomes and motivation. The initial display and initial homepage in this application are as in Figure 1a.

Figure 1

PHysBook start and home view



(1a) (1b) (1c) (1d) (1e)

If the user selects the student pocketbook sub-menu, a student pocketbook presentation will appear as in Figure 1b. Figure 1c shows *Student Pocketbook Sub-Menu To 'Pengukuran' (Measurement) Material.* If the user, especially the teacher, a presentation will appear to enter the access code so that students cannot access it freely. Previously, teachers would be assigned an access code. After typing the access code, namely *'GURUMODUL'* as in Figure 1d then a presentation of teaching modules will appear as shown in Figure 1e. Figure 1e shows *Teacher Teaching Module Sub-Menu Display After Access Code Successfully Entered.*

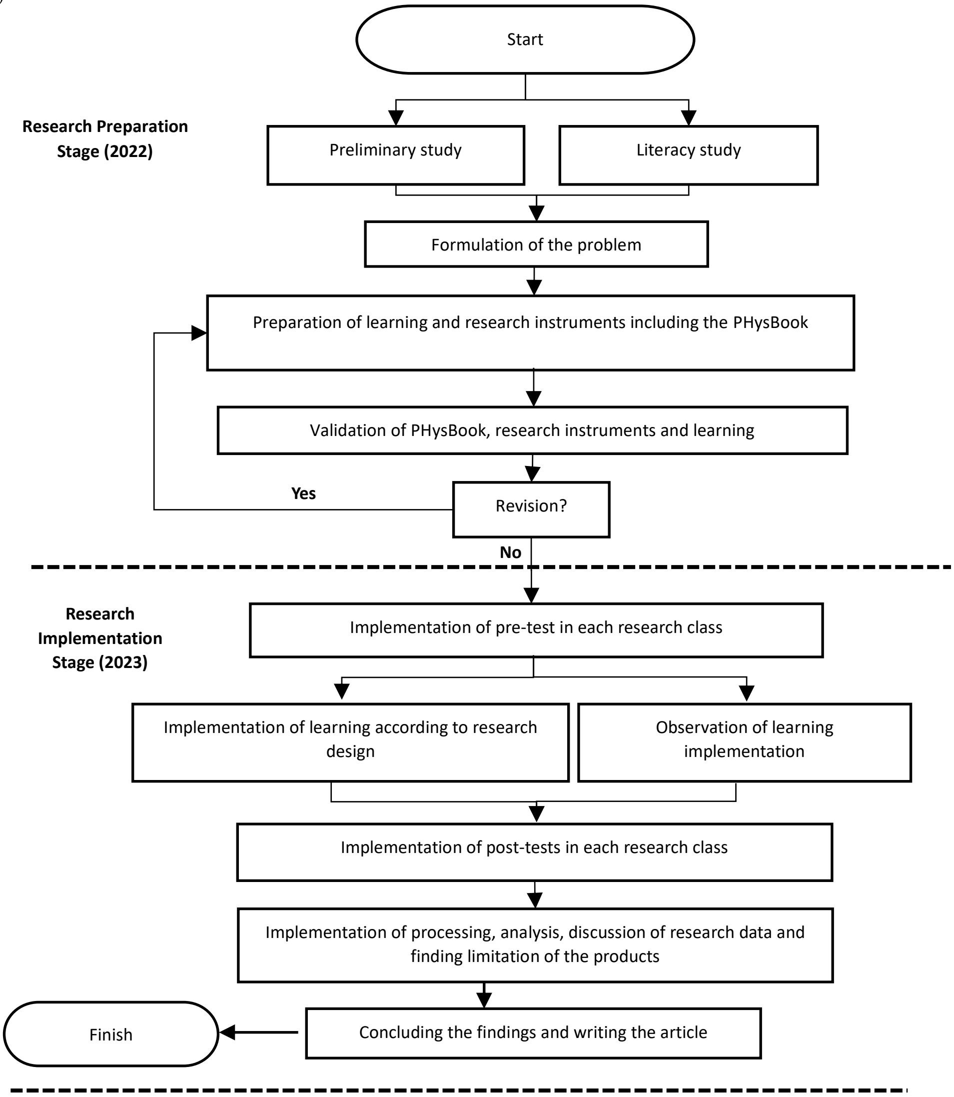
Methods

This quantitative descriptive research method details the application of the PBL model with PHysBook support. The study follows a true experimental research (TER) with a randomized control group O1 and O2 design (Jatmiko et al., 2018). TER design research uses comparison or control groups to obtain definite results after treatment in a particular class (Nisa & Hariyono, 2019). Furthermore, research flowchart is likely in Figure 2.

The implementation process including 14x45 minutes course hours in total and 2x45 minutes in each learning, with PBL model that including theories of Piaget's Individual Constructivism Theory, Vygotsky's Constructivist Social Learning Theory, Bruner's Discovery Learning Theory, Ausubel's Theory of Meaningful Learning and John Dewey's Theory (Inayati, 2022).

Figure 2

Research flowchart



Population and Research Sample

The study population is a subject or object with specific qualities and characteristics within the generalization area set by the researcher from whom conclusions are drawn. The research sample was taken based on the formulation by Slavin in equation (1) with an error tolerance (e) is 5.00%.

$$\text{Sample} = [\text{Population} / (1 + e^2 \text{ x Population})] \qquad (1)$$

(Jatmiko et al., 2018)

Thus, from 140 population students in this study, 104 samples of students were obtained, which will be used as research samples. Each class will be given an O1 as the initial stage of research. The pre-test (O1) is carried out so that researchers can analyze students' initial skills against critical thinking indicators. Then, applying the PBL model assisted by PHysBook will be applied to experimental class 1 (X1). While experimental class 2 (X2) will be applied learning with a PBL model but using PowerPoint media. For comparison, the conventional class (C) was enforced using the lecture method. In conventional classes, the learning process is carried out without unique learning models or media from researchers. After implementing these learning treatments, each class will be given a post-test (O2) to measure final CTS after classroom learning with specific models and media (Khoiri et al., 2021).

Learning and Research Instrument

This research uses learning tools to support the implementation of research, namely teaching modules, Student Worksheets (SW), and PHysBook. The research tools employed in this investigation include observation forms for monitoring the learning process and assessing CTS, alongside observation sheets and questionnaires to gauge student responses. The observation sheet for learning implementation and CTS is an assessment sheet filled out by one class teacher and two students designated observers to observe researchers during the learning process in class.

A learning tool is said to be suitable for use if it has gone through a validation and reliable assessment process. Learning devices and instruments are validated by selected lecturers at the Department of Physics, Surabaya State University. The devices that must go through the validation stage before use are teaching modules, SW, and PHysBook. Then, the research instruments that go through the validation stage are critical thinking test sheets, observation sheets on learning implementation and CTS. In order to ascertain the validity criteria of produced items and technologies, data on the outcomes of validity evaluation are conducted through descriptive analysis (mean) on the significance of the approach of each feature. Furthermore, Cronbach Alpha values are employed to assess the dependability of technologies and goods using validity result data (α).

Device validation is carried out by three expert lecturers as validators. The assessment range is between 1–4 with criteria (1) very poor, (2) poor, (3) good, and (4) excellent. The validation results and reliability of learning tools and research instruments are showing that the average validation mode value for 8 aspects of assessment in experimental class 1 teaching module is 3.14 or with valid categories. It was concluded that the teaching module in experimental class 1 was suitable for use. The average validation score for 8 aspects of assessment in the experimental class 2 teaching module is 3.25 or with a very valid category. It was concluded that the teaching module in experimental class 2 is worth using. Experimental media validation sheet 1 in the form of the PHysBook application which was assessed by validators with 19 aspects of learning media both the feasibility of content, language and presentation of 3.53 with very valid categories. The average value of validation mode for 19 aspects of assessment in experimental class 2 learning media in the form of power points is 3.42 with a very valid category. It was concluded that the learning media in both experimental classes were feasible to use. Further analyzed shows that the SW validation sheet consists of 18 aspects that will be assessed by validators in terms of format, language and content, the average validation mode value for 18 aspects of assessment in SW is 3.44 with a very valid category, so it is concluded that SW is feasible to use.

The question instrument validation sheet consists of two aspects in terms of content and language for each indicator of CTS. For each of the three research courses, pre- and post-test question forms were utilized. The average value of the validation mode is 3.19 with valid categories, so it is concluded that the question instrument is suitable for use. The validation sheet of the teacher activity observation sheet consists of 10 aspects of objectives, learning elements and language. The average validation mode value is 3.70 with a very valid category. The results of the student activity observation sheet showed an average validation mode value of 3.70 with a very valid category. It was concluded that the observation sheet of student activities was suitable for use.

In the study, reliability testing was carried out to determine the level of stability or accuracy of an assessment. The reliability of a learning device and instrument is measured using SPSS software. Learning aids and research equipment are regarded to be trustworthy if 0.60 ≤ ≤ 1.00 and unreliable if $\alpha < 0.60$ (Jatmiko et al., 2018). Assess the reliability of each learning tool and research instrument. Reliability is calculated using SPSS with regard to decision making. Experimental teaching module 1 has a value of 0.72 with a high category based on intervals. Experimental teaching module 2 has 0.61 with medium category. Experimental media 1 and experimental media 2 each have values of 0.75 and 0.72 with high categories. SW is rated at 0.74, indicating high reliability. The research instruments, including pre-test and post-test sheets, score 0.66, signifying a medium level of reliability. The response questionnaire achieves a reliability score of 0.83, classified as high. The observation sheets for both teachers and students score 0.78 and 0.77, respectively, falling within the high reliability range. In summary, all utilized learning tools and research instruments are considered reliable.

Data Analysis Techniques

Observational Analysis of Learning Implementation and CTS

Data analysis on the results of this observation aims to determine the implementation of a learning process carried out in experimental and control classes using the PBL model assisted by PHysBook with observers of one physics teacher and two physics education students. The analysis learning implementation carried out by observers is analysed using equation (2) with category intervals in Table 3.

$$\text{Response (\%)} = \frac{\text{Total Score}}{\text{Ideal Score}} \text{x}100 \qquad (2)$$

Table 3
Learning success rate interval

Learning Implementation Achievement	Category	Learning Success Rate	Learning Implementation Achievement	Category	Learning Success Rate
3.50 – 4.00	Excellent	Success	1.50 – 2.49	Moderate	It did not work
2.50 – 3.49	Good	Success	0.00 – 1.49	Less	It did not work

Analysis of Improving Learners' CTS

Learners' CTS can be measured in writing using O1 and O2 scores. Learners' O1 and O2 scores were analyzed using difference tests and N-gain analysis. Prior to the disparity test, the homogeneity testing and a normal distribution test are used to ascertain whether O1 and O2 are from a homogenous population and have a normal distribution. The N-gain criteria are based on Adilla & Jatmiko (2021) and Wardani & Jatmiko (2021) that $\langle g \rangle < 0.30$ is low criteria, $0.30 \leq \langle g \rangle < 0.70$ is in moderate criteria, and $\langle g \rangle < 0.70$ is in high criteria. Effect size is a value that measures the intensity of a population's link between two variables or a sample-based calculation for that amount. In this study, the effect size was calculated based on Cohen's d with intervals of 0.00 – 0.20, Very Low, 0.21 – 0.5 Low, 0.51 – 1.00, Moderate and > 1.00 Strong (Lestari et al., 2021b; Prahani et al., 2022,). Cohen's d concludes that the greater the value, the more significant the difference between the control and experimental groups (Goodman et al., 2019).

Analysis of Student Response Questionnaire Sheets

Positive and negative comments are applied equally in the Likert Scale evaluation of responses from pupils surveys. Then, convert the percentage of learner response values into categories, 0.00 – 19.00, Very lacking; 20.00 – 39.00, Lack; 40.00 – 59.00, Moderate; 60.00 – 79.00, Good; 80.00 – 10.00, Excellent (Lestari et al., 2021a).

Findings

Analysis of the Implementation of the PBL Learning Model Assisted by PHysBook

Teacher Activity

Teacher activities during learning are observed and assessed to determine the suitability of teacher activities with the stages of the PBL model and the media that have been implemented. Data from the analysis of observations of teacher activity are shown in Table 4.

Table 4

Results of the assessment of observations of teacher activities

No.	Assessment Aspect	Average	Percentage	Category
Opening				
1	The teacher opens the learning with greetings, prayers, giving receptions, and delivering learning steps.	4.00	100.00	Excellent
Phase 1				
2	The teacher provides a stimulus regarding the importance of measurement.	4.00	100.00	Excellent
3	The teacher gives a problem and asks students to give an initial interpretation.	4.00	100.00	
Phase 2				
4	The teacher asks students to form groups of 4-6 people and then distribute SW.	4.00	100.00	Excellent
5	Teachers provide opportunities for learners to analyze problems and get relevant information related to the material.	4.00	100.00	
Phase 3				
6	Teachers guide students to collect data or explore problems assisted by PHysBook.	3.67	91.67	Excellent
7	The teacher guides students to analyze the results of their group discussions related to the problems presented at SW.	4.00	100.00	
Phase 4				
8	The teacher guides the learners to make an inference from the solution they find.	3.67	91.67	Excellent
9	The teacher asked each group to present the results of their discussion through a presentation.	3.00	75.00	Good
Phase 5				
10	Teachers facilitate class discussion activities related to inter-group evaluations that present the results of their discussions.	4.00	100.00	Excellent
11	The teacher confirms the results of the class discussion.	4.00	100.00	
12	The teacher asks students to provide final inferences on the learning process that has been carried out.	3.67	91.67	
Closing				
13	Teachers provide opportunities for students to ask questions about what they still need to understand.	4.00	100.00	Excellent
14	The teacher ends the lesson by praying and greeting and thanking.	4.00	100.00	
Average		3.86	96.43	Excellent

Table 4 indicates that the mean value derived from the assessments of the three observers is 3.86. The analysis of teacher activity observations yields an average percentage of 96.43%, falling into the "very good" category. Considering the average scores and percentages from the three observers, it is evident that nearly all phases and components of the teaching module are executed exceptionally well during the learning process.

Student Activities

Student activities during learning are observed and assessed to determine the suitability of teacher activities with student activities to the stages of the learning model PBL assisted by learning media to train CTS of student activities are shown in Table 5.

Table 5

The results of observational activities of learners with indicators of CTS

Class	Average	Score	Category
X1	3.53	88.30	Excellent
X2	3.20	80.00	Good
C	2.44	60.89	Moderate

Overall, the evaluation of CTS in X1 yielded an average score of 3.53 out of a possible 4.00, signifying that student involvement in learning through the PBL model with PHysBook support falls within the excellent range. X2 achieved a score of 3.20, categorizing it as good, while the C class obtained an average score of 2.44, which is considered moderate.

Analysis of Learners' CTS Improvement with the PBL Model Assisted by PHysBook

Test Prerequisites

Prerequisite testing is fundamental for establishing which test statistics are required, whether the test uses parametric or non-parametric statistics. Normality tests were performed on O1 and O2 scores using Kolmogorov-Smirnov. Table 6 is the result of a normality test using Kolmogorov-Smirnov with SPSS. Table 6 shows that each class's normality test results in the O1 and O2 have a sig value. < 0.05 so that H_0 is rejected. It was concluded that the data was not normally distributed. Homogeneity test used based on Levene.

Table 6

Findings of normal distribution testing with kolmogorov-smirnov in SPSS

Classes	Kolmogorov-Smirnov[a]			Shapiro-Wilk			Hypothesis
	Statistic	df	Sig.	Statistic	df	Sig.	
O1 X1	0.21	35.00	0.00	0.88	35.00	0.00	H_0 rejected: Data is not normally distributed
O2 X1	0.16		0.02	0.83		0.00	
O1 X2	0.21		0.00	0.88		0.00	
O2 X2	0.17		0.01	0.91		0.01	
O1 C	0.19		0.01	0.88		0.00	
O2 C	0.26		0.00	0.86		0.00	

Table 7

O1 and O2, homogeneity test results, based on the mean

	Levene Statistic	Sig.	Hypothesis
O1	2.26	0.10	H_0 accepted: Data homogeneous
O2	2.70	0.07	

Table 7 shows that the homogeneity test results on the O1 based on the mean have a sig value. > 0.05 which is 0.10 > 0.05 so that H_0 is accepted. It was concluded that the data were homogeneously distributed for O1 assessment. Table 7 indicates that the homogeneity test result on the O1 based on the mean has a Sig value. > 0.05 i.e. 0.07 > 0.05 so that H_0 is accepted. It was concluded that homogeneously distributed data for O2 assessment.

Improved CTS of Learners

Several assessments were carried out to measure the impact of the educational tool on students' CTS in every research groups. The data proved abnormally distributed; the difference test analysis used the Wilcoxon non-parametric test. The results of the Wilcoxon difference test in each class did not show a decrease from O1 scores to O2 scores; this was seen based on the negative rank values in each class showing 0.00 results.

Table 8

Comparison of Average O1 and O2 Scores of CTS Indicators In Each Research Class

Classes	X	Interpretation (1)	Analysis (2)	Inference (3)	Evaluation (4)
X1	O1	0.80 (L)	0.51 (L)	0.40 (L)	0.06 (L)
	O2	8.89 (H)	8.43 (H)	7.31 (H)	6.40 (H)
X2	O1	1.54 (L)	0.69 (L)	0.23 (L)	0.06 (L)
	O2	3.43 (L)	1.91 (L)	0.29 (L)	0.11 (L)
C	O1	0.71 (L)	0.66 (L)	0.51 (L)	0.26 (L)
	O2	1.69 (L)	1.80 (L)	0.66 (L)	0.91 (L)

Note. L is Low category and H is High category

Based on Table 8 Interpretation indicators have the highest value from both O1 and O2 scores, while evaluation indicates CTS with the lowest value. The N-gain test was conducted to determine and analyse the level of improvement in students' CTS after being given learning treatment. Table 9 is the result of the N-gain calculation based on SPSS.

Table 9

N-gain and effect size results

N-gain			Effect Size		
Classes	Statistic	Category	Class	Effect Size	Category
X1	0.78	High	*X1-X2*	0.80	Moderate
X2	0.13	Low	*X1-C*	0.76	Moderate
C	0.10	Low	*X2-C*	0.40	Low

Table 9 shows that the N-gain result for X1 was 78.87 in the high category. X 2 showed a known N-gain of 13.91, while for the C class, an N-gain of 10.39. It was concluded that X 2 and C classes in the N-gain category were low. Furthermore, the effect size was calculated based on Cohen's d. Table 9 is the result of calculating the effect size value. Furthermore, Table 9 shows that the difference in effect between X1 and X2 is 0.80 with the medium category. The difference in effect size for experimental class 1 and control is 0.76 with the moderate category. X2 with C class has an effect size ratio 0.40 in the low category.

Analysis of Learner Responses After the PBL Model Assisted by PHysBook Implementation to Improve Learners' CTS

The student response questionnaire sheet applied to this study consists of 10 statements that will be assessed by each student in X1, X2, and C classes using per-item analysis with the Likert scale. Table 10 is the result of a student response questionnaire.

Table 10

Results of student response questionnaire

Statement	Students' response (%) (n=104)			
	1	*2*	*3*	*4*
S1	0.00 (0.00)	11.76 (4.00)	32.35 (11.00)	55.88 (19.00)
S2	41.18 (14.00)	58.82 (20.00)	0.00 (0.00)	0.00 (0.00)
S2	2.94 (1.00)	14.71 (5.00)	41.18 (14.00)	41.18 (14.00)

Discussion

Analysis of the Implementation of the PBL Learning Model Assisted by PHysBook

Observations are carried out according to the phase of the learning model applied in each research class. X1 and X2 have 14 assessment aspects in 5 phases of PBL. The opening and closing of the lesson also complement the assessment aspect. Observation of learning is carried out for 2x45 minutes in each learning meeting. At the opening stage, the teacher applied greetings, prayed, gave perceptions, and conveyed learning steps before starting learning (Anggraeni et al., 2023). Perception helps teachers attract students' attention and provide focus and attention to students so that learning begins immediately (Molloy et al., 2020; Qadir & Al-Fuqaha, 2020; Wolff et al., 2021).

Table 4 Showing phase 1, getting an average score in the very good category. Phase 1 has aspects of teacher assessment, provides stimulus about the importance of the material and provides a problem, and asks students to provide initial interpretation. Phase 1 of the PBL model has one indicator of CT: interpretation. Interpretation asks students to give impressions or opinions and initial views on the problems given by the teacher (Amin et al., 2020).

Observations in phase 2 show that the results of the assessment of teacher activity observations in Table 4 showed that phase 3 was carried out very well. In this phase, the indicator of CTS implemented is analysis. The analysis is performed to acquire data gathered from the issues that are supplied and while working on SW (Martawijaya et al., 2023; Suryawati et al., 2020). In line with this, the assessment of observations of student activities on the analysis indicators is in the very good category in X1 and X2. The C class had an assessment of learner activity in the sufficient category.

Phase 4 is the teacher's activity to guide students to make an inference from the solution of physical problems in everyday life that they have found and present their artifacts or findings through presentations carried out very well. In phase 5, the teacher's activity, namely facilitating class discussion activities and forming an evaluation and final inference on learning, was carried out very well. In both phases, students can make conclusions about what they have found as a solution to physical problems in everyday life with the help of PHysBook.

Table 4 also shows that the closing activities are carried out very well. At this stage, the teacher provides opportunities for students to ask questions related to what they do not understand to avoid misconceptions. In this aspect, the teacher ended the lesson by praying and saying greetings and thanks. Final learning sessions are necessary to give inferences from studying activities and confirmation of answers to physics issues in real life that pupils have provided during class through presentations (Monica et al., 2020).

Table 5 demonstrate an assessment of student activity with indicators of CTS in X1 in the excellent category. Learners successfully meet the assessment of each aspect of learning in each indicator of CTS. X2 is in a good category, in order that learners still need help with inference indicators. When making presentations, learners need help to conclude the solution to the problem they make based on the analysis. In line with this, the assessment of student activity in the control class has sufficient categories. This is because the learning model used by the C class still uses a conventional model in the form of lectures, so in each indicator of CTS, students still need help conveying initial opinions, analysing, evaluating, and inferring. This problem is continuous with students who are not trained in CTS in the physics learning process, and no learning media supports learning (Koes-H et al., 2023). However, based on the Table 5, X1 had the highest student activity observation value compared to X2 and C classes.

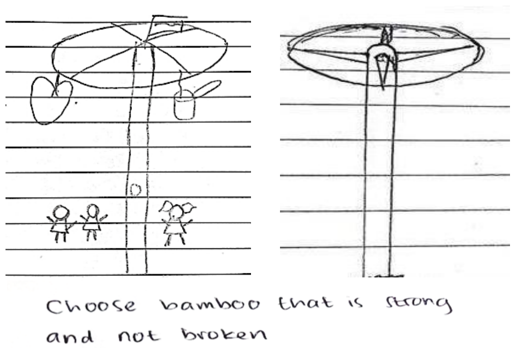
Analysis of Learners' CTS Improvement with the PBL Model Assisted by PHysBook

Improvement of CTS is carried out using O1 and O2 research instruments. Each O1 and O2 consists of two questions, including indicators of CTS, O1, and O2 instruments were given to the entire research class. O1s are given before the researcher conducts treatment. O2 is given after researchers treat learning using certain media-assisted models. O1 and O2 research instruments have the same questions. Before the analysis of improving CTS, O1, and O2 data were tested using prerequisite tests, namely normality tests and homogeneity tests.

Test normality using Kolmogorov-Smirnov with SPSS in Table 6 states that H_0 is rejected or the data is not normally distributed. This is because the samples used are more than 30 samples or include big data, so the tested data is not normally distributed (Orcan, 2020). Furthermore, the homogeneity test, which aims to determine whether the assumption of homogeneity in each criterion has been achieved (Ilkorucu et al., 2022; Muhfahroyin et al., 2023, 2024). Based on Table 7 the homogeneity test result using the Levene test is H_0 received or homogeneously distributed. Statistically, the measured population must be homogeneous for the measurement results to be valid and accurate (Clark et al., 2019; Sürücü, 2020).

Figure 3

Learners' O1 Answers on Interpretation Indicators



The analysis continued with a difference test using a non-parametric Wilcoxon test because, based on prerequisite tests, the data was not normally distributed. Wilcoxon is a non-parametric test to measure the significance of the difference between 2 groups of data in pairs of ordinal or interval scales but abnormally distributed (Budiono & Prasetia, 2022). The results shows that H_0 is accepted or there is a difference between CTS from O1 and O2. The difference is in the form of an increase in students' CTS. Based on the CTS of each class, it can be analysed based on indicators with the highest to lowest scores. Figure 3 is the average of O1 and O2 scores of CTS indicators. Interpretation is an indicator with the highest value in terms of O1 and O2.

Figure 3 is an example of an answer to a question to provide an interpretation (opinion) in the form of a design drawing and size of the areca nut climbing frame of the three students during the O1. The answers given by students still need to be detailed and appropriate. Students only describe the frame of *panjat pinang* (a competition carried out by climbing an areca tree) without providing details of the size of the initial plan of climbing the areca nut. One of the students also only wrote an opinion without a significant solution to the existing problem. Learners struggle due to the must have a deeper understanding of the idea and the problem information (Abidah et al., 2020). This causes the value on the interpretation indicator on the O1 to be still in the low category. However, compared to other indicators, interpretation has the highest value. Because many learners still answer to interpretation indicators, this is in line with the research of Basri et al. (2019), which concludes that interpretation indicators have a higher category than other indicators of CTS, such as evaluation and analysis. Refer to Figure 3 The value of the interpretation indicator on the O2 increased to the high category. There are examples of students' answers during the O2, as in Figure 4.

Figure 4

Learners' O2 answers on interpretation indicators

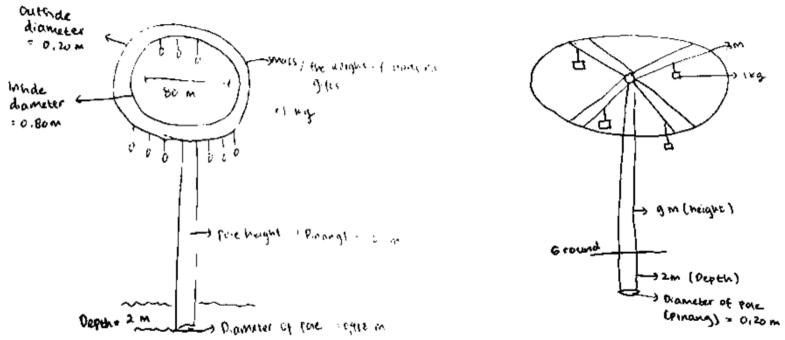


Figure 4 shows that learners have successfully written answers to the requested aspects. After learning, students have understood the terms value, unit, and magnitude. This causes the score on the O2 to increase. Based on Table 8 the second highest indicator is analysis. Students are asked to analyse measuring instruments that can be used to make areca nut climbing frames that they have made. Students are also asked to write down the measured quantity, type of quantity, and unit on the tool, but during the O1, students only give a blank table with answers, as in Figure 5.

Figure 5

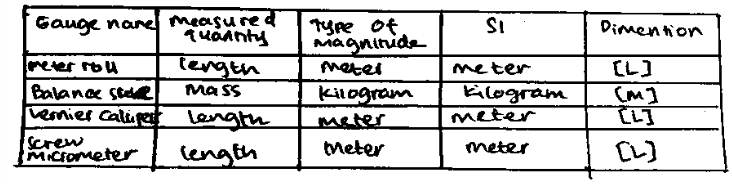
Learners' O1 answers on analysis indicators

Gauge name	Measured quantity	Type of magnitude	SI	Dimention
meter roll				

Most of these students need to explain how they will analyze the use of measuring instruments. Thus, students' answers must still meet a logical, systematic, and complete assessment. This discovery aligns with research by Saphira & Prahani (2022), which states that most students must explain how to model the problem in the analysis indicators. Students also do not add analysis based on the results of calculations they have done. The rise in CTS also showed up in the analysis indicators. The implementation of learning causes the value of the analysis indicator to increase from the low category to the high category. Figure 6 is an example of students' answers to analysis indicators during the O2.

Figure 6

Learners' O2 answers on analysis indicators

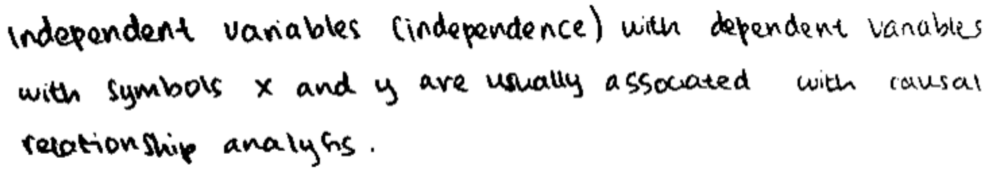


Gauge name	Measured quantity	Type of magnitude	SI	Dimention
meter roll	length	meter	meter	[L]
Balance scale	Mass	Kilogram	Kilogram	[M]
Vernier Caliper	length	meter	meter	[L]
Screw Micrometer	length	Meter	meter	[L]

Based on Figure 6 Students have successfully named several measuring instruments that they will use when realizing their design, along with magnitudes, units, and dimensions. Students have met the assessment criteria on the analysis indicators, so there is an increase in CTS in the analysis indicators during the O2. The next indicator is inference. Inference indicators ask learners to make inferences from what they have designed regarding the solution to the problem presented (Prahani et al., 2023). Figure 7 is the learner's answer to the inference indicator during the O1.

Figure 7

Learners' O1 answers on inference indicators

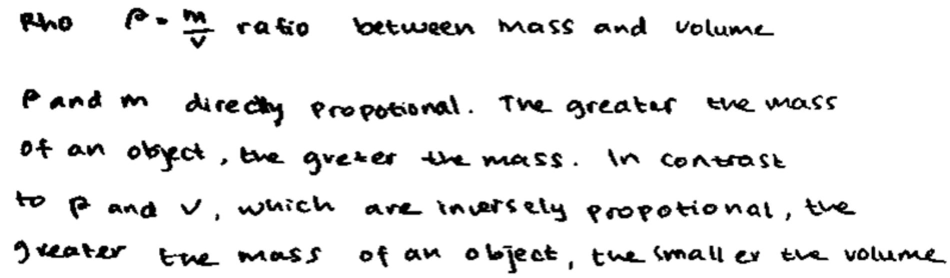


independent variables (independence) with dependent variables with symbols x and y are usually associated with causal relationship analysis.

Figure 7 is a learner's O1 answer on inference indicators. One of the questions on inference indicators is to provide conclusions about the relationship of each variable on density. Based on Figure 7 the answer does not match what is requested. This causes the scores of the O1 students to be in the low category. Improvement of CTS in inference indicators also occurs based on Table 8. As for O2 answers on inference indicators, as in Figure 8.

Figure 8

Learners' O2 answers on inference indicators



Rho $\rho = \frac{m}{v}$ ratio between mass and volume

ρ and m directly propotional. The greater the mass of an object, the greter the mass. In contrast to ρ and V, which are inversely propotional, the greater the mass of an object, the smaller the volume

Figure 8 shows that learners have been able to mention the relationship between variables in density based on the results of observations in the previous point. This causes the O2 value on the inference indicator to increase. The next indicator is the evaluation indicator, which has the lowest value among the four indicators of CTS, based on Table 8. The student's answers on the evaluation indicator at the time of the O1 are blank, so the O1 score on the indicator has an average of 0.12. Examples of student answers as in Figure 9.

Figure 9

Learners' O1 answers on evaluation indicators

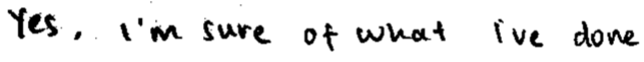


Figure 9 is a learner's O1 answer on the evaluation indicator. Students are asked to provide reviews related to what they have worked on. Evaluation indicators are indicators that students need to answer. Figure 9 is one of the answers filled in by students, but there is no further review of deficiencies or specific reviews related to the solutions they have described. Based on Table 8 however, evaluation indicators still have an increase in value after the O2. Figure 10 is the answer from students to the evaluation indicators during the O2.

Figure 10

Learners' O2 answers on evaluation indicators

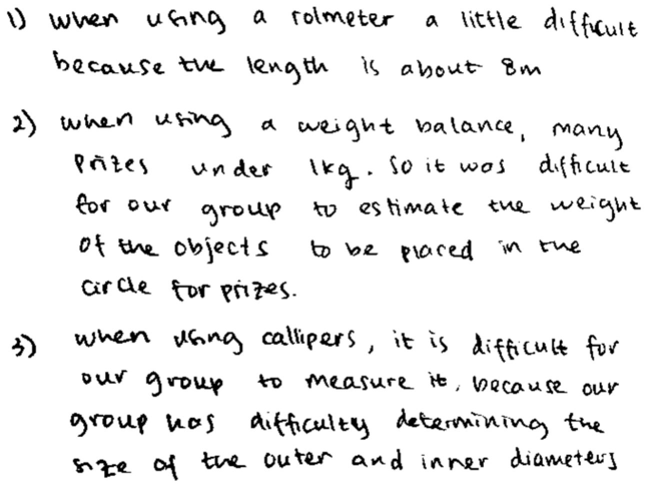


Figure 10 illustrates that students effectively identified challenges encountered while designing the areca nut climbing frame. They displayed critical thinking by recognizing the difficulty of measuring an 8.00-meter length of bamboo with a roller meter. Consequently, there was an enhancement in CTS in the evaluation indicators during O2. To determine the extent of CTS improvement, an N-gain test was performed using SPSS. Table 9 reveals that the increase in CTS was rated as high for X1, and low for both X2 and the C class. Accordingly, the most substantial CTS improvement occurred in X1 following the implementation of the PBL model assisted by PHysBook. The next step involves an effect size analysis, which aims to gauge the strength of the relationship between two variables in a population or sample through the estimation based on Cohen's d (Lestari et al., 2021b; Prahani et al., 2020). Based on Table 9 shows that the difference in effect between X1 and X2 with the moderate category. This shows that the treatment of the PBL model assisted by PHysBooks has a more influential field operational impact on improving students' CTS.

Analysis of Learner Responses After the PBL Model Assisted by PHysBook Implementation to Improve Learners' CTS

Student response data is obtained from student response questionnaires filled out after the learning process through Google Forms. Based on Table 10 as many as 44.12% of students did not agree that physics subjects were boring. Furthermore, 55.88% of students strongly agree that learning physics using PHysBook is fun and can be an innovation in classroom learning, and 58.82% of students disagree with the negative statement of using digital pocketbook-assisted PBL models in learning boring physics. Based on the results of interviews with several students, it was stated that:

I am interested in learning Physics, especially using interesting learning media such as PHysBook, as well as fun classroom activities so that Physics does not feel difficult. -Fs

Previously, physics lessons were troublesome and difficult to understand because learning only listened, but after learning to use applications and activities in class, I became interested in physics. My rational thinking about physics is getting more and more open. -Rz

Hence, it response also match with the other preliminary studies, it is stated that using this e-pocket book can be one of the alternative learning media that attract the interest and attention of students. In the following statement, all three research classes disagreed with the negative statement that CTS is not necessary for physics learning. Statements related to the use of digital pocketbook-assisted PBL models can improve CTS, all three classes agreed. In line with this, the implementation of the PBL model assisted by PHysBook to improve CTS has a good response from students so that it can be used as an innovation in learning.

Conclusion and Implications

The implementation of the PBL learning model with the help of PHysBook was successfully implemented with a very good category. Learners successfully meet the assessment of each aspect of learning in each indicator of CTS. Learners still need help with inference indicators. In line with this, the assessment of student activity in the control class has sufficient categories—the value of observation of student activities on CTS in the high category. There is a difference between O1 and O2 in class with the PBL model assisted by PHysBook in improving CTS with an increased rate in the high category with strong effect scores. Based on the research problem's limitations, this study's drawback is that the research subject is limited to PHysBook-assisted in the measurement of physics material with an operating system (OS) Android only as a representative of improving CTS. To broaden the applicability and impact of the findings, future research should explore other educational contexts, operating systems, languages, and physics materials. Researchers can extend the study to different schools or educational levels to compare results and measure CTS improvements using PHysBook. Furthermore, developing the application for other operating systems and in multiple languages could enhance its usability and effectiveness. Future research should also consider implementing or developing new approaches on other physics materials to measure additional skill variables. These expansions will provide more detailed implications for practice and offer specific areas for future research based on the study's limitations and findings.

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A systematic literature review on the integration of scientific reasoning skills into science education

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ABSTRACT
Scientific reasoning skills (SRS) have become essential abilities for the 21st century. Scientific reasoning skills constitute a set of interrelated cognitive processes that underpin effective science learning. This study aims to analyse SRS through a systematic literature review from the years 2014 to 2023. This study conducted a systematic literature review using the PRISMA approach. Document searches were conducted using the keywords "Scientific Reasoning Skill" "Scientific Reasoning Competence" "Scientific Reasoning" or "Scientific thinking" "science education" "science learning" "social science" or "science" or "education" through the Scopus database. A total of 43 documents were analysed as the final data in this study. The results of the study indicate that SRS research in science education became the most published research category in 2021. The use of Lawson's Classroom Test of Scientific Reasoning (LCTSR) is the most dominant instrument used by researchers in measuring SRS. In terms of strategies that can be used to facilitate the SRS, it is through inquiry-based learning that students are encouraged to actively explore, question, and construct their own understanding through investigation and critical thinking rather than relying solely on direct instruction. Given the importance of scientific reasoning skills in science learning, an emphasis on these skills within the science education curriculum is essential.

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Introduction

Science learning is closely related to the process of inquiry (Ekici & Erdem, 2020). Experimental activities in the inquiry approach begin with the observation of a phenomenon, then move onto identification of possible underlying variables, stating hypotheses, setting up experiments using control variables, analysing results, formulating conclusions, and writing reports. Each of these processes involves SRS-related thinking skills (Bhaw et al., 2023). This is in line with the essence of science, which recognises itself as a product, a process, and an attitude (Chiappetta & Koballa, 2010; Lederman et al., 2013; Irzik & Nola, 2014). Science as a product refers to a discipline that discusses the facts, concepts and theoretical principles that can explain and understand nature and the phenomena occurring within it. Science is necessary for acquiring knowledge and numerous skills to detect, apply and investigate natural phenomena at various stages. Science learning also requires the development of scientific attitudes (Kurniawan et al., 2019; Oh, 2017; Saputri et al., 2019; Suryandari et al., 2022).

Lehrer & Schauble suggest that science is theory, science is logic, and science is practice. Science, as a body of theory, regards experiments as theoretical tests that may lead to conceptual change. In this context, the term "theory" refers to a conceptual framework such as the Atomic Theory that guides the interpretation of experimental evidence and supports the evolution of scientific understanding (Driver et al., 1996; Posner et al., 1982; Lederman & Lederman, 2023) Science as logic focuses on the use of control variables during experiments. Lastly, Science as practice views science not merely as a body of knowledge, but as a dynamic process of constructing, testing, and refining ideas through reasoning, modelling, and representation. Within this perspective, theory and reasoning function as essential tools that guide the development of models and representations to make abstract or unobservable phenomena accessible and understandable. Through modelling, learners engage in authentic scientific practices such as explaining, predicting, and revising their understanding reflecting how scientists interpret and communicate complex natural processes. This approach emphasizes that knowledge in science is not transmitted passively but actively constructed through inquiry, argumentation, and collaboration. Consequently, *science as practice* bridges theoretical understanding with hands-on investigation, enabling students to think and act like scientists. Such an orientation aligns with contemporary science education goals that promote inquiry, modelling, and reasoning as central components of scientific literacy. (Lehrer & Schauble, 2007). These characteristics of science allow students to observe a phenomenon using scientific reasoning. The application of scientific reasoning is identified in pedagogical environments that require students to learn scientific methods during experimental activities (Bhaw et al., 2023). Science as practice views science not merely as a body of knowledge, but as a dynamic process of constructing, testing, and refining ideas through reasoning, modelling, and representation. Within this perspective, theory and reasoning function as essential tools that guide the development of models and representations to make abstract or unobservable phenomena accessible and understandable. For pupils at the primary and secondary levels, engaging in such practices enables them to experience science as a way of thinking and doing rather than as facts to be memorised. Through modelling and inquiry, they learn to explain, predict, and revise their understanding, reflecting authentic scientific activity. This approach emphasises that scientific knowledge is actively constructed through exploration, argumentation, and collaboration. Consequently, *science as practice* bridges theoretical understanding with hands-on investigation, fostering scientific literacy from an early age.

Scientific Reasoning Skill are prerequisite skills that must be possessed by learners to master scientific activities (Edward et al., 2017; Stylinski et al., 2020). (Hasruddin & Aulia, 2023; Kambeyo & Scapo, 2018). Student learning outcomes improve when they can engage more deeply in scientific activities (Burgess et al., 2017; Edward et al., 2017; Gray et al., 2017; Phillips et al., 2018; Stylinski et al., 2020). Science as practice views science not merely as a collection of facts, but as an active process of constructing, testing, and refining ideas through reasoning, modelling, and representation (Ülger, 2021). Within this framework, theory and reasoning guide the development of models that help pupils make sense of abstract or unobservable phenomena. By engaging in authentic scientific practices—

such as designing investigations, interpreting data, and revising explanations—pupils experience science as both a way of knowing and a way of doing. This experiential approach nurtures their ability to think critically and reason scientifically.

This is also supported by the findings of Bruckermann et al. (2020), which show that scientific reasoning skills foster pupils' conceptual understanding of scientific phenomena and their capacity to apply knowledge in new contexts. Consequently, developing scientific reasoning is not only essential for learning scientific content but also for deepening understanding of how scientific knowledge is generated and validated through practice. It is further explained that science learning, especially in inquiry activities, depends on certain prerequisites, namely students' proficiency in scientific reasoning (Bruckermann et al., 2023). Low scientific reasoning skills will have an impact on the decline in the process of inquiry received by students, it can also hinder the achievement of learning outcomes (Burgess et al., 2017; Edward et al., 2017; Gray et al., 2017; Phillips et al., 2018; Stylinski et al., 2020).

Previous research has consistently highlighted the importance of scientific reasoning skills (SRS) in enhancing pupils' understanding of scientific concepts and practices. These skills enable learners to formulate hypotheses, interpret evidence, and construct explanations that reflect authentic scientific inquiry. Bruckermann et al. (2020) demonstrated that the development of SRS contributes to pupils' conceptual understanding and their ability to apply knowledge across different contexts. Similarly, Zimmerman (2007) emphasised that reasoning processes such as control of variables, evidence evaluation, and causal inference are central to meaningful science learning. Building on this body of research, the present study seeks to explore how SRS can be effectively facilitated through inquiry-based learning approaches that encourage pupils to engage in modelling, reasoning, and reflection. This focus aims to deepen understanding of how learners develop and use scientific reasoning as part of their overall scientific literacy. The higher the scientific skill of students, the more likely they are to understand a broader range of knowledge (Ding et al., 2023; Moore & Rubbo, 2012). As per the study conducted by Bao et al., scientific reasoning is strongly correlated with cognitive abilities (Bao et al., 2009). Scientific reasoning skills will improve at all levels if taught with a focus on critical thinking skills (Blumer & Beck, 2019; Hester et al., 2018; Yanto et al., 2019). Other studies suggest that scientific reasoning can be developed at an early age (Zimmerman, 2007). There is increasing evidence that primary school pupils possess various scientific reasoning skills. Early development of scientific reasoning provides learners with greater opportunities to acquire higher-level reasoning skills (Nagy & Korom, 2023). Higher-level reasoning is necessary for problem-solving and decision-making, including understanding complex concepts (Lawson, 2004).

Many studies have examined the importance of scientific reasoning skills in science learning, but there has been relatively little in-depth investigation into scientific reasoning skills in science education (Rampean & Rohaeti, 2025). Analysing credible research on scientific reasoning skills provides a profound overview of the paradigm shift in education, moving from a focus on content memorisation towards the development of scientific thinking processes that prepare learners to solve real-world problems (Miftakhul Falah et al., 2024). While numerous studies examine scientific reasoning, the literature remains scattered across various subjects, educational levels, and methodological approaches, as well as the evaluations used, making it difficult for educators to implement evidence-based practices. Previous studies have underscored the significance of scientific reasoning skills (SRS) in promoting meaningful science learning (Bruckermann et al., 2020; Zimmerman, 2007). SRS enable pupils to interpret evidence, formulate hypotheses, and justify conclusions—core components of scientific literacy. However, research also indicates that these skills are often insufficiently developed in school contexts, where science instruction tends to emphasise factual recall rather than reasoning and inquiry (Istyadji & Sauqina, 2023). Moreover, the integration of inquiry-based learning (IBL) as a pedagogical approach to enhance SRS remains underexplored in certain educational settings. Addressing these issues is essential for cultivating learners who can think critically, reason scientifically, and engage in authentic scientific practices.

Considering the importance of this skill as a fundamental skill that students must possess in experimental and inquiry activities, conducting a systematic literature review can explore the efforts of researchers and educators in developing scientific reasoning skills (Illescas-Navarro et al., 2025). This systematic literature review aims to analyse learning models that facilitate scientific reasoning skills, the aspects and indicators of scientific reasoning skills, and the correlation between scientific reasoning skills and other variables. In addition, it will also explore the research trends on the topic in terms of countries, institutions, and most productive authors, as well as the differences in the types of research conducted by researchers. Accordingly, the present study aims to address this gap by exploring the role of inquiry-based learning in developing scientific reasoning skills among pupils in science classrooms. A literature review is used as an effective method for creating a strong foundation for facilitating knowledge and facilitating theory development (Webster & Watson, 2002). By integrating the results and perspectives of many empirical studies, The literature review informs the direction of this study by mapping existing knowledge, evaluating its limitations, and articulating the research questions that have not yet been empirically addressed (Snyder, 2019). While meta-analysis statistically aggregates results across studies, a literature review synthesises theoretical and empirical insights to construct a conceptual framework that guides further research (Snyder, 2019). This systematic literature review is important to provide information to researchers, teachers, and education practitioners (Ubaidillah et al., 2023), especially regarding the development of leaners' scientific reasoning skills. The results of this study can be used as a strong basis for planning and developing a science education curriculum that is more effective in encouraging and strengthening scientific reasoning skills as a very important skill in science learning.

The objective of this research is to analyse articles sourced from the Scopus database from 2014 to 2023, focusing on scientific reasoning skills in science learning. This study has the following problem statement:

1. What are the dominant trends and developments in research on scientific reasoning skills (SRS) in science education between 2014 and 2023?
2. Which science learning strategies have been reported to facilitate SRS development?
3. What aspects and instruments have been used to measure SRS across studies?
4. How does research on SRS vary according to educational level (e.g., primary, secondary, tertiary)?
5. What relationships between SRS and other variables have been explored in existing literature?

Methods

Research Type

This study is a systematic literature review research. The use of a literature review is an effective method for establishing a strong foundation for facilitating knowledge and facilitating theory development (Webster & Watson, 2002). This method is used to identify and critically assess relevant studies, as well as to collect and analyse data from these studies (Liberati, 2009). The purpose of this systematic review is to identify all empirical evidence that meets the predefined inclusive criteria to answer the research questions. By using a systematic method to review articles and all available empirical evidence, bias can be minimised, making the findings reliable for drawing conclusions and making decisions (Moher, 2009; Snyder, 2019).

Data Collection

Literature data collection was conducted using the Scopus database, spanning the last 10 years from 2014 to 2023. Scopus is one of the high-quality data sources, making it a consideration in document selection (Wei et al., 2023). Data selection was conducted using the PRISMA method developed by Moher, Liberti, Tetzlaff, & Altman (Moher, 2009). The PRISMA method is the most widely used method for systematic literature reviews (Page et al., 2021). The PRISMA method provides a roadmap for reporting systematic reviews in a transparent, objective, and explicit manner (Rehman et al., 2020). This systematic review (Fig. 1) adapted from Kulakli & Osmanaj; Yang, et al; Bonilla-Chaves & Palos-Sánchez; Wei, et al (Bonilla-Chaves & Palos-Sánchez, 2023; Kulakli & Osmanaj, 2020; Wei et al., 2023; Yang et al., 2017).

Data Analysis

The literature search was conducted in March-April 2024 through the Scopus database. This study was conducted using keywords with Boolean operators AND and OR resulting in the following search terms "Scientific Reasoning Skill" OR "Scientific Reasoning Competence" "Scientific Reasoning" OR "Scientific thinking" AND "science education" OR "science learning" OR "social science" OR "science" OR "education".

Table 1

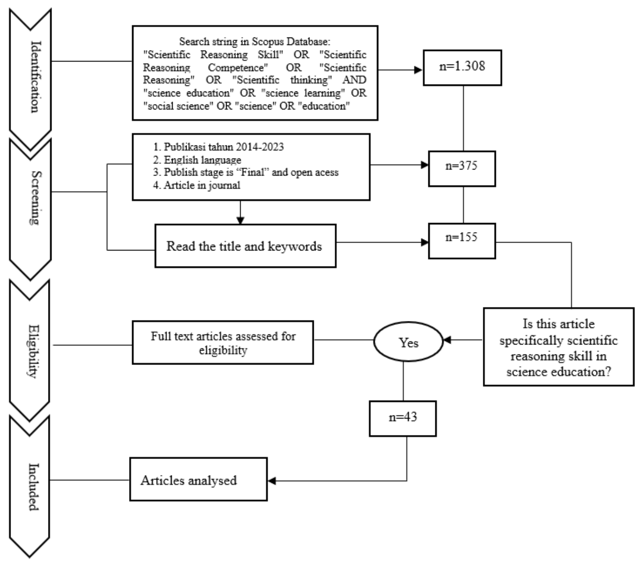
Presents a summary of these criteria

Criteria	Decision
When the predefined keywords exist as a whole or at least in the title, keywords, or abstract section of the paper.	Inclusion
The paper was published in a scientific journal.	Inclusion
The paper should be written in the English language.	Inclusion
Papers that were published before 2014.	Exclusion
Papers that are not accessible, review papers, and meta-data.	Exclusion

A total of 1,308 documents were obtained for the years 2014-2023. The obtained documents were then filtered to include only those in English, document types such as journal articles, final stage documents, and open access, resulting in 375 documents. Next, their relevance to the research topic was analysed through titles, abstracts, and keywords, resulting in 155 documents. After conducting an in-depth analysis through a full-text examination, a total of 43 final documents were obtained. The data were analysed using the PRISMA stages, which consist of four stages: identification, screening, eligibility, and inclusion.

Figure 1

Presents the flow of the research procedure applied in this review



The identification stage is the first stage in the PRISMA method. This stage involves identifying what, how, and where to find the relevant data. Once all the data is obtained, the data is then identified and filtered. This identification process is conducted as thoroughly as possible to avoid missing any important data. This process is referred to as sensitivity in the initial screening stage (Siddaway et al., 2019).

The next stage is screening, where articles are assessed to determine if they meet the criteria for inclusion in the qualitative synthesis. Assessment is based on inclusive assessment (Busalim & Hussin, 2016), meaning that document assessment is based on reputable journals or journals indexed in Scopus. In selecting data sources, Scopus was prioritised due to its extensive repository of peer-reviewed research and established reputation for quality indexing (Wei et al., 2023). Document screening is also conducted on documents that are only in the form of journal articles because they are considered the most recent records or the latest scientific studies of knowledge in any field, and journals are deemed more up-to-date than other sources (Cronin et al., 2008; Rehman et al., 2020) Therefore, documents other than journals, such as books and conference are ignored. Relevant studies were identified through searches of Scopus, Web of Science, and ERIC. To ensure comparability and methodological rigour, only peer-reviewed journal articles published in English were considered. English is an internationally recognised language so it is a recommended language in writing journal articles, especially in reputable journals. The period of 2014–2023 was chosen to provide a balanced representation of recent research trends in scientific reasoning skills. While extending the timeframe could yield a larger sample, Cronin et al. (2008) emphasise that an overly broad range may dilute focus and include conceptually obsolete studies. Thus, a ten-year span is adequate to ensure both scope and relevance (Cronin et al., 2008). Cronin et al. suggest that ideally, the document timeframe for a systematic literature review is 5-10 years, while Nundy et al. corroborated that systematic literature reviews have been conducted over the last 10 years (Nundy et al., 2022).

The next stage is eligibility, during this stage, the screened documents are read thoroughly, including their full papers. If it is in line with the research objectives, the next step is data extraction and qualitative analysis. This research uses Microsoft Excel for data extraction. This form is used to organise qualitative synthetic information (Rehman et al., 2020). Several columns containing notes of important information include the author's name, year, title, institution, research design, types of learning models supporting SR, research subjects, and the correlation between SR and other variables. Based on the analysis of the systematic literature review procedure steps, Figure 2 is a conceptual mapping obtained from the keyword search results.

Figure 2

Conceptual mapping

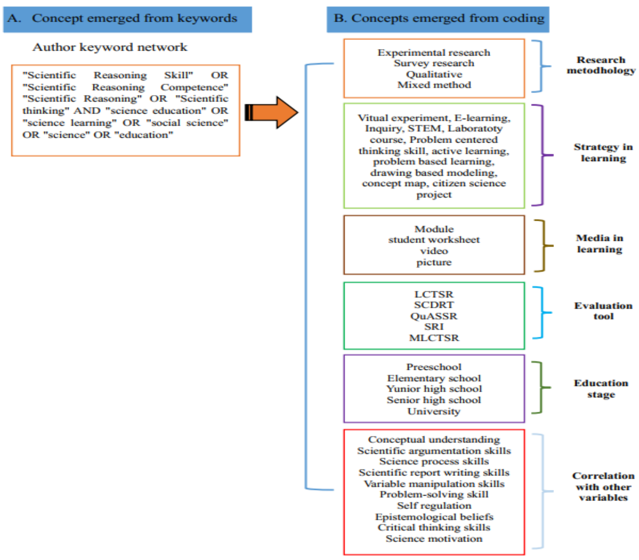


Figure 2 presents the conceptual mapping generated from the keyword analysis. This mapping served as the basis for developing the coding framework applied to the selected articles in the systematic review.

Findings

The study analyses the profile of studies on scientific reasoning skills, how to facilitate scientific reasoning skills, aspect and measurement instruments of scientific reasoning skills, differences in types of institutions, and the correlation between scientific reasoning skills and other variables.

The Profile of Research on Scientific Reasoning Skills in Science Education Based on the Number of Publications from 2014 to 2023

Research on scientific reasoning skills in science education over the past 10 years, from 2014 to 2023, sourced from the Scopus database, reveals that studies on this theme consistently contribute each year (Fig. 3).

Figure 3

Comparison of research on SRS from 2014 to 2023

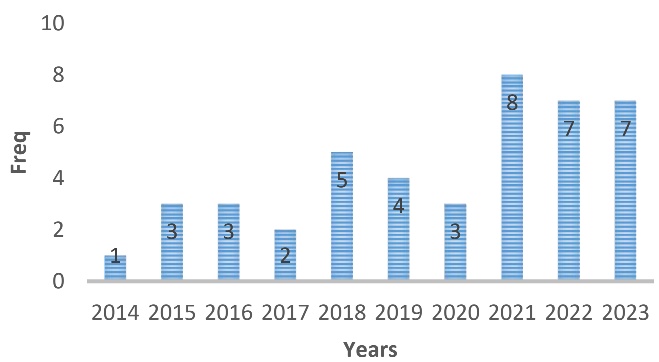


Figure 3 shows a modest increase in publications around 2021, when eight studies on scientific reasoning skills were published. Nonetheless, with fewer than fifty studies overall, this variation reflects a descriptive pattern rather than a statistically meaningful change in research productivity. However, a slight decline was observed in 2022. Over the ten-year period, nearly all studies were written collaboratively, with only a single publication authored individually. This indicates that research on scientific reasoning skills is typically conducted through collaborative efforts. These results indicate that researchers worldwide have extensively engaged in collaboration when researching scientific reasoning skills.

The apparent decline in the integration of scientific reasoning skills within science education research should be viewed as tentative. It may reflect contextual factors such as evolving research priorities, publication delays, or the emergence of alternative conceptual frameworks rather than a true reduction in scholarly attention. One of them is the limitations of a curriculum that focuses more on mastering material than developing scientific thinking skills (C. A. Dewi & Rahayu, 2024). This is exacerbated by a standardised test-based evaluation system that emphasises memorisation over analysis and synthesis of information. In addition, the readiness of educators is also an important factor, where many teachers have not received adequate training in teaching scientific reasoning explicitly. The continued dominance of lecture-based and memorisation-oriented teaching methods in tertiary science education may limit students' opportunities to develop higher-order cognitive and scientific reasoning skills, also do not provide enough space to develop learners' critical thinking skills. Another contributing factor is limited resources, including a lack of access to teaching aids, laboratories, and institutional support in the form of training and professional development. Low pupil motivation and limited engagement in science lessons can hinder the development of scientific reasoning skills, particularly when instructional materials are perceived as difficult or disconnected from students' everyday experiences. Furthermore, rapid changes in educational policy—such as the increasing emphasis on digitalisation and STEM literacy—may unintentionally divert attention away from cultivating scientific thinking skills in science education (Kaçar, 2023). These factors suggest that both pedagogical and systemic influences play important roles in shaping the extent to which scientific reasoning is integrated into classroom practice.

Although the data do not conclusively demonstrate a decline in the integration of scientific reasoning skills, there remains significant potential to strengthen their presence in science education. One promising direction is the adoption of inquiry-based and problem-based learning approaches, which provide pupils with authentic opportunities to investigate phenomena, conduct experiments, and engage in real-world problem-solving. These pedagogical strategies can help bridge the gap between theoretical knowledge and practical scientific reasoning. In addition, improving the quality of training for educators is also of key importance in ensuring that teachers have sufficient skills to teach scientific reasoning effectively (Kirya et al., 2024). The use of digital technologies and tools, such as simulations, virtual laboratories, and artificial intelligence-based learning platforms, can also help them analyse data, formulate hypotheses, and test their conclusions in greater depth. The integration of cross-disciplinary approaches, such as linking science with mathematics, engineering and social sciences, can also strengthen students' understanding of the importance of scientific reasoning in various contexts. In addition, reforms in the evaluation system, by replacing rote-based assessment methods with performance-based assessments such as open-ended investigations and concept mapping, can encourage students to further develop their critical thinking skills. Governments and educational institutions can also play a role in designing policies and curricula that explicitly accommodate the development of scientific reasoning skills as part of the main learning objectives. With these concerted efforts, scientific reasoning skills can once again become a central component of science education, equipping pupils with the critical thinking and problem-solving abilities necessary to navigate the challenges of the future.

Different Types of Research on the Theme of Scientific Reasoning Skill

Various types of research are conducted to study scientific reasoning skills. The reviewed studies were categorised into five types: empirical research articles, position papers, theoretical papers, review articles, and others. However, only papers presenting new empirical data were included in the final analysis. The differences in these types of research are adopted from Lin et al., 2014 and Tsai & Lydia Wen, 2005 Based on the analysis results, research on scientific reasoning skills is predominantly conducted empirically (41 documents). The remainder consists of review studies (1 document) and theoretical papers (1 document). The empirical research conducted by researchers consists of four classifications: qualitative research, quantitative research, and mixed methods.

Table 2

Differences in empirical research in scientific reasoning skills

Empirical Research Type	Freq
Experimental quantitative	25
Survey quantitative	6
Qualitative	8
Mixed method	3

Table 2 shows that experimental research is the most frequently conducted type of research by researchers in facilitating scientific reasoning skills, with a total of 25 documents. Experimental research is conducted by researchers to compare learning outcomes between experimental and control groups. Survey research is the second most dominant type of research after experimental research. Researchers extensively investigate the relationship between scientific reasoning skills and other skills or abilities through surveys. Additionally, researchers have extensively investigated the level of scientific reasoning skills using various standardized test instruments.

Strategies for Facilitating Scientific Reasoning Skills

Scientific reasoning skills can be facilitated through hands-on activity-based science learning. Hands-on activities are conducted through practicum activities, either performed in person or online. Table 3 explains the strategies used to facilitate scientific reasoning skills.

Table 3

Strategies for facilitating scientific reasoning skills

Authors	Strategy	Freq.
(Omarchevska et al., 2022; Parmin et al., 2022)	Virtual experiment	2
(Acar & Patton, 2016; Blumer & Beck, 2019; Kaiser & Mayer, 2019; Malone & Schuchardt, 2023; Novia & Riandi, 2017; Olschewski et al., 2023; Omarchevska et al., 2022; Orosz et al., 2022; Schlatter et al., 2020; Willemsen et al., 2023)	Inquiry	10
(Owens et al., 2020; Özkul & Özden, 2020; Van Vo & Csapó, 2023)	STEM	3
(Coleman et al., 2023; Russ & Odden, 2017; van der Graaf et al., 2018)	Laboratory course	3
(L. Dewi et al., 2023)	Problem Centred Thinking Skills (PCTS)	1
(Acar & Patton, 2016; Iwuanyanwu, 2023)	Scientific Argumentation	2
(Marušić & Dragojević, 2020)	Active Learning	1
(Mendoza et al., 2018)	Problem Based Learning	1
(Heijnes et al., 2018)	Drawing based modelling	1
(Dowd et al., 2019)	Concept map	1
(Bruckermann et al., 2023)	Citizen science project	1
(Rost & Knuuttila, 2022)	Epistemic artifact	1
(Cheng et al., 2018)	Problem-Solving Instruction	1
(Hardy et al., 2021)	Scaffolding	1
(Mendoza et al., 2018)	Collaborative learning	1
(Owens et al., 2020)	SSI	1
(Cabello et al., 2021)	Image Representation	1
(Upmeier Zu Belzen et al., 2021)	Abductive Learning Model	1
(Vaesen & Houkes, 2021)	Gieres' Framework Model	1
(Alabdulaziz et al., 2022)	E-learning	1

Table 3 shows that inquiry-based learning has been identified in several empirical studies as the most effective strategy for facilitating scientific reasoning skills. Science learning through inquiry focuses on experimental activities, whether conducted in-person or online. Some types of inquiry-based learning used are inquiry learning through virtual laboratories (J. Chen et al., 2018; Omarchevska et al., 2022), *guided inquiry* (Acar & Patton, 2016; Blumer & Beck, 2019; Kaiser & Mayer, 2019; Orosz et al., 2022), and *argumentation based inquiry course* (Acar & Patton, 2016). These results show that the majority of researchers are using guided inquiry in conducting investigations as a model to facilitate SRS.

Strategies for integrating scientific reasoning skills in science education can be more effective if they are tailored to the educational level and cultural context. Each level of education has different cognitive characteristics and learning needs, while cultural backgrounds also influence how students understand and apply scientific concepts. Therefore, a flexible approach is required for these strategies to be optimally implemented.

At the primary level, learning strategies should emphasize inquiry-based and exploratory approaches that engage pupils through enjoyable, hands-on experiences. Pupils can be introduced to scientific concepts through simple experiments, storytelling, and guided questions that encourage curiosity. As noted in previous studies, inquiry-based and exploratory approaches enable pupils to observe, predict, and reason about phenomena logically, while avoiding the difficulties associated with abstract conceptual understanding at early developmental stages (Harlen, 2021). Meanwhile, at the intermediate and senior levels, strategies can be more oriented towards problem-based learning (PBL) and STEM (Kurniahtunnisa et al., 2024). Learners can be involved in case studies, data analysis, and evidence-based discussions that demand critical thinking skills. The use of virtual laboratories and digital tools can also help them understand the scientific process more interactively. At the higher education level, inquiry-based approaches, STEM, PBL, and Problem solving become more effective. Students can be encouraged to critique scientific literature, design experiments, and engage in academic discussions to strengthen analytical and problem-solving skills in various disciplines.

In addition to adapting strategies to the level of education, adaptations also need to be made to the cultural context. In Western education systems that tend to emphasise inquiry-based learning and student autonomy, more open strategies such as independent projects, democratic discussions, and evidence-based investigations can be applied to improve scientific reasoning. In contrast, in collectivist cultures such as in many Asian, African and Latin American countries, cooperation-based approaches are more effective. Strategies involving group projects, collaboration-based learning, and peer teaching can help students develop scientific thinking skills in an environment that fits their social norms. Meanwhile, in resource-constrained areas, strategies need to be adapted to the availability of facilities. The use of local materials for experiments, and community-based projects, as well as the utilisation of open digital resources and mobile learning, can be solutions to ensure that scientific reasoning skills can still be taught effectively despite limited infrastructure.

By customising strategies based on educational level and cultural context, the integration of scientific reasoning skills in science education can be done more effectively. This approach not only assists students in better understanding and applying scientific concepts but also ensures that they have critical thinking and problem-solving skills relevant to their learning environment.

Besides the learning models, various media can be used to facilitate scientific reasoning skills. The media used include modules, student worksheets, pictures, and videos. For more details, refer to Table 4.

Table 4

Media for facilitating scientific reasoning skills

Authors	Media	Freq.
(Blumer & Beck, 2019; Coleman et al., 2023)	Modules	2
(Orosz et al., 2022; Russ & Odden, 2017; Schlatter et al., 2020, 2021, 2022)	Student worksheets	5

Authors	Media	Freq.
(Bicak et al., 2021; Kaiser & Mayer, 2019; Russ & Odden, 2017)	Videos	3
(Cabello et al., 2021)	Pictures	1

Table 4 shows that the media used in science learning is student worksheets, with 5 researchers utilising this media to facilitate SRS. Based on the data analysis results, 80% of video media is used in inquiry-based learning.

Aspects and Instruments for Measuring Scientific Reasoning Skills

Scientific reasoning skills have dimensions related to the inquiry process. Starting from analysing problems to concluding. This becomes an aspect measured by researchers in analysing scientific reasoning skills. Based on the results of the meta-analysis, it was found that all researchers measured scientific reasoning skills used test-based instruments. A total of 27% of studies used the Lawson Classroom Test Scientific Reasoning (LCTSR) instrument developed by Lawson (Lawson, 2004). Table 5 illustrates the complete types of instruments for measuring scientific reasoning skills.

Table 5

Aspects and instruments for measuring scientific reasoning skills

Aspect	Instrument	Freq.
Conservation of matter and volume, proportional reasoning, control of variables, probability reasoning, correlation reasoning, and hypothetical-deductive reasoning	Lawson Classroom Test Scientific Reasoning (LCTSR)	14
Understanding scientific concepts and problem-solving	Scientific Concept Dependent Reasoning Test (SCDRT)	1
Complexity, perspective taking, inquiry, scepticism, fracking, Branville	The Quantitative Assessment of SSR (QuASSR)	1
Generating investigable questions, evaluating evidence, designing experiments, drawing conclusions	Scientific Reasoning InventoryThinking (SRI)	2
Conservative reasoning, proportional reasoning, controlling variables, combinatorial reasoning, probabilistic reasoning, correlational reasoning	Modified *Lawson* Classroom *Test* of Scientific Reasoning (MLCTSR)	1

Table 5 shows that research on scientific reasoning skills is frequently measured using the Lawson Classroom Test of Scientific Reasoning (LCTSR) instrument. The dimensions of scientific reasoning skills according to LCTSR include Conservation of matter and volume, proportional reasoning, control of variables, probability reasoning, correlation reasoning, and hypothetical-deductive reasoning.

Different Types of Institutions in Scientific Reasoning Skills Research

Research on scientific reasoning skills in science education has been conducted extensively in various institutions from preschool to university level.

Figure 4

Different types of institutions in scientific reasoning skills research

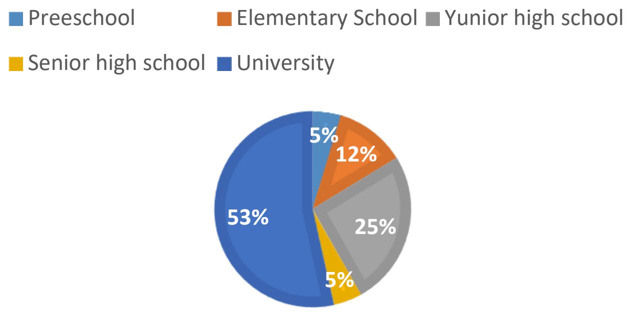


Figure 4 illustrates that the university level is the most frequently studied institution, accounting for 53%. This indicates that the measurement of scientific reasoning skills has been extensively conducted at the university level, particularly targeting prospective science teachers.

The Correlation of Scientific Reasoning Skills with Other Variables

Scientific reasoning skills are correlated with other variables. Some researchers associate scientific reasoning skills with other skills. Table 6 represents the correlation of scientific reasoning skills with other variables.

Table 6

The correlation of scientific reasoning skills with other variables

Authors	Correlation between variables	Freq.
(Acar & Patton, 2016; Cheng et al., 2018; Ding et al., 2016; Malone & Schuchardt, 2023)	Conceptual understanding	4
(Fischer et al., 2022; Iwuanyanwu, 2023)	Scientific argumentation skills	2
(Coleman et al., 2023)	Science process skills	1
(Dowd et al., 2019)	Scientific report writing skills	1
(van der Graaf et al., 2015; Van Vo & Csapó, 2023)	Variable manipulation skills	2
(Cheng et al., 2018; Hejnová et al., 2018; Iwuanyanwu, 2023; Olschewski et al., 2023)	Problem-solving skill	4
(Blumer & Beck, 2019)	Experiment design skills	1
(Omarchevska et al., 2022)	Self regulation	1
(Bruckermann et al., 2023)	Epistemological beliefs	1
(L. Dewi et al., 2023)	Critical thinking skills	1
(Van Vo & Csapó, 2023)	Science motivation	1

Table 6 shows that conceptual understanding and problem-solving skills are the variables most frequently researched by researchers about SRS.

Understanding the correlation between scientific reasoning skills and the effectiveness of science education can be the basis for designing a more integrative and effective curriculum. The integration of these skills into the curriculum should be done systematically by ensuring that each stage of learning supports the development of students' critical and analytical thinking. One way of utilising this correlation is by adopting an inquiry-based approach that emphasises not only concept mastery but also scientific thinking processes. An effective curriculum can incorporate methods such as problem-based learning (PBL), and STEM, as well as inquiry-based approaches that require students to analyse data, design experiments, and draw evidence-based conclusions. In addition, the curriculum needs to adapt learning strategies to the cognitive development level of learners.

At the primary level, exploratory approaches with simple experiments and guided discussions can be used to build the foundation of scientific thinking, while at the middle and upper levels, pupils can be given more complex challenges through case studies, data analysis, and independent hypothesis testing. To ensure its effectiveness, the curriculum also needs to adapt to the cultural context and available resources. In environments with limited laboratory facilities, simulation-based technologies or community-based projects can be an alternative to still practicing scientific reasoning skills. By designing a curriculum that links conceptual understanding with scientific thinking skills, science education not only improves students' science literacy but also equips them with critical thinking abilities that can be applied in various aspects of life and future careers.

Discussion

Based on content analysis results, inquiry-based learning is predominantly used by researchers worldwide to facilitate SRS. These analysis results are relevant to the explanation that Scientific Reasoning Skill (SRS) is a prerequisite skill that learners must possess to master scientific activities, particularly in inquiry-based learning (Edward et al., 2017; Stylinski et al., 2020). Low scientific reasoning skills will have an impact on the decline in the inquiry process received by students (Burgess et al., 2017; Edward et al., 2017; Gray et al., 2017; Phillips et al., 2018; Stylinski et al., 2020). This explanation corroborates the research findings that the majority of researchers utilise the inquiry model to facilitate SRS (Acar & Patton, 2016; Blumer & Beck, 2019; Kaiser & Mayer, 2019; Malone & Schuchardt, 2023; Novia & Riandi, 2017; Olschewski et al., 2023; Omarchevska et al., 2022; Orosz et al., 2022; Schlatter et al., 2020; Willemsen et al., 2023).

Guided inquiry-based science learning is the majority choice used by several researchers in facilitating SRS (Acar & Patton, 2016; Blumer & Beck, 2019; Kaiser & Mayer, 2019; Orosz et al., 2022). Guided inquiry makes it easy for learners to conduct investigations, allowing the inquiry process to be carried out systematically. Sahin & Oren found that the guided inquiry model proved to be able to influence the SRS (Sahin & Sasmaz Oren, 2022). In guided inquiry, the teacher plays a crucial role in directing pupils to understand the questions, conducting investigations, reaching accurate conclusions, and reflecting on the results (Orosz et al., 2022). Without appropriate guidance from the teacher, pupils are unlikely to grasp the purpose or process of scientific investigations, as they often lack the procedural knowledge and experience needed to conduct such inquiries independently (Hmelo-Silver et al., 2007). Blumer et al. corroborate that learning through guided inquiry can effectively facilitate SRS (Blumer & Beck, 2019).

Media-based inquiry models provide educators with ease in facilitating SRS. The use of worksheets is the media used by the majority of researchers worldwide. The use of inquiry-based worksheets makes it easier for students to conduct investigations. In inquiry-based learning, the worksheets used by researchers are the steps learners must take to test a hypothesis. Schlatter et al. found that inquiry-based learning facilitated by tiered worksheets is capable of enhancing scientific reasoning skills (Schlatter et al., 2022).

Science learning in facilitating SRS is often conducted using experimental research, which compares the experimental group with the control group. This type of research is chosen by researchers worldwide because, through experiments, treatments can be applied to determine whether they affect the dependent variables (Creswell, 2012). The existence of these treatments provides empirical evidence of the effects of the treatments. Thus, it can be clearly and accurately observed how SRS is developed in science learning.

The measurement of Scientific Reasoning Skills in science education is often conducted using the Lawson Classroom Test Scientific Reasoning (LCTSR). The LCTSR measures SRS across five dimensions: Conservation of matter and volume, proportional reasoning, control of variables, probability reasoning, correlation reasoning, and hypothetical-deductive reasoning. The Lawson Classroom Test Scientific Reasoning (LCTSR) is a popular instrument that measures the development of students' scientific reasoning skills (Cahyaningrum, 2019; Zhou et al., 2021). It is known that the

LCTSR instrument has good overall reliability. This test has been given to several thousand students and the results have been published where the test referred to using the LCTSR (Hrouzková & Richterek, 2021). Many researchers use this test because it is suitable for broader contexts, such as in universities, high schools, and middle schools (Hrouzková & Richterek, 2021). The results also have relevance to research subjects involving students, as conducted by researchers worldwide. The analysis results indicate that the majority of research on SRS is conducted in higher education institutions, as evidenced by studies (Alabdulaziz et al., 2022; Bruckermann et al., 2023; Coleman et al., 2023; Iwuanyanwu, 2023; Karakoyun & Asiltürk, 2021; Olschewski et al., 2023; Omarchevska et al., 2022; Parmin et al., 2022; Upmeier Zu Belzen et al., 2021; Vaesen & Houkes, 2021; Yoon et al., 2020).

In terms of the correlation between SRS and other variables, Problem-solving skills and conceptual understanding are the variables that have the most correlation with SRS. SRS is a skill that can encourage students to understand science concepts in depth. The search for these concepts requires good problem-solving skills. These skills will be needed later to find a solution. These results are relevant to the research conducted by Acar & Patton which demonstrates that SRS is closely related to students' conceptual understanding or misconceptions. (Acar & Patton, 2016). Other research has shown that students with low SRS also have high misconceptions (Acar, 2014). SRS plays an important role in developing problem-solving skills. The activities of observing phenomena, seeking literature to test hypotheses, conducting investigations, and drawing conclusions are activities that can improve problem-solving skills (Charysma et al., 2018; Iwuanyanwu, 2023).

Conclusion and Implications

The study showed that in 2021, SRS research in science education emerged as the most extensively studied area. In studies on scientific reasoning skills, empirical research predominates, as researchers seek measurable evidence of learners' reasoning processes and the effectiveness of instructional strategies through experimental or quasi-experimental designs. *Lawson's Classroom Test of Scientific Reasoning (LCTSR) became the most used instrument in research to measure SRS.* In terms of strategies that can be used to facilitate the SRS, it is through inquiry-based learning. The university level is the most studied institution to be the subject of research. Conceptual understanding and problem-solving skills are the skills that are most relevant to SRS research. Inquiry-based learning has been proven to be a learning model used by researchers worldwide to facilitate scientific reasoning skills. Modified inquiry learning can maximise scientific reasoning skills, such as using STEM-based inquiry learning.

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Effectiveness of problem-based learning on science problem-solving skills: A meta-analysis

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ABSTRACT

The research aimed to test the effectiveness of problem-based learning in improving science problem-solving skills through a meta-analysis of summary effect-size data. The sample in this study included 25 articles that discussed learners' science problem-solving skills through problem-based learning (PBL) application at the primary, lower secondary, upper secondary, and university levels. The fields of study include integrated science, physics, chemistry, biology, and ICT. This study used the group contrast meta-analysis method. The research consisted of an effect size analysis of the experimental and control classes of articles. The analysis used JASP software to test heterogeneity, summary effect size, and publication bias. The results showed that the summary effect size using the random effect model was 1.33, with a lower limit interval of 0.58 and an upper limit interval of 2.08. This value is in the high category with Cohen's U_3 (%) 90,82%. Therefore, it can be concluded that problem-based learning is effective for improving science problem-solving skills. The overall moderator test shows that educational level ($p > 0.05$) and science discipline ($p > 0.05$) do not have significant differences. Thus, the level of education and scientific disciplines in the application of PBL does not affect problem-solving skills. Therefore, PBL can be applied at various levels of education and scientific disciplines. The novelty of this study is that there are significant differences between individual studies ($p < 0.001$), which indicates the possible influence of other factors or variables that occur during the implementation of PBL in the classroom.

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Introduction

The benefit of problem-based learning is that it can enhance learners' problem-solving abilities by requiring active engagement and critical thinking at each stage of learning (Pitriah et al., 2018). One of the 21st-century skills learners must acquire is problem-solving (Jayadi et al., 2020), as goal-achievement and academic achievement depend on effective problem-solving techniques (Setiawan & Supiandi, 2019). The problem in schools is that pupils still have very low problem-solving skills due to the impact of teacher-centred learning activities, which make them passive during the learning process (Sahyar et al., 2017). Therefore, a learner-centred learning process is needed, one aspect of which is problem-based learning. In problem-based learning, there is an activity stage that involves independent learning by solving problems from various sources (Sahyar et al., 2017). Learners thereby acquire the capacity for critical thought and to deal with challenging situations (Supiandi & Ege, 2019). Research by Argaw et al. (2017) suggested that demonstrated activeness and problem-solving abilities were enhanced by problem-based learning.

Problem-solving skills training can be carried out through the application of learning models that create an effective learning environment to encourage learner activity and achieve learning goals (Nurhidayati et al., 2018). Research conducted by Pitaloka & Suyanto (2019) suggested that problem-based learning is effective in improving problem-solving skills in biology. Problem-solving is enhanced when problem-based learning is applied in science lectures. (Argaw et al., 2017). Research by Simanjuntak et al. (2021) states that problem-based learning helps learners understand a problem and find solutions. Bilgin et al. (2009) reported that students who used the problem-based learning (PBL) method demonstrated better problem-solving skills than those who did not. Fauziah et al. (2014) emphasized that students' problem-solving ability in PBL was superior to that in other learning models.

Problem-based learning (PBL) models can be applied in various fields of study. PBL has been proven to improve problem-solving skills in biology, ecology, physics, and other fields (J. Damayanti et al., 2021). This method is suitable for all levels of education, including high school students, as shown by Mundilarto & Ismoyo (2017), who reported an increase in students' problem-solving abilities. Various studies also show that applying PBL improves critical thinking, scientific literacy, and problem-solving skills at various levels of education (Chileya & Shumba, 2020; Jandrić et al., 2016). In addition to its positive aspects, PBL also has weaknesses. Abidin (2014) points out several weaknesses of PBL, such as first-year students who are reluctant to seek solutions because they consider the problems too difficult; students who are accustomed to obtaining information directly from primary sources find it difficult when they have to study independently; and they need to understand the reasons why they have to seek solutions. Therefore, applying PBL to improve science problem-solving skills also poses challenges for teachers, especially during implementation.

The widespread adoption of problem-based learning in education requires a summary of studies on its effectiveness (Cebrero, 2025). It is about how well learners' problem-solving skills have improved through problem-based learning at various levels of education and disciplines. Hopefully, this would improve the organisation of the existing research findings and make them more accessible to readers and prospective researchers. A meta-analysis of PBL's impact on students' science problem-solving at various educational levels is required. Various studies conducted by earlier researchers exclusively explore PBL concerning problem-solving at specific educational levels, for instance, only at the junior high school level or only at the senior high school level. In addition, earlier research covered only one branch of science, such as physics, chemistry, or biology. This meta-analytic study can serve as a foundation for future research and as a guide for educational institutions as they make decisions about existing curricula across all scientific disciplines, from primary schools to post-secondary universities. In light of this, researchers conducted a meta-analysis to examine the impact of PBL on learners' problem-solving abilities and interpret the findings of diverse PBL studies. The purpose of this study is to test the effectiveness of problem-based learning on science problem-solving skills through a meta-analysis of summary effect-size data. Specifically, the research aims to answer the following questions:

1. How effective is PBL in improving learners' problem-solving skills?
2. Is there a significant difference between the effect size of educational level on problem- solving skills using PBL in science?
3. Is there a significant difference between the effect size of scientific disciplines on problem-solving skills using PBL in science?

This research can expand on and complement several previous studies that discuss the effect of problem-based learning on students' problem-solving skills. This study examines the extent of the problem-based learning model's effect across various fields of science and at different educational levels, from elementary school through junior high school, senior high school, and university. This study summarizes several fields of science, including natural sciences, physics, chemistry, biology, and ICT. This research is different from previous meta-analysis studies. For example, research by Funa & Prudente (2021) explains the effectiveness of PBL on student achievement at the secondary education level. The lack of meta-analyses examining the influence of PBL on problem-solving across all levels of education and scientific disciplines has prompted this meta-analysis. The results of this study provide educators with guidance on improving learners' problem-solving skills by applying problem-based learning in science instruction across various educational levels.

Methods

Research Design

This research is a meta-analysis that synthesizes the findings of similar studies. The meta-analysis uses results from previous research to draw systematic, accurate quantitative conclusions (Retnawati et al., 2018). This study applies the group contrast method, whereas some earlier meta-analyses used the correlation approach based on correlation coefficients. The data analyzed include the number of students, the mean scores, and the standard deviations from two different groups. This study includes various articles that examine how problem-based learning (PBL) might help learners improve their problem-solving abilities in the sciences. To examine whether there is a difference in effectiveness between problem-based learning (PBL) and other (non-PBL) models in science problem-solving skills, this meta-analysis comprises two groups: an experimental and a control group. The meta-analysis procedure of this study refers to Borenstein et al. (2009) and Retnawati et al. (2018), which are: (1) determine the inclusion criteria; (2) collect data and code variables; and (3) conduct data analysis.

Inclusion Criteria

A quantitative research design must be applied in all articles cited in this study. The criteria for the articles used in this study are (1) articles that examine how problem-based learning (PBL) affects or has an impact on solving scientific problems; (2) articles present data in the form of the number of samples, average values, standard deviations (group contrast); (3) articles published in reputable international journals and accredited national journals. Articles that do not meet the criteria will not be included in the meta-analysis procedure.

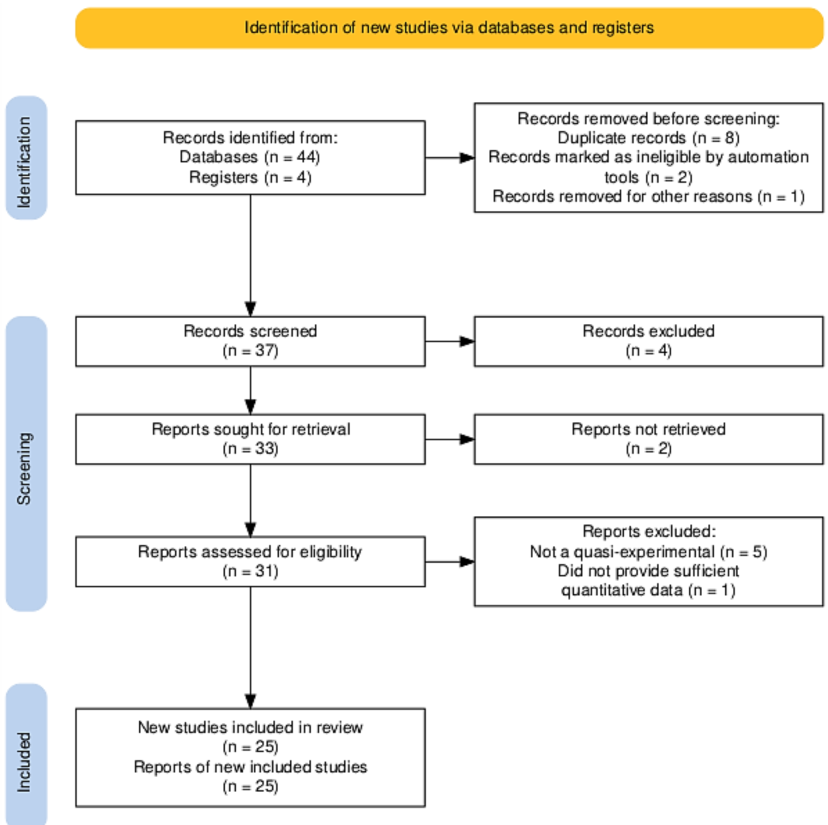
Data Collection

The primary data used are research articles on the relationship between learners' problem-solving ability and problem-based learning. The article collection technique involves searching for articles from various online journal portals such as the Education Resources Information Center (ERIC), Journal Storage

(JSTOR), and SCOPUS. Researchers collected 48 articles relevant to the research focus. Of the 48 articles, only 25 were found, and these included data on the number of samples, the mean, and the standard deviation. 25 papers met these requirements and discussed the value of problem-based learning across different educational levels, specifically in primary and junior high schools, as well as in senior high schools and universities. The fields of scientific study discussed include integrated science, physics, chemistry, biology, and ICT. Figure 1 depicts the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) diagram-based flowchart of the article search process.

Figure 1

PRISMA search strategy diagram



Statistical Analysis

The JASP (Jeffrey's Amazing Statistics Program) software was utilised for this investigation. JASP has several advantages, which are: (1) it is free; (2) it is multisystem; (3) its display is simple and easy to use; (4) it has a complete analysis menu; (5) there are various techniques in the meta-analysis, such fix and random effects analysis, fixed and mixed effect meta-regression, forest and funnel plots, trim and fill, and fail-safe N analysis. The steps of this study's meta-analysis are (1) the calculation of the effect size (g) and standard error (SEg), sourced from data on the number of samples, averages, standard deviations, and standard correlations using Microsoft Excel software; (2) heterogeneity testing; (3) summary effect size calculation; and (4) publication bias analysis. Effect size parameters of 0.1 (low), 0.1-0.4 (moderate), and 0.4

(high) values (Cohen, 1988).

The random-effects model was employed under the assumption that true effect sizes vary across studies, with heterogeneity indicated by $I^2 > 25\%$ (Retnawati et al., 2018). The parameters tau-squared (τ^2) and I^2 are used in a heterogeneous test. Heterogeneous test results indicate that the analysis is suitable for the random-effect model (Rosdiana, 2021). A statistical study must be tested for publication bias (Juandi & Tamur, 2020; Retnawati et al., 2018). The Fail-Safe N approach, the Trim and Fill approach, and the Begg-Mazumdar test are all used in the bias publication test (Rosenthal, 1979). If fail-safe N > (5K + 10), where K is the number of samples, then the meta-analysis is not biased. (Mullen et al., 2001). If the Trim and Fill method detects changes in the forest plot and displays white circles in the funnel plot, this indicates publication bias (Retnawati et al., 2018).

Findings

Primary Data Review

There are two studies at the primary school level (f = 2), four at the junior high school level (f = 4), eleven at the high school level (f = 11), and eight at the tertiary level (f = 8), as per Table 1.

Table 1

Data on the distribution

Educational Level	Frequency(f)	Percentage
Primary School	2	8%
Junior High School	4	16%
Senior High School	11	44%
College	8	32%
Total	25	100%

As shown in Table 2, there are nine natural science studies (f = 9), eight physics studies (f = 8), two biology studies (f = 2), four chemistry studies (f = 4), and two ICT studies. (f = 2).

Table 2

Data on the distribution of science study fields

Field of Study	Frequency (f)	Percentage
Natural Science	9	36%
Physics	8	32%
Biology	2	8%
Chemistry	4	16%
ICT	2	8%
Total	25	100%

Data Coding

The researcher coded the data from each study using the 25 articles that met the meta-analysis requirements. Based on the number of samples, mean, and standard deviation for each experimental and control group, a total of 25 articles were coded.

Table 3

Coding of study data based on contrast group data

No	Studies	Experiment Group			Control Group		
		n	Mean	SD	N	Mean	SD
1	(Pitaloka & Suyanto, 2019)	30	80	13.1	28	54.91	11.84
2	(Simanjuntak et al., 2021)	68	79.34	8.47	64	68.25	10.5
3	(Yuberti et al., 2019)	34	81.56	9.93	36	71.08	10.02
4	(Argaw et al., 2017)	40	50.25	16.091	41	38.54	15.742
5	(Sahin, 2010)	55	30.05	3.66	69	29.03	3.7
6	(Simone, 2008)	38	2.61	0.495	38	2.18	0.457
7	(Bilgin et al., 2009)	40	15.8	2.31	38	15.16	2.14
8	(Aidoo et al., 2016)	51	31.76	4.394	51	19.98	7.279
9	(Valdez & Bungihan, 2019)	46	0.73	0.41	50	0.4	0.21
10	(Surur et al., 2020)	60	6.47	2.062	60	5.38	2.164
11	(Anazifa & Djukri, 2017)	30	59.77	16.05	30	59.45	17.07
12	(Mundilarto & Ismoyo, 2017)	32	73.01	9.75	32	53.75	10.99
13	(J. Damayanti et al., 2021)	30	69	14.35	30	60.5	12.41
14	(Fauziah et al., 2014)	91	61.32	11.21	89	60.4	11.39
15	(Nantha et al., 2022)	29	63.91	0.31	31	60.42	0.28
16	(Sari et al., 2021)	32	68.44	9.019	30	59.83	7.008
17	(Santuthi et al., 2020)	28	84.44	6.839	30	75.19	12.945
18	(Simarmata & Sirait, 2019)	33	66.9	5.77	32	43.3	4.6
19	(Sahyar & Fitri, 2017)	34	84.47	6.34	34	77.18	5.62
20	(Chileya & Shumba, 2020)	41	62	10.583	51	34.16	9.72
21	(Çeliker & Dere, 2022)	21	59.8	7.21	22	57.09	6.92
22	(Akınoğlu & Tandoğan, 2007)	25	12.76	4.265	25	10.12	3.9404
23	(Jandrić et al., 2016)	58	36.41	6.74	54	28.33	6.87
24	(Tsai & Tang, 2017)	26	114.62	9.06	15	107.38	4.71
25	(M.Damayanti &Jirana, 2022)	29	83.43	10.13	30	79.67	10.12

Calculation of Effect Size

Using group contrast calculations, the researcher can estimate the effect size and the standard error based on the sample size, the average, and the given standard deviation. Table 4 presents effect sizes and standard errors for each study.

Table 4

Effect size and standard error based on contrast group data

Studies	Swithin	D	SEd	Df	J	g	SEg
(Pitaloka & Suyanto, 2019)	12.508	2.006	0.322	56	0.987	1.979	0.320
(Simanjuntak et al., 2021)	9.508	1.166	0.188	130	0.994	1.160	0.188
(Yuberti et al., 2019)	9.976	1.050	0.255	68	0.989	1.039	0.254
(Argaw et al., 2017)	15.915	0.736	0.230	79	0.990	0.729	0.229
(Sahin, 2010)	3.682	0.277	0.182	122	0.994	0.275	0.181
(Simone, 2008)	0.476	0.903	0.241	74	0.990	0.893	0.240
(Bilgin et al., 2009)	2.229	0.287	0.228	76	0.990	0.284	0.227
(Aidoo et al., 2016)	6.012	1.959	0.241	100	0.992	1.945	0.240
(Valdez & Bungihan, 2019)	0.322	1.026	0.217	94	0.992	1.018	0.216
(Surur et al., 2020)	2.114	0.516	0.186	118	0.994	0.512	0.185
(Anazifa & Djukri, 2017)	16.568	0.019	0.258	58	0.987	0.019	0.257
(Mundilarto & Ismoyo, 2017)	10.389	1.854	0.299	62	0.988	1.831	0.297
(J. Damayanti et al., 2021)	13.415	0.634	0.265	58	0.987	0.625	0.263
(Fauziah et al., 2014)	11.299	0.081	0.149	178	0.996	0.081	0.149
(Nantha et al., 2022)	0.295	11.836	1.111	58	0.987	11.682	1.104
(Sari et al., 2021)	8.110	1.062	0.271	60	0.987	1.048	0.270
(Santuthi et al., 2020)	10.456	0.885	0.275	56	0.987	0.873	0.273
(Simarmata & Sirait, 2019)	5.227	4.515	0.467	63	0.988	4.461	0.464
(Sahyar & Fitri, 2017)	5.991	1.217	0.264	66	0.989	1.203	0.263
(Chileya & Shumba, 2020)	10.113	2.753	0.292	90	0.992	2.730	0.291
(Çeliker & Dere, 2022)	7.063	0.384	0.308	41	0.982	0.377	0.305
(Akınoğlu & Tandoğan, 2007)	4.106	0.643	0.290	48	0.984	0.633	0.288
(Jandrić et al., 2016)	6.803	1.188	0.205	110	0.993	1.180	0.204
(Tsai & Tang, 2017)	7.783	0.930	0.340	39	0.981	0.912	0.337
(M. Damayanti & Jirana, 2022)	10.125	0.371	0.263	57	0.987	0.366	0.261

Table 4 presents the calculated effect sizes for each included study. The Cohen's d (D) values were obtained from the mean and standard deviation of the respective groups and then adjusted using the correction factor J to produce Hedges' g (g), which provides a less biased estimate for small sample sizes. The columns SEd and SEg indicate the standard errors of Cohen's d and Hedges' g, while **df** refers to the degrees of freedom derived from the sample size of each study. These results serve as the basis for subsequent analyses, such as constructing the forest plot and estimating the overall effect size in the meta-analysis.

Heterogeneity Test

Based on effect sizes and standard errors from all studies, an analysis was conducted using JASP. Based on the data in Table 5, τ^2 is 3.545 and τ is 1.883. The effect sizes of the studies used in the meta-analysis are heterogeneous if $\tau^2 > 0$ or $\tau > 0$. In addition, the data shows that I2 reaches 98.341%. If the I^2 value is >25% and is approaching 100%, the heterogeneity of the effect sizes across studies will be greater (Retnawati et al., 2018). Thus, it can be concluded that there is high heterogeneity in the effect size of each study, so that the selection of this random effect model is suitable for use and meets the criteria

Table 5

Heterogeneity Test Results

Residual Heterogeneity Estimates			
		95% Confidence Interval	
	Estimate	Lower	Upper
τ^2	3.545	2.409	9.647
τ	1.883	1.552	3.106
I^2 (%)	98.341	97.578	99.384

Summary Effect Size Analysis (Forest Plot)

To test the effectiveness level of applying problem-based learning. A summary effect size analysis was conducted using forest plots of all studies. According to the statistics in Table 6, there is a strong positive relationship between PBL and problem-solving abilities. The summary effect size was 1.329, with a 95% confidence interval ranging from 0.580 to 2.078. It found that PBL has a strong impact on learners' capacity to solve scientific problems.

Table 6

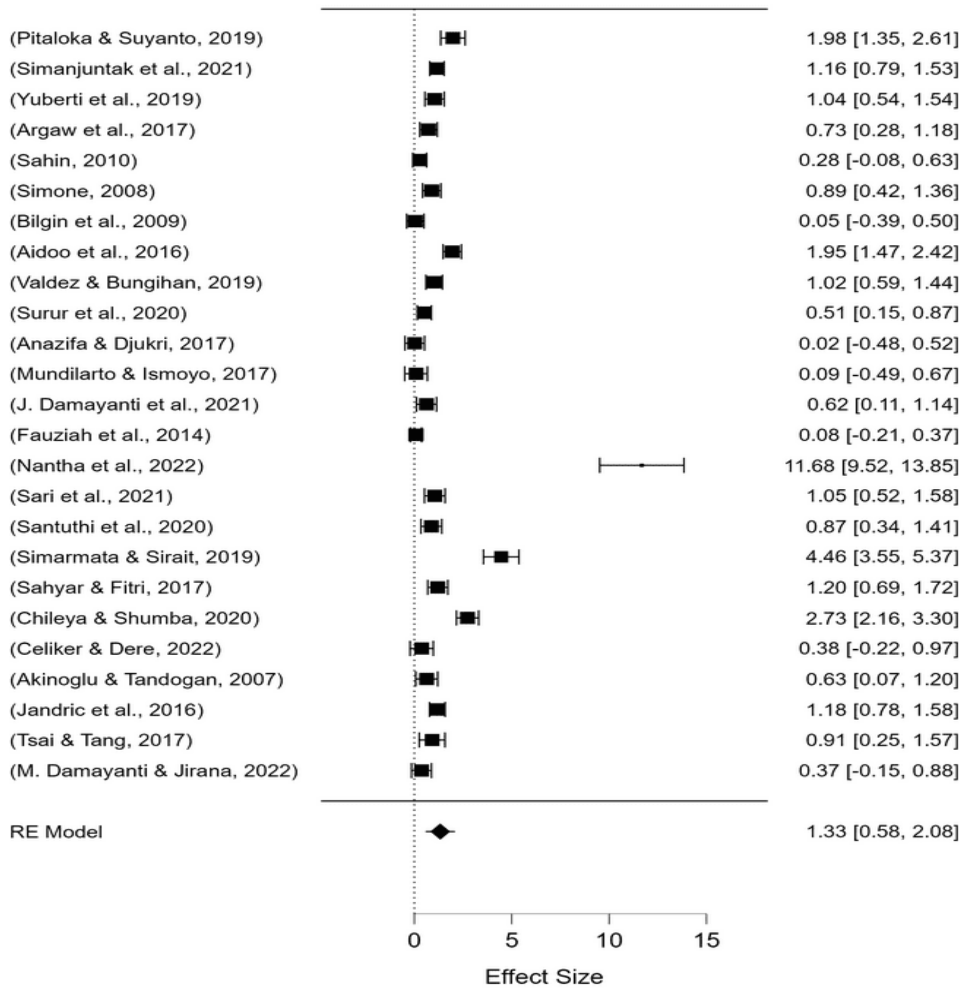
Summary of effect size results

					95% Confidence Interval	
	Estimate	Standard Error	Z	p	Lower	Upper
Intercept	1.329	0.382	3.477	< .001	0.580	2.078

The distribution of effect sizes across studies was presented in a forest plot. Figure 2's statistics demonstrate a summary effect of 1.33. There is a 133% difference between the experimental group (students who study using the PBL model) and the control group in terms of their ability to solve science-related problems, with Cohen's U_3 (%) at 90,82%. The summary effect size is in the range of 0.58 to 2.08, indicating that it is > 0. This demonstrates that using the PBL model to improve science problem-solving is highly effective. Students who study using the PBL model have much better problem-solving skills than those who learn using non-PBL models. These findings support previous research suggesting that PBL effectively improves learners' problem-solving capabilities in science courses (Argaw et al., 2017; Pitaloka & Suyanto, 2019; Santuthi et al., 2020; Sari et al., 2021; Simarmata & Sirait, 2019; Valdez & Bungihan, 2019).

Figure 2

A forest plot illustrating the effect size distribution for each study



The forest plot illustrates the effect sizes and 95% confidence intervals of the included studies. Each black square represents the effect size of an individual study, with the horizontal line indicating the confidence interval. The size of the square reflects the study's weight in the meta-analysis. The overall effect size, estimated using a random-effects model, is represented by the diamond (◆) at the bottom of the plot. The pooled effect size was 1.33 [0.58, 2.08]**,** indicating **a** moderate-to-large effect**,** with a confidence interval that does not cross zero, suggesting statistical significance. Some studies reported very large effect sizes, such as Nantha et al. (2022) with 11.68 [9.52, 13.85] and Simarmata & Sirait (2019) with 4.46 [3.55, 5.37]**,** while others showed negligible effects, for example, Anazifa & Djukri (2017) with 0.02 [-0.48, 0.52]**.** Despite this variability, the pooled result suggests that the intervention had a positive and meaningful impact overall.

Publication Bias Analysis

The fail-safe N method and the trim-and-fill method are used to test for publication bias in the following stage. Publication bias in meta-analysis can be examined using several statistical approaches. The Fail-safe N method (Rosenthal, 1979) estimates the number of unpublished or non-significant studies required to reduce the overall effect size to a non-significant level. A large fail-safe N indicates that the results are robust against publication bias. Meanwhile, the Trim and Fill method (Duval & Tweedie, 2000) detects asymmetry in the funnel plot. It corrects it by trimming asymmetric studies and imputing the missing ones, providing an adjusted estimate of the effect size. With a target significance of 0.05 and an observed significance of 0.001, Table 7 reveals that the fail-safe N value was 3563.000. The value (5K + 10) is 135. No publication bias exists in this meta-analysis study, as indicated by the value of fail-safe N > (5K + 10).

Table 7

Publication bias test through the fail-safe N method

File Drawer Analysis			
	Fail-safe N	Target Significance	Observed Significance
Rosenthal	3563.000	0.050	< .001

The trim-and-fill method test uses a funnel plot generated from JASP output. The funnel plot image shows that there are no white circle dots, and all dots are completely black. Based on these data, no unpublished research was found. Therefore, there is no evidence of publication bias in the researcher's meta-analysis. The funnel plot's appearance after the trim-and-fill method analysis supports this. As noted in Figure 3, there are no white open circles in the funnel plot, indicating that there is no publication bias. Thus, the conclusion from the random-effect model regarding the effectiveness of PBL on students' science problem-solving skills is valid and free of publication bias. This is supported by the forest plot in Figure 4, which shows the results before and after applying the Trim and Fill technique. Apart from that, to strengthen this, the Begg-Mazumdar Test was performed, as presented in Table 8.

Table 8

Publication bias test through the Begg-Mazumdar

Rank correlation test for Funnel plot asymmetry		
	Kendall's τ	p
Rank test	0.268	0.062

The Begg and Mazumdar’s rank correlation test yielded a Kendall’s τ of 0.268 with a p-value of 0.062. The result indicates a positive but weak correlation between sample size and effect size, which was not statistically significant ($p > 0.05$). Therefore, there is insufficient evidence to suggest funnel plot asymmetry or publication bias in this meta-analysis.

Figure 3

Funnel plot publication bias test using the trim and fill method.

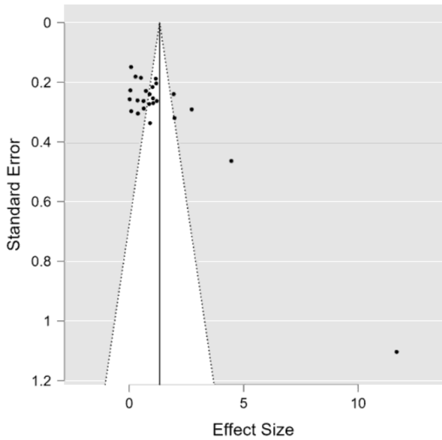
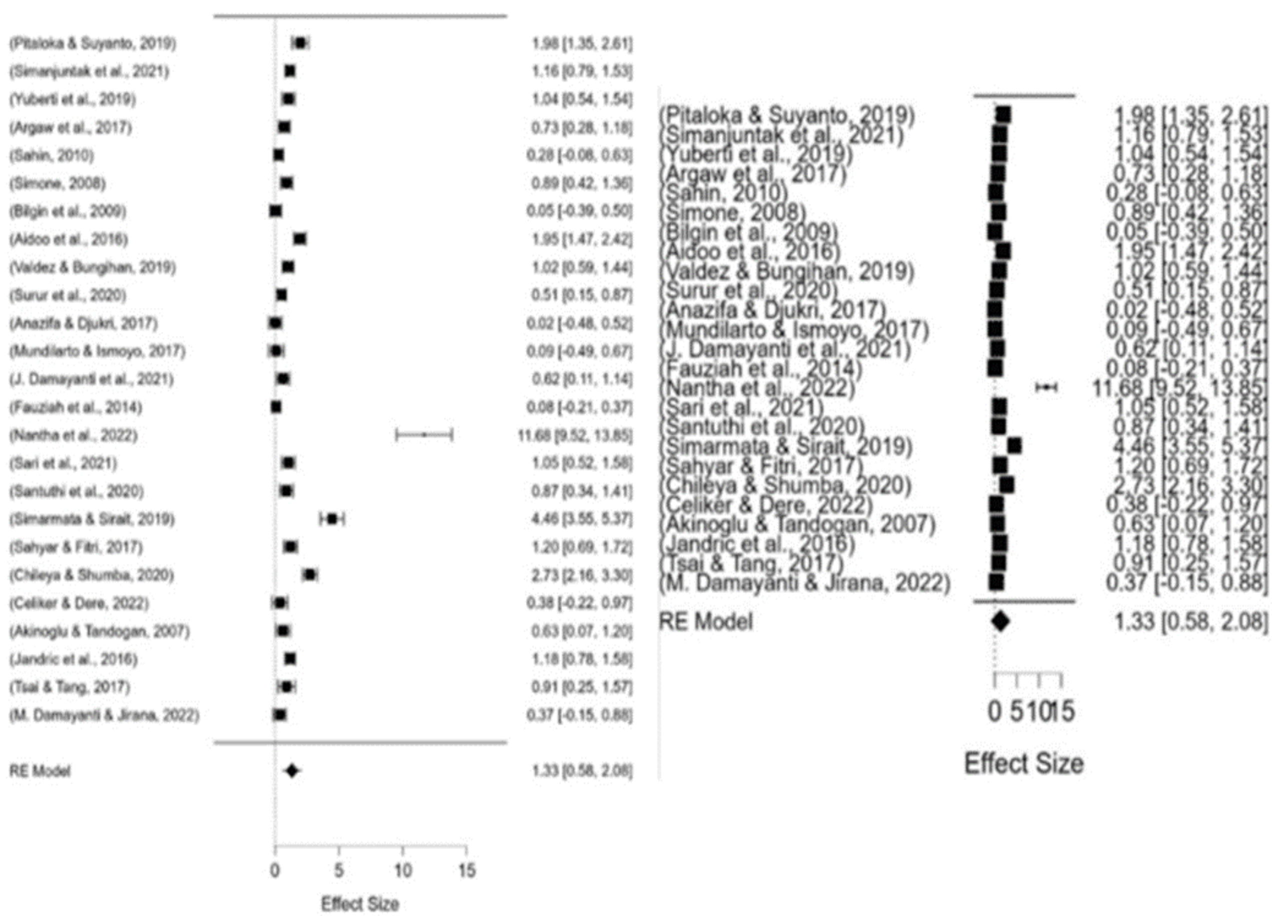


Figure 4

(a) Forest plot before publication testing; (b) Forest plot after publication testing, using the trim and fill method



(a) (b)

Based on the data in Figure 2, the funnel plot is asymmetric. However, the Begg-Mazumdar test yielded a p-value of 0.062 ($p > 0.05$). This shows that there is no publication bias in this meta-analysis. The rank correlation test is a statistical development proposed by Begg and Mazumdar. The funnel plot asymmetry does not necessarily indicate publication bias in the meta-analysis, especially when the sample sizes are small (Harbord *et al.*, 2009). It is not possible to determine if a funnel plot is symmetrical or asymmetrical using funnel plot analysis (Retnawati *et al.*, 2018). To determine significant differences in effect sizes between groups based on educational level and scientific discipline, a moderator analysis was conducted and is presented in Table 9.

Table 9

Moderator Analysis of educational level and scientific discipline

Moderator Random Effects Model	K	ES	SE	95% CI		Z	P	Heterogenity		
				Lower	Upper			Q	df	p
Level of Education	25	0.87	0.23	0.39	1.36	3.51	<.001	4.65	3	0.20
PS	2	0.62	0.55	-0.46	1.67	1.13	0.26			
JHS	4	0.63	0.13	0.34	0.89	4.73	<.001			
SHS	11	1.35	0.34	0.68	2.02	3.96	<.001			
Tertiary	8	1.82	1.32	-0.76	4.40	1.38	0.17			
Scientific Discipline	25	0.77	0.16	0.47	1.07	4.97	<.001	3.03	4	0.55
Natural Science	9	0.66	0.13	0.41	0.91	5.17	<.001			
Physics	8	1.09	0.48	0.16	2.02	2.29	0.02			
Biology	2	1.00	0.98	-0.93	2.91	1.01	0.31			
Chemistry	4	1.13	0.45	0.25	2.01	2.5	0.01			
ICT	2	6.56	5.07	-3.37	16.5	1.23	0.20			

The moderator analysis aims to determine significant differences in effect size by educational level and scientific discipline in students' problem-solving skills when using problem-based learning. The effect size for the overall level of education was large, at 0.87. According to the results of heterogeneity based on educational level, $p > 0.05$, there is no significant difference. PBL applied at different educational levels, including primary school (PS), junior high school (JHS), senior high school (SHS), and college, has the same effect size, indicating that PBL's influence on students' problem-solving skills is not affected by educational level. Heterogeneity across scientific disciplines ($Q < df$ and $P > 0.05$) does not indicate significant differences and has the same effect size. This means that the effect of PBL on problem-solving skills does not vary across science disciplines. These findings indicate that neither the level of education nor the science disciplines in PBL classes influences students' problem-solving skills. Therefore, PBL can be applied at all levels of education and in all scientific disciplines. However, based on individual studies at the class level, JHS ($P < 0.001$), SHS ($P < 0.001$), and science disciplines in the field of natural science ($P < 0.001$) show significant differences; this can occur due to differences in strategies or the presence of other variables that influence it.

Discussion

The researcher conducted a meta-analysis of 25 articles, with the highest frequency at the senior high school level (44%) and the most common field of study, natural science (36%). Based on effect-size calculations and forest-plot analysis, a summary effect size of 1.33 is obtained. This indicates that learners utilising problem-based learning exhibit these skills for addressing science problems, with Cohen's U_3 (%) of 133%, which is categorized as very high. The results of this meta-analysis have positive implications for various educational issues today. That PBL is effective in improving science problem-solving skills can be one effort to enhance 21st-century skills, namely critical thinking and problem-solving. This is supported by Edens's (2000) finding that problem-based learning can equip learners to fulfil 21st-century skills. The next implication is that PBL can be integrated with various educational technologies, enabling continued problem-solving through PBL to keep pace with technological developments. In this era of society 5.0, teachers are required to master digital and creative skills to deliver learning in schools (Asih et al., 2022). In addition, PBL has been shown to improve various science-process skills that students need to support increased understanding of science (Kasuga et al., 2022). This can be one of the efforts to achieve 21st-century skills and student success in the learning process.

This supports the findings of Sari et al. (2021), who found that PBL significantly increases scientific problem-solving skills. The results of this meta-analysis are consistent with those of Siregar et al. (2022), who found that PBL is effective in improving students' problem-solving skills in physics at the high school level. However, this meta-analysis only examines the effectiveness of PBL in the physics branch. In contrast, the present study's meta-analysis shows its effectiveness for students' problem-solving skills across various fields of science and at different educational levels. This is the uniqueness of the present meta-analysis compared to previous PBL meta-analyses. Research by Pitaloka and Suyanto (2019), Simanjuntak et al. (2021), Yuberti et al. (2019), Argaw et al. (2017), Simone (2008), Aidoo et al. (2016), Surur et al. (2020), Mundilarto & Ismoyo (2017), J. Damayanti et al. (2021), Nantha et al. (2022), Sari et al. (2021), Santuthi et al. (2020), Simarmata & Sirait (2019), Sahyar & Fitri (2017), Chileya & Shumba (2020), Akınoğlu & Tandoğan (2007), Jandrić et al. (2016), Tsai & Tang (2017) get a high effect size value. While research by Sahin (2010), Bilgin et al. (2009), Çeliker & Dere (2022), and M. Damayanti & Jirana (2022) has a moderate effect size, namely with effect size values of 0.275, 0.284, 0.377, and 0.366, respectively. Meanwhile, research by Anazifa & Djukri (2017) and Fauziah et al. (2014) reported small effect sizes of 0.019 and 0.081, respectively. The limited number of studies necessitated a test for publication bias. The funnel plot showed an asymmetry; hence, the Begg-Mazumdar test was used and obtained a result of ($p > 0.05$), indicating that there is no publication bias in this study. which indicates that the PBL effect on students' science problem-solving skills at certain levels of education and in certain fields of science is of high magnitude. The application of PBL across various scientific disciplines is more effective than that of conventional learning models. Problem-based learning trains students to work together in groups according to their respective roles, so that they are responsible for the knowledge they gain (Torres et al., 2022).

The results of this meta-analysis support the findings of all the studies included. This has been researched by Simarmata & Sirait (2019), who state that PBL improves students' skills in solving problems related to momentum and impulse material (physics). Physics subjects rely on students' problem-solving skills in a structured manner, so productive learning is needed at the secondary and higher education levels (Pelobillo, 2022). Between the experimental group using problem-based learning and the non-PBL group, there are disparities in the ability to solve chemical problems (Valdez & Bungihan, 2019). Problem-based learning demands student activity to increase student creativity in solving problems (Pitriah et al., 2018). Similar results were obtained by M Damayanti and Jirana (2022) in their research, which found that PBL could enhance students' capacity to solve science-related problems. In general, the studies in this meta-analysis only address the application of PBL in certain branches of science and at certain educational levels. Therefore, future PBL studies are needed to demonstrate its effectiveness in improving students' problem-solving skills through comprehensive research across various educational levels. Thus, a clearer picture will emerge of the efforts to train students' problem-solving skills appropriately. Through problem-based learning, students' problem-solving skills can be effectively developed. This aligns with research by Akınoğlu & Tandoğan (2007), which shows that PBL can train problem-solving skills. In addition, PBL learning requires expertise in resources, so teachers must be able to maximize student learning, especially in terms of learning time (Magaji, 2021). The problem-based learning approach successfully fosters a positive atmosphere that encourages student engagement. Research by Surur et al. (2020) suggests that students can improve problem-solving skills through PBL. The application of PBL results in significant improvements in students' problem-solving abilities (Sahyar & Fitri, 2017). Based on research by Çeliker & Dere (2022), student learning outcomes are improved compared to previous PBL implementations. The goal of the PBL model is to foster learning so that students can develop their problem-solving abilities (Sofyan et al., 2017). Anazifa & Djukri (2017) found that implementing problem-based learning enhanced students' problem-solving skills. According to Nantha et al. (2022), students in PBL and non-PBL classes differ in their science problem-solving abilities.

The implementation of PBL at the primary and junior high school levels yielded moderate effect sizes of 0.62 and 0.63, respectively. Meanwhile, at the senior high school and college levels, the effect sizes were very high, namely 1.35 and 1.82. Across educational levels, the overall effect size is 0.87 in the high category. The effect size obtained in the natural science discipline was in the medium category (0.66), while in the physics, biology, chemistry, and ICT disciplines, it was in the very high category (1.09, 1.00, 1.13, and 6.56, respectively). Overall, the effect size based on differences in scientific disciplines is in the medium category, namely 0.77. These results show that PBL across various levels of education and science disciplines is effective in improving students' science problem-solving skills compared to conventional instruction. Based on the heterogeneity test, differences in education levels and science disciplines between PBL and conventional classes were not significant ($p > 0.05$), indicating that these factors do not affect students' science problem-solving skills. Therefore, it is recommended to conduct further studies and analyses of the factors that influence students' problem-solving skills during PBL, such as motivation and self-confidence. Current trends in PBL research focus on the factors influencing the dependent variables measured in this study. Research by Suratno et al. (2020) shows that implementing the PBL model influences students' higher-level thinking abilities and learning motivation. In addition, research by Surur and Tartilla (2019) shows that applying PBL to students with high motivation yields the highest problem-solving abilities.

Conclusion and Implications

The meta-analysis revealed notable differences in problem-solving abilities between students in the experimental group who used problem-based learning and those in the control group who used non-PBL models. According to the forest plot analysis, the summary effect size is 1.33, indicating that students who use problem-based learning have 133% better problem-solving abilities than those who do not. This meta-analysis of the effect of PBL on students' problem-solving skills has a unique feature that distinguishes it from other studies. This study summarizes the effect of PBL on students' problem-solving skills at various levels of education, from elementary school to university, across various fields of science. The results of this study can guide educators in improving students' science problem-solving skills to achieve educational goals and support student success. The fail-safe N approach, the trim-and-fill method, and the Begg-Mazumdar test were used to assess publication bias, and the results indicated no publication bias in the researchers' meta-analysis. Thus, the conclusion that problem-based learning is more effective than the non-PBL model is unbiased. Based on the moderator test results for educational level ($P > 0.005$) and scientific discipline ($Q < df$; $P > 0.005$), there is no significant interaction, indicating that the effect of PBL on problem-solving skills is not influenced by educational level or scientific discipline. Therefore, PBL is effectively applied across all levels of education and in all scientific disciplines to improve problem-solving skills. However, PBL has its limitations; it can hamper its effectiveness in developing problem-solving skills among students with low motivation and self-confidence. Teachers must understand that each student has a different way of learning; they can combine PBL with other models. In addition, it is also recommended to conduct more empirical studies on the application of PBL to facilitate meta-analysis in science learning, especially regarding factors that influence students' problem-solving skills. Therefore, the author recommends conducting further empirical studies on other variables that influence students' problem-solving skills through PBL.

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Design, implementation, and assessment of complex engineering problems for the undergraduate engineering programme

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ABSTRACT
In the era of the Industrial Revolution 4.0, Outcome-Based Education (OBE) has been adopted worldwide to meet the growing demand for engineering graduates with the knowledge, skills, and attitudes to solve complex engineering problems. In this work, a methodology is presented for designing, implementing, and assessing students' performance in a Complex Engineering Problem group project, in accordance with the guidelines of the Board of Accreditation for Engineering and Technical Education (BAETE) in Bangladesh. The mapping of course outcomes (COs) to programme outcomes (POs), the knowledge profile, attributes of complex engineering problem-solving, and complex engineering activities is presented. The design and implementation of an effective assessment key to measure students' performance is presented using a case study in the Microprocessor and Embedded System course in the Electrical and Electronic Engineering programme. This contribution will be very useful to the teaching community in developing the OBE curriculum as well as researchers in the field of engineering and technical education.

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Introduction

In the era of the Industrial Revolution 4.0, technological development has had a tremendous impact on the demands placed on engineering graduates in industry. According to the World Economic Forum's Schools of the Future (2020), IR 4.0 has made it imperative that educational institutions and systems change their curricula to meet its demands. Due to the revolution, many of today's engineers will have to work in new job environments that did not exist previously. The gap between engineering programmes and jobs is widening because current teaching/learning systems do not equip students with the new skills needed for IR 4.0. In the wake of reviewing the teaching/learning method, the existing curriculum needs to be revised to create a link between the graduates and the rapidly changing industrial world. To facilitate high-quality learning in IR 4.0, the World Economic Forum (2023) has recently defined "Education 4.0" with eight critical characteristics in learning content - global citizenship skills, innovation and creativity skills, technology skills, interpersonal skills, personalised and self-paced learning, accessible and inclusive learning, problem-based and collaborative learning, and lifelong and student-driven learning.

In the 21st century, technical and vocational education faces a multitude of challenges, especially amid rapid advancements in information technology and automation, the globalisation of the job market, a broad and unfocused curriculum, and a complex work environment (Le et al., 2022). Based on a comprehensive literature review, the authors recommended a project-based learning model as an effective approach to develop critical 21st-century skills, including 4Cs – creative thinking, critical thinking, communication, and collaboration (Le et al., 2022). Curricula should focus on building specialisation in a particular domain, fostering literacy in information, media, and technology, and integrating life skills such as flexibility, leadership, initiative, productivity, and social skills. They highlight the need for an educational paradigm shift and emphasize the importance of holistic student preparation to address the challenges and opportunities of the 21st century (Le et al., 2022). Baran et al. (2021) also recommended a project-based learning model to foster essential 21st-century skills, including autonomy, cooperation, and environmental awareness. Their findings underscored the positive impact of project-based learning on skills such as communication, collaboration, problem-solving, creativity, critical thinking, responsibility, and information technology literacy. STEM (science, technology, engineering, and mathematics) education is seen as an opportunity for students to acquire 21st-century skills, and engineering design-based activities have been shown to improve these skills, even among middle school students (Uzel & Bilici, 2022).

As education shifts toward a more hands-on, skill-based approach (Ülger & Çepni, 2020), complex engineering problem-solving (CEPS) has become a crucial pillar of Outcome-Based Education (OBE) in engineering education. CEPS projects ensure that students develop critical problem-solving skills aligned with industry demands. As accreditation bodies focus on bridging the gap between theoretical knowledge and real-world challenges, structured methodologies for integrating CEPS have become a priority (Ling, 2024). To make this happen, structured evaluation keys and project-based assessments are being integrated into engineering curricula, helping students enhance both their analytical thinking and hands-on problem-solving skills. This approach ensures that by the time they enter the workforce, they are not just graduates—they are engineers ready to take on the challenges of a rapidly evolving world. With Industrial Revolution 4.0 (IR 4.0) transforming industries at an unprecedented pace, it is more important than ever for engineering education to keep up, adapt, and prepare students for the future. According to the Global Competitiveness Report Special Edition 2020 by the World Economic Forum (2020), complex problem-solving is the top-most important skill for the upcoming IR 4.0. Students with an engineering background would require improved skills in knowledge acquisition, reasoning, problem analysis, and evaluation (Funke & Frensch, 2007). Therefore, engineering students should be able to handle complex problems and solve them. Therefore, both the facilitators/instructors and learners/students must equip themselves with the necessary knowledge, capability, and motivation to think of problems critically and creatively, and solve at the same time, because these factors can strongly influence how effectively the teachers carry out teaching-learning activities and assessments, as well as what the students can achieve.

Outcome-Based Education (OBE) Framework

Outcome-Based Education (OBE) stands at the forefront of modern pedagogical approaches, shifting the educational paradigm from a traditional teacher-centric model to a student-centric philosophy. Embracing the principles of revised Bloom's taxonomy (Anderson et al., 2001), OBE promotes holistic student development, fostering rational thinking, ethical values, and innovative capabilities. As institutions undertake this transition, challenges emerge in today's dynamic educational landscape, among them those related to assessment processes and tools. Accreditation bodies, such as the Accreditation Board for Engineering and Technology (ABET) (2020) and the

Washington Accord (WA) of the International Engineering Alliance (IEA) (2021), have defined Programme Outcomes (POs) to evaluate the effectiveness of engineering education. In Bangladesh, the Board of Accreditation for Engineering and Technical Education (BAETE) (BAETE, 2019) aligns itself with the twelve widely accepted POs or graduate attributes from WA of IEA.

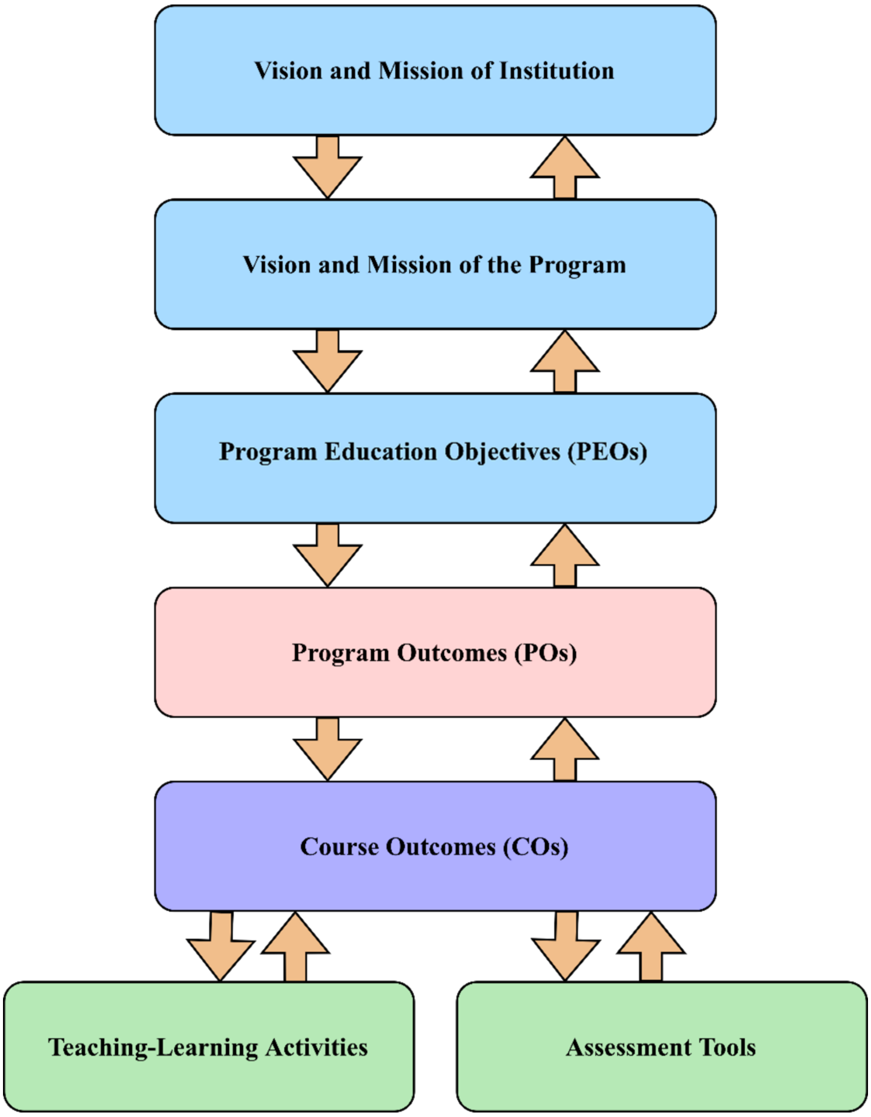
This section briefly explores the fundamental components of OBE, focusing on Programme Outcomes, the attributes of Complex Engineering Problem Solving, and the assessment models used to measure students' achievement. The framework presented here provides a comprehensive understanding of OBE, offering educators and institutions a roadmap to navigate the ever-changing landscape of engineering education.

OBE Model

Figure 1 presents a framework for implementing OBE in undergraduate engineering programmes, depicting its core components.

Figure 1

Outcome-Based Education (OBE) model



There should be positive alignments between components. For example, the programme's vision and mission must align with the institution's. The Programme Educational Objectives (PEOs) are broad statements that describe the career and professional accomplishments the programme prepares graduates to achieve. It is expected that graduates will attain the PEOs within three to five years of graduation, and attainment is judged based on graduates' actual field performance. Programme Outcomes (POs) are statements of the knowledge, skills, and attitudes students acquire as they progress through the programme. PO achievements are evaluated throughout the programme. Course Outcomes (COs) are statements of the knowledge, skills, and attitudes students are expected to acquire by the end of a course.

Once all components are defined, continuous quality improvement (CQI) should be carried out regularly at each level, based on the progress of each component. As part of the CQI, primarily, the modification in teaching learning methods and assessment tools should be done, and if required, COs may be redefined. In OBE, there are four major stakeholders, namely: students, alums, employers, and faculty. In CQI, all stakeholders' opinions/feedback should be collected through regular surveys.

Programme Outcomes

Programme Outcomes (POs) or Graduate Attributes are statements related to the knowledge, skills, and attitudes obtained by students while progressing through the program. Students are expected to know and achieve these graduate attributes by the time of graduation. According to the BAETE manual (BAETE, 2019), edition 2.1, the POs are presented in Table 1 of the Appendix.

Attributes of Knowledge Profile, Complex Engineering Problem Solving, and Activities

The Board of Accreditation for Engineering and Technical Education (BAETE), Bangladesh, has emphasised the Complex Engineering Problems and Complex Engineering Activities in the second edition of the Accreditation Manual for Undergraduate Engineering programmes. Any question, assignment, or project on the Complex Engineering Problem should require in-depth engineering knowledge to be solved. It should also cover a wide range of technical, engineering, and related topics, and there might be no obvious solutions. According to the manual (BAETE, 2019), Complex Engineering Problems exhibit characteristics of P1 and some or all of P2-P7. The attributes are described in Table 2 in the Appendix.

There are 8 Knowledge Profiles (K1–K8) described in the BAETE manual, and any engineering programme that aims to attain the POs should ensure its curriculum covers all of them. The attributes of the Knowledge Profile and their relationship with POs, as given in Table 1, are presented in Table 3 in the Appendix.

Table 3 shows that Complex Engineering Problem Solving is associated with PO1–PO7. According to its characteristics presented in Table 2, a Complex Engineering Problem must have the characteristic of P1, which cannot be resolved without one or more of K3, K4, K5, or K8. Therefore, the COs mapped to one or some of the programme outcomes from PO1-PO7 should be assessed via Complex Engineer Problem Solving. If any of the COs are mapped with PO10, then the assessment should include Complex Engineering Activities. According to the BAETE manual (BAETE, 2019), Complex Engineering Activities should have at least one or all of the attributes shown in Table 4 in the Appendix.

It can be seen from Table 4 that Complex Engineering Activities involve a range of resources, including people, finance, information, and materials, and require understanding the interactions among technical, engineering, and other topics to solve problems in novel ways while considering the consequences for society and the environment.

PO Assessment Model

POs may be assessed directly through COs, indirectly through a survey, or through a weighted combination of direct and indirect methods. In direct assessment, several models exist, such as the culminating, dominant, and accumulating models. In the culminating model of PO measurement, only a few selected final-year courses are used to measure CO and PO achievements. In the dominating model, a few key core courses are considered for CO and PO achievements. In the accumulating model, all core courses are considered for the measurement of CO and PO achievements. The most balanced model is the dominant one, and most engineering programmes at universities in Bangladesh use it to measure PO achievement. In this work, we shall describe how a course, i.e., EEE 3311 – Microprocessor and Embedded Systems, can be designed to contribute to the PO achievement using a dominating model.

Literature Review

Additional engineering education programmes often face criticism that their teaching materials and/or theories have never been translated into practice. On top of that, the current grading system is highly dependent on how well students can memorise. This directly leads to a poor assessment of a graduate's practical abilities. Another important factor is how well the instructors deliver the engineering course lecture materials and assist learners in developing the skills to solve complex problems. Typically, project work is considered a vital tool in developing problem-solving skills. Nevertheless, it is very common for project work to involve simulation-based, limited work and to lack the real-life details of a practical working environment. It is very important to create an environment where students can become creative and solve complex problems by learning engineering skills. At the same time, the instructors should modify the current teaching method and incorporate relevant projects, tools, and/or technology to assist students. In a series of works (D. Jonassen et al., 2006; D. H. Jonassen, 1997; D. H. Jonassen & Hernandez-Serrano, 2002), the authors provided several guidelines for the facilitators to make successful complex problems for students. Briefly, the problem should be grounded in a well-defined conceptual framework, with no obvious solution and multiple possible solutions, so that students need to examine it thoroughly from multiple perspectives.

Outcome-Based Education (OBE) has been adopted by over 47 countries worldwide to produce engineering graduates capable of solving complex engineering problems. At the outset of adoption, OBE was promoted by the International Engineering Alliance (IEA) and mandated for the accreditation of engineering degree programmes. OBE can be described as a method of curriculum design, teaching, and learning that focuses on what students can actually achieve in terms of specified outcomes for individual student learning. One of the central foci of OBE is to emphasize the importance of complex engineering problems. This emphasis is put into operation through the definition of appropriate graduate attributes, which are then embedded in teaching and learning processes. OBE incorporates innovative teaching and learning practices, such as problem-based learning, oral presentations, capstone projects, professional talks, and industry attachments (Rajak et al., 2018). Although Outcome-based education (OBE) has been adopted internationally for three decades, Bangladesh has only recently actively embraced it to enhance the quality and relevance of engineering education. Despite challenges in implementing OBE in Bangladesh (Hassan, 2012), some universities in Bangladesh began practising OBE independently (Syeed et al., 2022). The University Grants Commission (UGC) of Bangladesh and the Bangladesh Accreditation Council (BAC) only began taking significant steps to implement the OBE curriculum in 2018. In March 2018, a committee of seven experts from diverse fields prepared OBE templates. The template for the OBE curriculum was prepared by the Strategic Planning and Quality Assurance (SPQA) division of UGC. It was sent to all the universities on June 30, 2021, and they submitted their revised OBE curriculum in 2022 (University Grants Commission of Bangladesh, 2020). The Bangladesh Accreditation Council Act was approved in 2017 (Bangladesh Accreditation Council, 2017), and accreditation rules were completed and published in 2022 (Bangladesh Accreditation Council, 2022).

Apart from the design factor in an OBE curriculum, another major factor is the assessment of OBE implementation and complex engineering problems. In the context of OBE, assessment must not only be accurate and measurable but also explicitly aligned with defined course outcomes (COs) and programme outcomes (POs). This distinguishes it from conventional assessment, which may focus primarily on content recall or isolated skills. Typically, the assessment methods are categorised into direct and indirect methods (Easa, 2013). Direct assessment includes a set of indicators to examine the student's knowledge or skills. These indicators typically include final examination, midterm examination, class test, viva voce (oral examination), class performance, presentation, and project. Assessment strategies in engineering education vary widely and can be broadly categorized into formative and summative approaches. Formative assessments include class tests, assignments, or presentations that provide ongoing feedback to guide student learning, while summative assessments, such as final examinations or project evaluations, measure overall achievement at the end of a course. Within both categories, marking key-based evaluations is widely used to ensure transparency and consistency. While key-based assessment provides a structured mechanism for evaluating problem-solving competencies, it is often complemented by assessment of outputs derived from pedagogical approaches such as case-based learning (CBL). Dewi & Rahayu (2023) found that CBL fosters critical thinking by immersing students in authentic problem-solving scenarios. However, in engineering education, structured marking keys remain the preferred tool for ensuring transparent and measurable competency assessments. Isa et al. (2021) presented an overview of the implementation of complex engineering problems (CEP) and complex engineering activities (CEA) in an engineering programme in Malaysia. They observed that most universities use assignments or projects to assess CEP and CEA. They also discovered that a lack of resources and training for educators is one of the challenges to successfully implementing outcome-based education in CEP and CEA (Isa et al., 2021). The importance of ongoing training and access to relevant learning materials for educators cannot be overstated. Although this article primarily aims to contribute to ongoing efforts to implement the OBE curriculum effectively in Bangladesh and to offer educators navigating this changing landscape of engineering education a guideline, it should also be helpful to educators worldwide in a dynamic system such as the OBE curriculum.

The current work is primarily concerned with the marking of key-based assessments of complex engineering problems. Key design for complex engineering problems is an ongoing process that has revealed various strengths and weaknesses. There are many benefits to key-based assessment, as it evaluates a particular project/assignment against multiple criteria, including the project's overall goals, expected outcomes, and opportunities for improvement. Therefore, rubrics can be highly helpful for scoring complex engineering problems using a standard assessment form. Previous research highlights the role of structured learning models in improving students' ability to analyse and synthesise engineering problems (Kasuga et al., 2022). By integrating key-based assessments, educators can systematically measure students' competencies in solving complex engineering problems while maintaining alignment with accreditation standards. Several studies provide an overview of the assessment of student and programme outcomes (Mohammad & Zaharim, 2012; Premalatha, 2019; Wahab et al., 2011). However, to the best of our knowledge, few studies provide designs for the keys to complex engineering problems. The authors in Ali et al. (2017) proposed a set of criteria to evaluate the outcomes of senior design projects at Old Dominion University. A total of 12 categories (such as design methodology, design quality, analysis, testing, etc) were assessed using four grades (unacceptable, marginal, acceptable, exceptional). The authors claimed that the assessment method has led to improvements in attaining the design goals. Another study (Bahsan et al., 2014) presented a marking key for assessing complex engineering problems in a thermal engineering course.

The study utilised 7 categories (such as application of engineering principles, integration of mathematical solutions, interpretation of results, and discussions) and a scale of 1 – 5 for assessment. Recently, a research group presented a simplified key for assessing a capstone project (Basir et al., 2019). The authors proposed using 18 categories (e.g., structural key plan, design using tools, communication skills, presentation), each assessed on a 5-10 scale. Several designs have demonstrated the potential for assessing complex engineering problems. Nevertheless, there is a need for a well-structured key that can be reliably used to assess complex engineering problems.

Research Objectives

The existing literature makes it clear that the significance of continuous training and the availability of appropriate learning resources for educators cannot be emphasized enough. One of the primary purposes of this study was to propose an approach to designing, implementing, and assessing students' performance through a group project on complex engineering problem-solving. Another primary objective was to prepare a marking key and then implement it in assessing the complex engineering problem-solving project. In alignment with the primary aim of this work to contribute to the ongoing efforts on effective implementation of OBE curriculum in Bangladesh, a course-level continual quality improvement (CQI) process - a cornerstone of OBE - is explored. A secondary purpose was to provide an elaborate linkage between complex engineering problem solving and outcome-based education in the context of real-world engineering challenges posed by IR 4.0. This analysis is helpful to the teaching community in developing OBE curriculum, as well as to researchers in the field of engineering and technical education. In order to meet these research objectives, we try to address the following research questions:

a. How can an effective and clear approach be developed for the design, implementation, and assessment of Complex Engineering Problem Solving within the OBE framework?

b. How can a well-structured and effective marking key be developed and implemented to reliably assess various aspects of complex engineering problem-solving, and calculate the Course Outcomes (COs) and corresponding Programme Outcomes (POs)?

c. How can a strong and meaningful linkage be established between complex engineering problem-solving and the principles of outcome-based education, emphasising real-world engineering challenges posed by Industrial Revolution 4.0?

d. Based on the OBE principle, how can a course-level continuous quality improvement (CQI) cycle be executed in order to continuously improve the quality of course contents and outcomes, teaching-learning activities, assessment tools, and students' attainments?

Methods

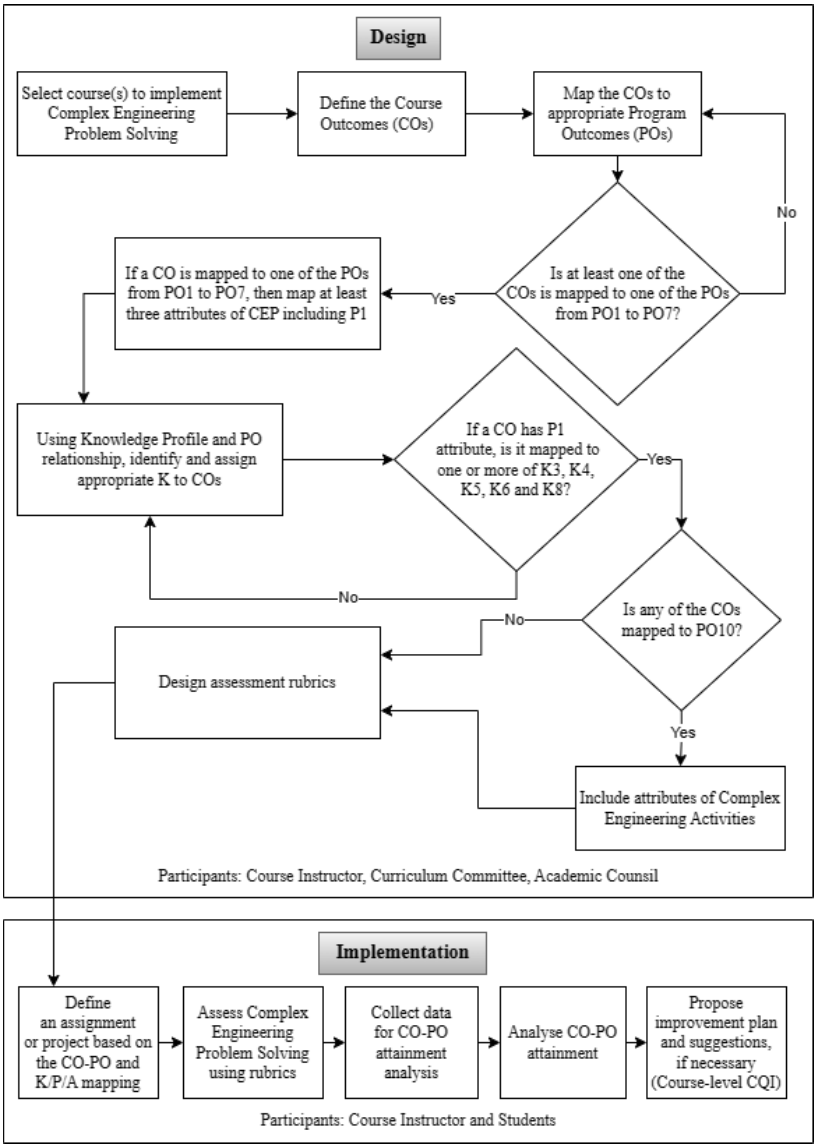
Research Design

This work primarily aims to demonstrate an effective approach to designing, implementing, and evaluating students' performance in group projects focused on Complex Engineering Problem Solving. With an emphasis on outcome-based education principles, the study also aims to establish a clear link between these principles and complex engineering problems. real-world engineering challenges. Based on OBE principles, this work also demonstrates how a course-level continuous quality improvement (CQI) cycle can be implemented to enhance teaching and learning quality.

In the dominating model, a set of core courses is selected to measure PO attainments. Among these courses, a few specific courses are chosen to implement complex engineering problem-solving. First, the COs of such a course are defined and mapped with appropriate POs. As discussed earlier, any CO mapped to one of the PO from PO1 to PO7 is assessed via Complex Engineer Problem Solving. If this criterion is not met, the CO-PO mapping must be revised to make necessary changes. A crucial element of implementing complex engineering problem-solving is ensuring that assessment strategies align with accreditation standards. In the next step, the appropriate Knowledge Profile is identified based on its relationship, as presented in Table 3. Including P1 as a mandatory attribute, a Complex Engineering Problem Solving must have at least three attributes from P1 to P7. The characteristic of P1 cannot be resolved without one or more of K3, K4, K5, K6, or K8. Therefore, if required, the CO-PO, Knowledge Profile, and Complex Engineering Problem attributes mapping are revised again. If any CO is mapped to PO10, then appropriate Complex Engineering Activities are included. Once all criteria are satisfied, the assessment rubric is finalized. The marking key should provide the instructor with benchmarks for marking and guide students to achieve better marks. In this work, the design of a sample assessment rubric is discussed in the results section and provided in full in the Appendix. A well-defined rubric not only provides benchmarks for assessment but also guides the formulation of problem statements and project design. The CO-PO attainments are recorded and analysed in the course-level continuous quality improvement (CQI) process.

Figure 2

Stages of designing and implementing complex engineering problem-solving



Participants

All three stages, i.e., design, implementation, and assessment of complex engineering problem solving, were carried out in the course of the Bachelor of Science (BSc) in Electrical and Electronic Engineering (EEE) programme at the University of Liberal Arts Bangladesh (ULAB), a private university, based in the city of Dhaka in Bangladesh. The course instructors were primarily responsible for creating appropriate course content, course outcomes (COs), mapping COs to programme outcomes (POs), designing teaching-learning activities, developing assessment tools, and preparing marking keys. All courses were then presented and discussed at the departmental curriculum committee meetings. Upon this committee's recommendation, the curriculum was placed before the Academic Council for approval. The course instructor followed the approved methodology presented in this work to design and implement a group project on complex engineering problem-solving. Forty-one undergraduate students, aged 18 to 25, were assessed using a well-defined marking key that included clearly articulated criteria, performance levels (poor to excellent), and weightings for the project's components to ensure transparency and consistency in grading. After analysing the CO-PO attainments, the course instructor is also developing quality improvement plans and making suggestions for the course.

A Case Study – EEE 3311: Microprocessor and Embedded Systems

To demonstrate the effectiveness of the methodology described in Figure 2, we applied it in EEE 3311 – Microprocessor and Embedded Systems. This is a core course offered to the third-year students of a 4-year undergraduate programme in the Department of Electrical and Electronic Engineering. The objective of this course is to study the architecture of computer systems, to understand the design and function of the various units, and interpret the instruction sets of digital computers. Another aim of this course is to prepare students with the competence to design and understand embedded systems. A summary of the course contents related to embedded systems is shown in Table 5 in the Appendix.

As presented in Table 6, there are a total of 6 COs in the EEE 3311 - Microprocessor and Embedded Systems course. It also shows the definitions of COs, their mapping to Programme Outcomes (POs), the knowledge profile (K), and the attributes of complex engineering problem-solving (P) and complex engineering activities (A).

Table 6

Course outcomes (COs) and their mapping with POs, K, P, and A, and Bloom's taxonomy domain and level

CO	Description	POs	K/P/A	Bloom's Taxonomy Domain/Level	Assessment Tools
CO1	Analyse the design specifications of a microcontroller-based embedded system.	PO2	K4/ P1, P3, P4	Cognitive/L4	
CO2	Identify the need for, and search for and find appropriate research literature relevant to the problem.	PO12		Cognitive/L2	
CO3	Develop a methodology outlining principles and a general procedure based on what information is known and what needs to be determined, with a relevant literature review.	PO4	K8/P1, P2, P6	Cognitive/L3	Group Project on Complex Engineering Problem
CO4	Design a microcontroller-based embedded system	PO3	K5/ P1, P2, P5	Cognitive/L6	
CO5	Implement the microcontroller-based embedded systems	PO5	K6/ P1, P2, P7	Psychomotor/L3	

CO6	Write a comprehensive report and orally present the key concepts and results of the embedded system you designed effectively.	PO10	A2, A3	Affective/L3

The COs are associated with levels 2 to 4 of the cognitive domain, and level 3 of the psychomotor and affective domains in Bloom's Taxonomy. Table 6 shows that CO1, CO2, CO3, CO4, CO5 and CO6 are mapped to PO2, PO12, PO4, PO3, PO5, and PO10 respectively. Since CO1, CO3, CO4, and CO5 are mapped to POs from PO1 to PO7, they are assessed through a CEPS project. The CO6, which is mapped to CO10, is assessed from CEA.

A detailed example of the complex engineering problem-solving project assigned to students, including the scope, problem statement, and tasks, is provided in the Appendix. This example illustrates how the CO–PO mapping and assessment keys were applied in practice. It also demonstrates how to establish a strong, meaningful linkage between complex engineering problem-solving and the principles of outcome-based education, emphasising the real-world engineering challenges posed by Industrial Revolution 4.0.

Data Collection and Analysis

Building on the mapping framework, data were collected using a single instrument: students' marks in the project on complex engineering problem solving. The students had 5 weeks to complete the project in groups of 4. While the project output was prepared collaboratively, the assessment was conducted at both the group and individual levels. Most marks were awarded at the group level, but a component of CO6 related to communication was assessed individually through oral presentation and viva voce. The marks obtained by each student are recorded and analysed. As shown in (1), a student's marks are divided by the total marks to determine the student's attainment.

$$marks\ in\ percentage = \frac{Obtained\ marks\ for\ a\ CO}{Total\ Marks\ for\ a\ CO} \times 100$$

The BSc in EEE programme at ULAB has set a benchmark of 55% in achieving a CO and corresponding PO. A course is considered successful in achieving its course outcomes (CO) if 60% of students attain each CO.

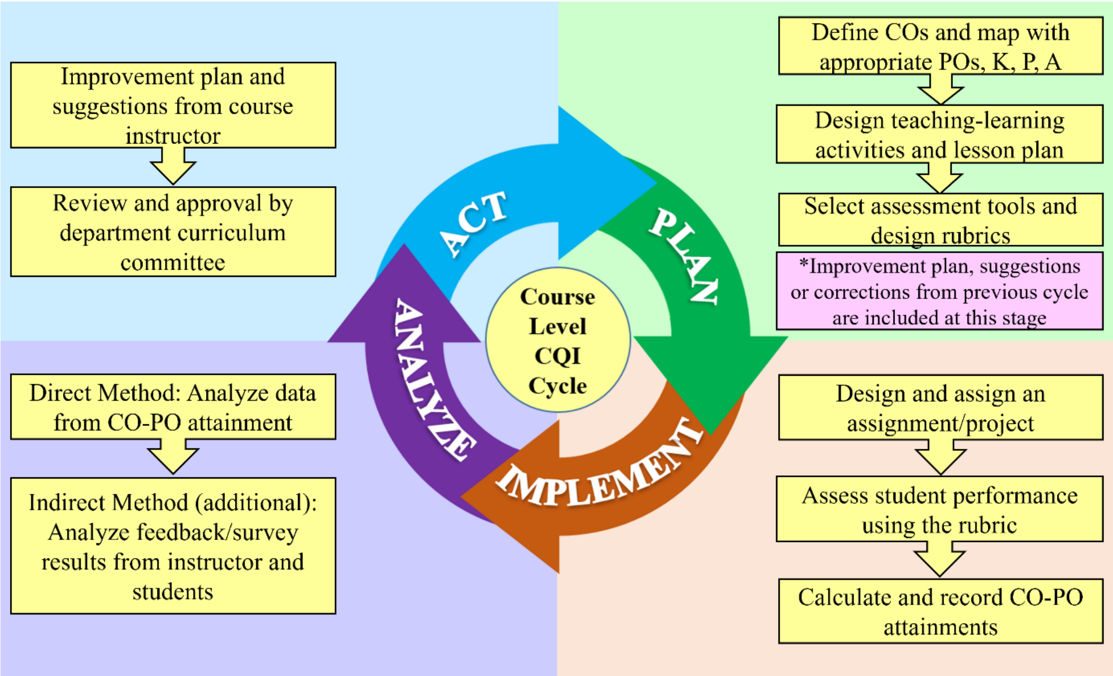
Course-level Continuous Quality Improvement (CQI) Process

Every OBE-based education system should have a continuous quality improvement (CQI) mechanism at three levels, i.e., PEOs, POs, and COs. In this work, we suggest a CQI cycle at the course level.

The CQI process at the course level should demonstrate an established system for collecting and analysing the attainment levels of COs and POs for each course at the end of each semester. The outcomes should be measured and analysed using both the direct and indirect methods. Once the shortcomings and limitations are identified, action should be taken, if necessary, to refine and improve the course contents and outcomes, CO-PO mapping, teaching-learning methods, and assessment tools. In the BSc in EEE programme at ULAB, direct methods, i.e., assignments or group projects on complex engineering problem-solving, are used to assess attainment of CO and the corresponding PO. The process has been depicted in Figure 3.

Figure 3

Course level continuous quality improvement (CQI) process



Results

The effectiveness of the proposed methodology, implemented in EEE 3311 – Microprocessor and Embedded Systems, was evaluated by analyzing student performance and attainment data. The results focus on the application of the assessment rubrics, the measurement of course outcome (CO) and programme outcome (PO) attainment, and the course-level continuous quality improvement (CQI) process.

Designing Assessment Keys

According to the BAETE manual, POs should be assessed using direct methods, which involve the direct examination or observation of students' knowledge or skills against measurable performance indicators or rubrics. In addition, indirect methods based on stakeholder opinions or self-reports may be used to assess PO. Therefore, assessing student performance is essential to the teaching and learning process and is a cornerstone of continuous quality improvement (CQI). The evaluation is done using an assessment form with well-defined rubrics based on the mapping of COs with POs, K, CEP, and CEA. Generally, marks, in conjunction with qualitative remarks, are used in assessment against a certain benchmark (Ali and Hui Natalie Chuang, 2017; Bahsan et al., 2014; Pejcinovic, 2020). The assessment rubrics are presented in Table 7 in the Appendix.

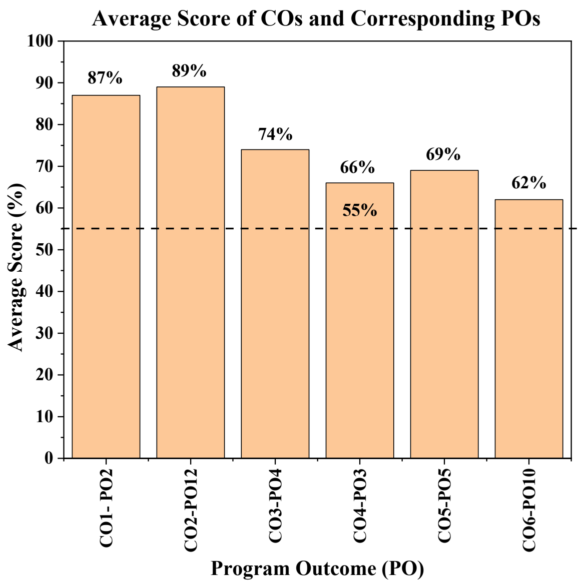
As shown in Table 7, each project criterion is rated on a scale of 1 to 4, with qualitative remarks of poor, satisfactory, good, and excellent, respectively. The marking key provides the benchmarks for each standard. In some cases, a criterion is divided into sub-criteria, and the mark is calculated using a weighted average. This form, with an assessment rubric, is explained to students and provided while assigning the group project, which accounts for 20% of the total marks in the course. The students are required to submit project reports and present their work. The students' performance regarding problem analysis (CO1-PO2), design/development of solutions (CO4-PO3), investigation (CO3-PO4), application of modern tools (CO5-PO5), and engagement in life-long learning (CO2-PO12), reflected in their ability to identify research needs and consult relevant literature, is evaluated via the report. The report also allows for assessing their written communication skills (CO6-PO10). During the presentation, viva voce (oral examination) is conducted to measure their oral communication skill (CO6-PO10).

Analysis of CO and PO Attainment

The attainments of COs by individual students are calculated using equation (1), and the attainments of corresponding POs are obtained subsequently. Fig. 4 shows the average marks obtained by the 41 students in each CO and the corresponding POs in the project, based on complex engineering problem-solving over one semester.

Figure 4

Average Score of COs and Corresponding POs



Course-level CQI Process

Once the attainment levels of the COs and POs in this course are calculated, the results are analysed at the end of the semester as part of an established course-level CQI cycle. Table 8 shows the percentage of students achieving Course Outcomes (COs).

Table 8

Percentage of students achieving course outcomes (COs)

Course Outcomes (CO)	Criteria for Achievement	Percentage of Students Attaining COs
CO1	60% of the students to achieve 55% of the allocated mark	90%
CO2		90%
CO3		78%
CO4		68%
CO5		68%
CO6		71%

Since at least 60% of the students in the semester found this course successful in achieving the course outcomes (CO), no improvement plan was necessary.

Discussion

The present study focuses on the design, implementation, and assessment of complex engineering problems for undergraduate engineering programmes. The findings from student attainment data suggest that the presented methodology can effectively contribute to shaping the outcome-based education (OBE) curricula in engineering and technical education.

One of the significant findings arises from mapping course outcomes (COs) with programme outcomes (POs), the knowledge profile, attributes of complex engineering problem-solving, complex engineering activities, and their attainment levels. Complex engineering problem-solving is associated with PO1-PO7, and COs to be assessed via complex engineering problem-solving should be mapped to one or more of these programme outcomes. The results show that all six COs reached the benchmark of at least 60% of students achieving ≥ 55% marks, with stronger performance in problem analysis (CO1, 90%) and lifelong learning skills (CO2, 90%), and lower attainment in design (CO4, 68%) and implementation (CO5, 68%). These differences indicate that, while students are generally effective at analysing problems and reviewing the literature, more support is needed in translating designs into functioning implementations. When any of the COs is mapped to PO10, the assessment should include complex engineering activities. In line with BAETE's framework, such activities involve a range of resources, including people, finance, information, and materials, and require understanding the interactions among technical, engineering, and other topics to solve the problem in novel ways while considering the consequences for society and the environment. In this study, these criteria served as guiding standards for assessment design. This aligns with a prior study by Liew et al. (2020), which highlights complex problem-solving as a necessary ability to address the evolving socio-technical challenges of the 21st century (WEF, 2020). Both studies highlight the need to properly map course outcomes to programme outcomes to design effective assessments and conclude that project-based teaching-learning approaches are most appropriate for addressing complex engineering problem-solving. However, the current research contributes a detailed, step-by-step methodology for individual courses, offering guidance on assessment rubric design and student attainment level analysis.

Another important contribution of this study is the design of an effective assessment rubric to measure students' performance in COs and POs. While rubric development represents a methodological contribution rather than an empirical finding, its application provided valuable evidence on student performance and attainment. The marking key provides the instructor with a benchmark for assessing student work and guidance for students to achieve better marks and improve their outcomes. Our study aligns with the findings of Lanziner & Strong (2016), who also discussed the development of rubrics for assessing engineering design, professional practice, and communication. Their emphasis on alignment with course outcomes (COs) and mapping to Canadian Engineering Accreditation Board (CEAB) graduate attributes resonates with our own research, as we also have carefully mapped our assessment to the standards set by the Bangladesh Accreditation and Evaluation Agency (BAETE, further ensuring the relevance and applicability of our methodology. This study is also in line with the work of Ayadat et al. (2020) as both studies emphasize the design, implementation, and assessment of complex engineering problems within the framework of OBE for undergraduate engineering programmes. In addition to an important similarity in the detailed methodologies for mapping COs to POs, both studies underline the importance of assessment rubrics in evaluating students' performance in solving complex engineering problems. While Ayadat et al. (2020) provide an institutional-level analysis within civil engineering, this study focuses on electrical and electronic engineering. By including a specific example—a project on designing an embedded system —this work offers a specialized perspective within this discipline. Other researchers and instructors can use the sample rubric presented in this study to reliably and effectively assess complex engineering problems.

At the course level, the outcomes should be measured and analysed each semester, and any shortcomings or limitations should be identified to refine and improve the course contents, teaching-learning methods, and assessment tools, if necessary, as part of the CQI process. The results of this study also point to areas for continuous quality improvement (CQI). Specifically, lower attainment in CO4 (design) and CO5 (implementation) suggests the need for additional instructional support in system design and for more opportunities to use tools hands-on in future iterations.

However, the study presented in this paper has several limitations that should be considered. Firstly, while the methodology presented in this paper can be applied to a range of engineering courses, it has only been verified in the context of the Microprocessor and Embedded System course in the Electrical and Electronic Engineering programme. Future studies should test the methodology presented in this paper across a range of engineering courses to validate its effectiveness further. Secondly, while measuring students' attainment of a CO and corresponding PO, a benchmark of 55% marks has been set as the achievement criterion. However, it can vary depending on the specific course and context. Therefore, further research is needed to explore the impact of varying the achievement criteria on the results obtained. Finally, the study has focused on a single cycle of the CQI process. The effectiveness of the methodology presented in this paper needs to be investigated over multiple cycles of the CQI process.

Despite these limitations, the major findings of this study indicate that the presented methodology can be beneficial to the teaching community in developing and implementing OBE curricula and researchers in the field of engineering and technical education. The study provides a comprehensive guide to designing, implementing, and assessing complex engineering problems in undergraduate engineering programmes. This can hopefully help produce engineering graduates with the necessary knowledge, skills, and attitudes to solve complex engineering problems in the era of Industrial Revolution 4.0.

Conclusions

This study presented a structured methodology for integrating CEPS into an undergraduate Electrical and Electronic Engineering programme. Using the BAETE framework for CO–PO mapping, knowledge profiles, and CEP/CEA attributes, the approach was applied in a Microprocessor and Embedded Systems course. A structured assessment rubric was developed and applied to measure attainment of COs and corresponding POs.

The assessment results showed that all six COs met the minimum attainment benchmark of 60% of students achieving ≥55% marks. Strong performance was observed in CO1 (problem analysis) and CO2 (lifelong learning/research skills), with 90% attainment in each. In contrast, CO4 (design) and CO5 (implementation/tool use) showed lower attainment at 68%. These findings demonstrate that while students are generally capable of analysing problems and reviewing literature effectively, they face challenges in translating designs into functioning implementations. Individual oral assessments complemented the group projects, ensuring that collaborative skills were assessed alongside individual accountability. This combination strengthened the validity of the rubric-based evaluation.

The CEPS project required students to carry out realistic design and implementation tasks, moving beyond theoretical exercises toward practical problem-solving. In doing so, the study showed how outcome-based education can be directly linked to real-world engineering challenges aligned with Industry 4.0 demands. This highlights the need to prepare students not only for analytical problem-solving but also for the technological, social, and environmental complexities of modern engineering practice.

Finally, by grounding CQI actions in empirical attainment data, this methodology provides a replicable model for other engineering programmes seeking to implement OBE requirements.

Conflicts of Interest

The authors declare no conflict of interest.

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Appendix

Table 1

Programme outcomes (POs) or graduate attributes

PO	Attribute	Description
PO1	Engineering Knowledge	Apply knowledge of mathematics, natural science, engineering fundamentals and an engineering specialization as specified in K1 to K4 respectively to the solution of complex engineering problems.
PO2	Problem Analysis	Identify, formulate, research literature & analyse complex engineering problems reaching substantiated conclusions using first principles of mathematics, natural sciences, and engineering sciences (K1 to K4)
PO3	Design / Development of Solutions	Design solutions for complex engineering problems and design systems, components, or processes with appropriate consideration for public health and safety, cultural, societal, and environmental considerations (K5)
PO4	Investigation	Conduct investigations of complex problems using research-based knowledge (K8) and research methods including design of experiments, analysis and interpretation of data, and synthesis of information to provide valid conclusions
PO5	Modern Tool Usage	Create, select, and apply appropriate techniques, resources, and modern engineering and IT tools including prediction and modelling to complex engineering problems, with an understanding of the limitations (K6)
PO6	The Engineer and Society	Apply reasoning informed by contextual knowledge to assess societal, health, safety, legal and cultural issues and the consequent responsibilities relevant to professional engineering practice and solutions to complex engineering problems (K7)
PO7	Environment and Sustainability	Understand and evaluate the sustainability and impact of professional engineering work in the solution of complex engineering problems in societal and environmental contexts. (K7)
PO8	Ethics	Apply ethical principles and commit to professional ethics and responsibilities and norms of engineering practice. (K7)
PO9	Individual and Teamwork	Function effectively as an individual, and as a member or leader in diverse teams and in multi-disciplinary settings
PO10	Communication	Communicate effectively on complex engineering activities with the engineering community and with society at large, including comprehending and writing effective reports and design documentation, making effective presentations, and giving and receiving clear instructions.

PO11	Project Management and Finance	Demonstrate knowledge and understanding of engineering management principles and economic decision making and apply these to one's own work, as a member and leader in a team, to manage projects and in multidisciplinary environments
PO12	Lifelong Learning	Recognize the need for and have the preparation and ability to engage in independent and lifelong learning in the broadest context of technological change.

Table 2

Attributes of complex engineering problem solving

P	Attribute	Description
P1	Depth of knowledge required	Cannot be resolved without in-depth engineering knowledge at the level of one or more of K3, K4, K5, K6 or K8 which allows a fundamentals-based, first principles analytical approach
P2	Range of conflicting requirements	Involve wide-ranging or conflicting technical, engineering, and other issues
P3	Depth of analysis required	Have no obvious solution and require abstract thinking, originality in analysis to formulate suitable models
P4	Familiarity of issues	Involve infrequently encountered issues
P5	Extent of applicable codes	Are outside problems encompassed by standards and codes of practice for professional engineering
P6	Extent of stakeholder involvement and conflicting requirements	Involve diverse groups of stakeholders with widely varying needs
P7	Interdependence	High level problems including many component parts or sub-problems

Table 3

Knowledge profile (K) and program outcome (PO) relationship

K	Attribute	Description	PO
K1	Natural Sciences	A systematic, theory-based understanding of the natural sciences applicable to the discipline	
K2	Mathematics	Conceptually based mathematics, numerical analysis, statistics and the formal aspects of computer and information science to support analysis and modelling applicable to the discipline	PO1, PO2
K3	Engineering Fundamentals	A systematic, theory-based formulation of engineering fundamentals required in the engineering discipline	
K4	Specialist Knowledge	Engineering specialist knowledge that provides theoretical frameworks and bodies of knowledge for the accepted practice areas in the engineering discipline; much is at the forefront of the discipline	
K5	Engineering Design	Knowledge that supports engineering design in a practice are	PO3
K6	Engineering Practice	Knowledge of engineering practice (technology) in the practice areas in the engineering discipline	PO5
K7	Comprehension	Comprehension of the role of engineering in society and identified issues in engineering practice in the discipline: ethics and the engineer's professional responsibility to public safety; the impacts of engineering activity; economic, social, cultural, environmental and sustainability	PO6 PO7 PO8
K8	Research Literature	Engagement with selected knowledge in the research literature of the discipline	PO4

Table 4

Range of complex engineering activities

A	Attribute	Description

A1	Range of resources	Involve the use of diverse resources (and for this purpose resources include people, money, equipment, materials, information and technologies)
A2	Level of interaction	Require resolution of significant problems arising from interactions between wide-ranging or conflicting technical, engineering, or other issues
A3	Innovation	Involve creative use of engineering principles and research-based knowledge in novel ways.
A4	Consequences for society and the environment	Have significant consequences in a range of contexts, characterized by the difficulty of prediction and mitigation
A5	Familiarity	Can extend beyond previous experiences by applying principles-based approaches

Table 5

Course contents related to embedded systems

Serial No.	Topics
1	Embedded Systems Descriptions: Characteristics, Terminologies, Technologies, Architecture, and Design Challenges
2	Embedded System Design and Development Lifecycle Model
3	Design Considerations in Embedded Systems: Specification/Requirements, Selection of Development Tools, Issues related to energy, cost, and power, Trade-offs
4	Interfacing with Embedded System Peripherals: Hardware and Software Requirements.
5	Designing Embedded Systems.

Table 6

Assessment keys for the group project on complex engineering problem solving in EEE 3311 – microprocessor and embedded systems

CO-PO	Remarks	Poor (1)	Satisfactory (2)	Good (3)	Excellent (4)
CO1-PO2: Analyse the design specifications of a microcontroller-based embedded system.	K4 (Engineering Specialisation) Understanding the design and development process of an embedded system by successfully analysing the design specifications and determining the requirements, and understanding the design challenges of optimizing various design metrics	No understanding of the problem statement.	The problem statement shows some understanding of the problem.	The problem statement shows almost full understanding of the problem.	The problem statement clearly shows a full understanding of the problem.
CO2-PO12: Identify the need for, and search for and find appropriate research literature in the context of the problem	Recognize the need for and have the preparation and ability to engage in independent and lifelong learning in the broadest context of technological change.	Little evidence of ability to identify the need for, and search and find appropriate research literature independently, and to discuss	Evidence of ability to sometimes identify the need for, and search and find appropriate research literature independently, and to discuss the results of 2 references in the	Evidence of ability to usually identify the need for, and search and find appropriate research literature independently, and to discuss the results of 3 references in the	Evidence of ability to always identify the need for, and search and find appropriate research literature independently, and to discuss the results of 4 references in the

		the results of 1 reference in the context of the project.	context of the project.	context of the project.	context of the project.
CO3-PO4: Develop a methodology outlining principles and a general procedure based on what information is known and what needs to be determined, with a relevant literature review	K8 (Research Literature), P1 (Depth of Knowledge),, P2 (Conflicting Requirements), P6 (Extent of stakeholders) Background Study – 30%	No or very little Information with a relevant literature review.	To some extent, states what information is known and what needs to be determined, with a relevant literature review.	Mostly states what information is known and what needs to be determined with the literature review.	Clearly and completely states that the reported information is known, with a relevant literature review.
	Methodology – 35%	No methodology, instead, tries things out unsystematicall y.	Describes the methodology by outlining principles and a general procedure, but with errors in the principles or procedure.	Describes the methodology with a clear presentation of correct principles and procedure, but with some minor errors in the equations.	Describes the methodology with a clear presentation of correct principles, procedure, and equations.
	Analysing and Interpreting Results – 35%	No correct conclusion can be reached by analyzing and interpreting results.	Some correct conclusions can be drawn by analysing and interpreting results.	Mostly correct conclusions by analysing and interpreting results.	Fully correct conclusions by analysing and interpreting results.
CO4-PO3: Design a microcontroller-based embedded system	K5 (Engineering Design) Design – 40% Consideration of Social and Environmental Issues – 20% (if applicable*) Final Solution / Implementation – 40% *Otherwise, 50% each	Design done with mistakes. Design has no consideration for relevant public health and safety, cultural, societal, and environmental considerations. The final solution is incorrect or not provided.	Design done without mistakes, but no design/detailing sketches. Design considers relevant public health and safety, as well as cultural, societal, and environmental factors. The final solution is not correct. Major corrections are required.	Design done without mistakes and unclear sketches/ drawings. Design considers most public health and safety, cultural, societal, and environmental considerations. The final solution would be correct if the minor errors were corrected.	Design done without mistakes and complete sketches or drawings. Design considers all relevant public health and safety, cultural, societal, and environmental considerations. Final solution is correct. No errors or some very minor calculation errors.
	P1 (Depth of Knowledge), P2 (Conflicting Requirements), P5 (Extent of applicable codes) Compare the conflicting technical, engineering, and other issues arising to solve the problem. – 50% Assess the conflicting requirements and	Considers only 1 issue and provides a satisfactory solution to the problem.	Compare 2 issues with acceptable discussion. Assess 2 conflicting requirements and provide a satisfactory solution to the problem.	Compare 3 issues with good discussion. Assess 3 conflicting requirements and provide a satisfactory solution to the problem.	Compare 3 or more issues with excellent discussion. Assess 3 conflicting requirements and provide an optimum solution to the problem.

	propose a satisfactory solution to the problem. – 50%				
CO5-PO5: Implement the microcontroller-based embedded systems	K6 (Engineering Practice), P1 (Depth of Knowledge), P2 (Conflicting Requirements), P7 (Interdependence) Selection – 10% Expertise – 60% Analyzing Results – 30%	Little evidence of ability to select and use appropriate tools, techniques, and skills to effectively solve problems or design systems, and draw correct conclusions of results gained from the tool.	Evidence of the ability to sometimes select and use appropriate tools, techniques, and skills to effectively solve problems or design systems, and draw correct conclusions of results gained from the tool.	Evidence of ability to usually select and use appropriate tools, techniques, and skills to effectively solve problems or design systems, and draw correct conclusions of results gained from the tool.	Evidence of ability to always select and use appropriate tools, techniques, and skills to effectively solve problems or design systems, and draw correct conclusions of results gained from the tool.
	Design and integration of several interdependent sub-systems	Can design only one sub-system is partially	Can design more than one sub-system completely, but there is no integration.	Can design all subsystems completely; however, integration is incomplete.	Can design all subsystems completely and successfully integrate them.
CO6-PO10: Write a comprehensive report and orally present the key concepts and results of the designed embedded system effectively	Organization, Formatting, Errors, and Effectively Comprehend and Write / Present	Poor organization and formatting, and contains errors. Cannot communicate key concepts.	Some organization: proper formatting and relatively error-free. Communicates the key concepts to some extent.	Well organized, properly formatted, and error-free. Mostly communicates the key concepts.	Well organized, properly formatted, and error-free. Communicates the key concepts effectively.
	A2 (Level of interactions) (Related to P2) Gives solutions to significant problems arising from interactions between wide-ranging or conflicting technical, engineering, or other issues; and justifies the solutions achieved arising from the level of interactions involving wide-ranging or conflicting technical, engineering, or other issues.	Considers 1 issue, gives a solution, and justifies	Considers 2 issues. Gives solutions considering 2 issues, and justifies the solutions	Considers 3 issues. Gives solutions to significant problems arising from interactions between 3 issues, and justifies the solutions satisfactorily	Considers 3 or more issues. Gives solutions to significant problems arising from interactions between 3 issues, and justifies the solutions excellently
	A3 (Innovation) Involves creative use of engineering principles and research-based knowledge in novel ways. Justify creativity	Improves one feature with creative use of engineering principles and justifies with research-based knowledge	Improves two or more features with creative use of engineering principles and justifies with research-based knowledge	Introduces one new feature or improves three or more features with creative use of engineering principles, and justifies the	Introduces one or more new features using engineering principles and justifies the creative principle used with research-based

towards the achievement of novelty		creative principle used with research-based knowledge	knowledge

An Example Project on Complex Engineering Problem Solving

In this section, we look at an example in which students were assigned a Complex Engineering Problem-Solving task focused on designing an embedded system. The students had 5 weeks to complete the project in groups of up to 4 students.

Scope of the Project

In this project, students have the opportunity to design and implement an embedded system to address local issues, including but not limited to farming, aquaculture, and energy, while considering relevant environmental and social impacts. In the group project, the students analyse the design specifications, review the published literature, and propose their own methodology to develop the solution, and finally implement and verify their system by analysing the results. In addition, the students address trade-offs to optimize the system for energy, cost, size, and power, which often have conflicting requirements. The students also demonstrate their written and oral communication skills through reports and presentations.

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Problem Statement

The world population is estimated to reach 9.6 billion by 2050. In addition, urbanization, declining water supply, and ongoing climate change due to global warming have reduced the amount of land available for agriculture. As a result, there is a growing need to modify agricultural practices and adopt technologies to maximize crop yields and reduce labor requirements. Moreover, technologies are expected not only to improve productivity but also to protect the environment through sustainable cultivation. Urban smart vertical farming is the practice of planting plants in vertically stacked layers to optimize land use and enable implementation in indoor environments. The main idea of vertical farming is to use a sensor-based monitoring and control system that allows all environmental factors, such as temperature, humidity, light intensity, soil moisture, pH, and CO2 concentration, to be controlled for optimal plant growth.

Tasks	Course Outcome	Corresponding PO/K/P/A
Analyze the specifications and identify the various elements of the monitoring and control system.	CO1	PO2 / K4 / P1, P3, P4
Identify the need for, and search for and find appropriate research literature.	CO2	PO12
Develop a methodology grounded in embedded system design and development principles, supported by a relevant literature review.	CO3	PO4 / K8 / P1, P2, P6
Design a microcontroller-based embedded system to monitor and control the important parameters for urban smart vertical farming in real time.	CO4	PO3 / K5 / P1, P2, P5
Implement the designed system using appropriate tools and components	CO5	PO5 / K6 / P1, P2, P7
Write a comprehensive report describing the key concepts, literature review, methodology, procedure, and results.	CO6	PO10 / A2, A3

To address the challenges of modern agriculture, the following criteria should also be taken into consideration:

Cost: Farmers will be more likely to adopt the system if it is inexpensive. Therefore, the design must be low-cost to make it accessible to farmers, especially those in developing countries.

Simplicity: The design should be user-friendly and require minimal human input. This will reduce the need for specialized knowledge or training, making it easier for farmers to adopt the technology.

Renewable Energy: The design should use renewable energy. This is crucial to ensure that the system is sustainable and has a minimal environmental impact.

Durability: The design should also be durable to ensure the system withstands harsh environmental conditions and continues to operate effectively over an extended period.

Energy Efficient: The design should be energy efficient. This is important to ensure the system operates with minimal energy consumption, reducing overall environmental impact and ensuring it is cost-effective to operate.

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STEAM-5E: A new methodological approach to STEAM based on a critical literature review

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ABSTRACT
Educational institutions and organisations around the world recognise the STEM (Science, Technology, Engineering and Mathematics) and STEAM (A for Arts) paradigms as appropriate frameworks for achieving the key competences needed for the 21st century. However, there are ongoing debates within them and different methodologies to address these debates. First, this work aims to analyse these debates and the diversity of methodologies proposed through a narrative review of the literature following a qualitative content analysis methodology. Secondly, a new framework, STEAM-5E, is proposed to address this complexity. Its basic pillars are the 5E methodology, the integration of STEAM disciplines broadly, the development of creativity across its multiple facets, special consideration for equity, and the search for learner motivation through inquiry, manipulative activities, and collaborative work. Metacognitive and dialogic processes mediate all learning. Collaboration between researchers and teachers is particularly relevant, according to the basic principles of Design-Based Research, to develop classroom materials adapted to their real context. Several tools are included for implementation evaluation and assessment. Finally, a STEAM-5E project designed for upper primary education (9-11 years old) is presented, along with evidence of its validity and effectiveness. This model could serve as a guide for teachers and researchers in creating and evaluating new STEAM projects.

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Introduction

The STEM (Science, Technology, Engineering, and Mathematics) movement emerged in the early 1990s but gained significant momentum at the beginning of the 21st century. From a research perspective, numerous studies indicate a substantial increase in publications on STEM education in recent years, with a focus on goals, policies, curricula, evaluation, and assessment (Li et al., 2020).

Despite this growth, the National Academy of Sciences in the United States warned as early as 2014 that it is common to find inconsistent language, a lack of term definition, and, as a result, a theoretical framework that makes STEM education difficult to understand (NAS, 2014). In this regard, many studies have since highlighted the broad conceptual challenges within the STEM movement (Kelley & Knowles, 2016; Akerson et al., 2018; Toma & García-Carmona, 2021), which is not surprising given the field's complexity and the diverse objectives it seeks to achieve. For example, in a systematic review, Martín-Páez et al. (2018) found that 55% of the selected studies failed to provide a clear definition of STEM, and most did not incorporate such definitions into their theoretical frameworks. Additionally, Thibaut et al. (2018) reported that in another systematic review, less than one-third of the analysed studies referenced an underlying learning theory to support their instructional practices.

More recent systematic reviews indicate that varying perspectives on STEM integration persist, as well as differing views on the relative importance of each discipline within STEM education (Larkin & Lowrie, 2023; Wan et al., 2023). This epistemological debate extends to the question of whether there truly exists a "Nature of STEM" (NoSTEM). This discussion is examined by Aguilera et al. (2024), who argue that while most scholars recognize that STEM is not a single discipline and that a distinct NoSTEM does not exist, opinions on the issue differ. Some argue that STEM has a practical expression underlying its transdisciplinary integration, whereas others believe it emerges from the interaction of the individual disciplinary natures (NoS, NoT, NoE, and NoM).

The landscape becomes even more complex with the incorporation of the arts (represented by the "A") in the emerging STEAM movement. This shift was particularly fostered after the National Science Foundation organised a 2007 symposium on the relationship between the arts, STEM learning, and workforce development in the United States (Colucci-Gray et al., 2017). Over the past decade, the STEAM movement has attracted increasing interest in both educational research and practice (Khine & Areepattamannil, 2019) and has expanded globally (Belbase et al., 2021). However, the challenges previously identified in STEM education persist within STEAM. Marín-Marín et al. (2021) highlight that there is still a lack of sustained, robust research in this field, further complicating its theoretical and practical development.

The challenges are not solely conceptual and epistemological. Recent reviews indicate a wide variety of methodologies used to implement STEM/STEAM in classroom practice (Nugraha et al., 2024), though there remains some obscurity about how these approaches translate theoretical principles into practical applications (Portillo-Blanco, 2024). In addition, some systematic reviews have found that direct instruction remains the most commonly employed methodology, at least at the primary education level (Larkin & Lowrie, 2023).

In response to these challenges, some researchers have sought to identify the defining elements of STEM education. For instance, following a systematic review, Portillo-Blanco et al. (2024) conclude that there is broad consensus on key principles, including integration, real-world problems, inquiry, design, and teamwork. Other researchers have developed conceptual frameworks to provide both epistemological and practical support for the STEM approach. Aguilera et al. (2024) propose a model grounded in situated learning and co-teaching as its core pillars. Nugraha et al. (2024) stress integration, the use of multiple representations, engagement with realistic and relevant problems, application of the engineering design process, active collaboration, and student-centred learning approaches in their framework. Similarly, Ortiz-Revilla et al. (2022) develop a comprehensive model of integrated STEM education, structured around epistemological, psychological, and didactic dimensions. ElSayary (2021) proposes a model linking the design of a transdisciplinary STEAM curriculum to the implementation of authentic assessment. These more comprehensive and integrative proposals address the STEM approach, but only a few include concrete classroom implementation examples. Consequently, there is a clear need to expand the discussion to encompass a broader perspective—one that considers the STEAM approach and incorporates aspects that are not sufficiently addressed in existing conceptual frameworks, such as assessment and the evaluation of the validity of projects designed under these approaches.

This study conducts a narrative literature review using a content analysis methodology, aiming to shed light not only on the complex landscape of STEM and STEAM education but also on their essential components. Not only are the most common methodologies identified, but their principles and benefits are also discussed within the STEM/STEAM framework—an aspect absent in other reviews. Furthermore, they are categorised based on their epistemological origins. The ultimate goal is to design a methodological framework, called STEAM-5E, that brings coherence to the STEAM approach, addressing its practical challenges by establishing a clear connection between conceptual and epistemological foundations and their application in educational practice. The work includes assessment tools and questionnaires designed to gather feedback from both students and teachers, ensuring alignment with the proposed framework. Finally, the study illustrates the framework with a project designed for primary education and cites its effectiveness. Specifically, this paper addresses the following research questions:

1. What aspects are under debate within the STEM and STEAM communities?
2. What are the strengths and commonalities of the diverse existing methodologies?
3. How can this complexity be addressed from a methodological point of view?

To answer these questions, three research objectives are proposed:

O1. Summarise and categorise the diversity of open debates in STEM and STEAM education.

O2. Analyse and classify the variety of methodologies proposed.

O3. Develop a new, methodologically and theoretically well-supported framework for STEAM education, along with appropriate tools for its evaluation.

This model could serve as a guide for teachers and researchers in creating and evaluating new STEAM projects.

Method

We carried out a qualitative, narrative, and intentional literature review. The narrative review approach is particularly useful for exploratory reviews that seek to synthesize ideas with a broad focus (Sovacool et al., 2018). The analytical process is illustrated in Figure 1 and aligns with the qualitative content analysis approach (QCA), which is typically structured around four phases (Kleinheksel et al., 2020): identify, code, group, and describe.

The identification phase begins with data collection via searches of the WOS and SCOPUS databases. The search utilises keywords aligned with the research objectives: "education", "learning", "teaching", "approach", "framework", "methodology", or "review", combined with "STEM" or "STEAM." Figure 1 includes the inclusion and exclusion criteria applied in the selection process. The selection includes papers written in English and Spanish, as these are the two predominant languages in STEAM literature, with English being the most widely used (Marín-Marín et al., 2021), as is also the case for STEM research. References to books by highly relevant authors in the field were repeatedly cited in the selected articles. Therefore, it was decided to include these books in the selection process on an exceptional basis.

Following this, an initial evaluation of the articles is performed, excluding those with low epistemological or methodological quality and selecting studies based on relevance criteria, such as the number of citations and the relevance of the journals or the authors in the field. This evaluation is carried out independently by multiple authors and subsequently refined through consensus.

The coding phase is based on thematic notes, where ideas are organised through an inductive coding process. In the grouping phase, codes are clustered, allowing categories and sub-categories to emerge. This process was conducted collaboratively by the authors, through consensus, to enhance comprehension and define codes based on agreed-upon decisions. This inductive approach aligns with a conventional QCA.

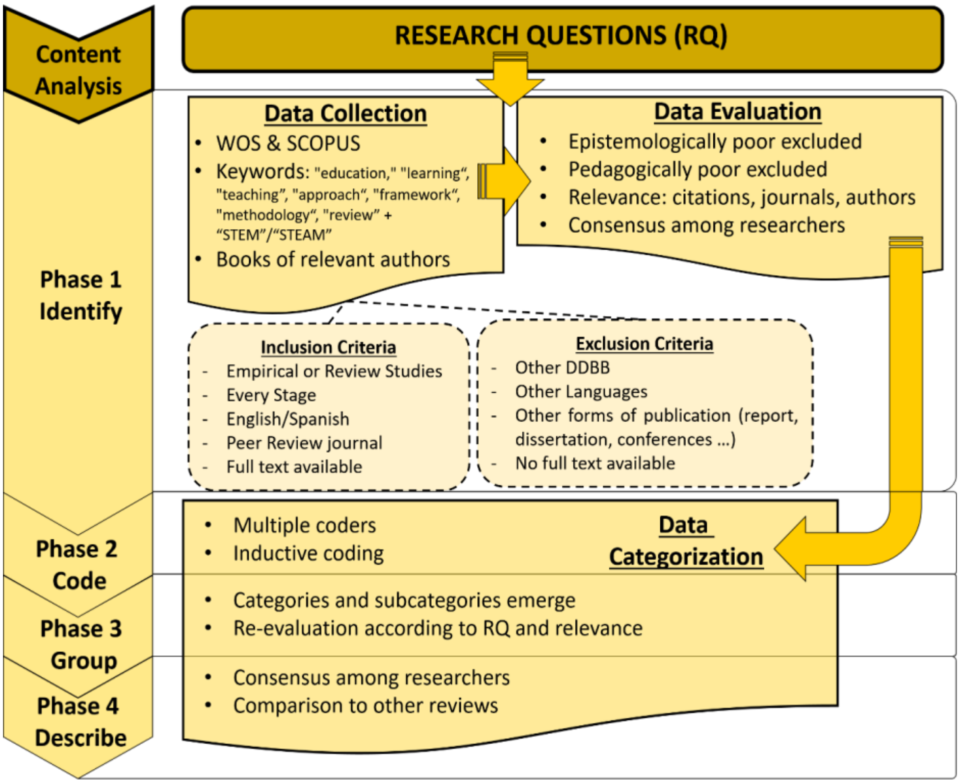
Finally, in the description phase, categories and sub-categories are reorganised based on their relevance and their connection to the research questions. They were also analysed alongside other systematic reviews on the topic to validate the final categorisation. These final steps constitute a more deductive classification and ordering process characteristic of directed QCA. The combination of both inductive and deductive processes is common in QCA (Kleinheksel et al., 2020).

The credibility of the results is ensured by selecting the most relevant databases and applying quality and relevance criteria in article selection. Reliability is achieved through a multi-step review process involving multiple authors, with consensus enhancing consistency. This approach also aims to reduce author bias, a common critique of narrative reviews (Sovacool et al., 2018). Although this study does not seek to conduct a systematic review, a degree of generalisability is achieved in the analysis categories by comparing the final selection with other existing reviews.

According to the last objective of the study, the new methodological approach presented in this work, called STEAM-5E, arose from meetings and discussions between the authors on the aforementioned topics. They were looking for a model that considers the most relevant elements found in the previous review and allows for addressing the problems encountered in a realistic and well-founded manner.

Figure 1

Flowchart of the narrative review process following the content analysis approach



Results

The results are presented below, organised in sub-sections according to the three objectives of the research.

Complexity in STEM and STEAM

The literature review identified five fundamental categories of topics under debate within the community of STEM/STEAM researchers and educators, along with their subcategories, summarised in Table 1 and presented in more detail below.

Table 1

Categories of topics under debate in STEM and STEAM education

Conceptualisation	STEM construct Definition and understanding of technology Definition and understanding of engineering Distinction between technology and engineering STEAM construct Role of the arts Consider various artistic manifestations. Inclusion of the humanities
Disciplinary Integration	Number of disciplines to be considered: STEM/STEAM Multi, inter, or transdisciplinary integration
Creativity	Diversity of conceptions and models Adaptation and concreteness in STEM/STEAM Implementation, measurement, and assessment
Equity	The role of STEM/STEAM in challenging inequalities The characteristics STEM/STEAM must have to effectively reduce the gender gap.
Difficulties of application	Teachers' knowledge and pedagogical content knowledge of STEAM disciplines Lack of support for the teachers Schedule and spaces Tested and valid materials, realistically connected with the curriculum Assessment Diversity of methodologies Evaluation of the application

Conceptualization

A general definition of STEM Pedagogy is given by Leung (2020, p.5): "STEM pedagogy is about situated contextual teaching and learning where participants from educational Communities of Practice (e.g., teachers, learners) socially co-construct solutions and knowledge for addressing relevant real-world problems through boundary crossing dialogical and problem-solving processes that involve more than one STEM discipline". Different projects developed within the STEM framework share this vision of situated learning (Aguilera et al., 2024), grounded in students' active participation in solving real problems (Portillo-Blanco et al., 2024), and a common integrated vision of science. However, each emphasises different aspects, and not all emphasise communities of practice.

On the other hand, a lack of an unequivocal conceptualization in STEM (Kelley & Knowles, 2016) and an epistemological foundation (Akerson et al., 2018) have been highlighted. For example, the idea of bringing science and mathematics education together dates back to the 1970s, and the science-technology-society education movement, which began in the same decade, already proposed integrating science and technology (Toma & García-Carmona, 2021). On the other hand, the concept of technology itself and its differentiation from engineering is complex (Cavanagh & Trotter, 2008), and it varies across different countries (Yata et al., 2020), often being approached only through the inclusion of ICTs (Information and Communication Technology) and through robotics and programming activities. Other authors suggest that engineering and technology are so closely related that they should be taught together (Barak, 2013).

The challenges increase as STEAM emerges. The construct of STEAM education itself has also been conceptualised in different ways: as a movement seeking innovative pedagogical experiences, as integrative classroom practices, as an integrated teaching approach, or as a complete educational model (Bautista, 2021). The inclusion of the 'A' alludes in principle to the Arts to highlight the importance of creativity in learners' development and learning (Perignat & Katz-Buonincontro, 2019). However, the role of the arts in the STEAM movement has been described from several perspectives (Lage-Gómez & Ros, 2021): as a disciplinary value; as a contribution to the teaching and learning processes of STEM areas fostering motivation; as a tool for the development of creativity, innovation, and invention; or as an instrument for narrowing the gender gap that exists in scientific-technological careers. In addition, visual and plastic arts, as well as music, are usually included in STEAM. However, other authors consider the arts in a broader sense, encompassing aesthetics and artistic design, as well as graphic design and performing arts (dance, theatre, film). Moreover, an extensive interpretation of the STEAM acronym has been encouraged to include the humanities and promote comprehensive knowledge (Ge et al., 2015), thereby demonstrating a more complex approach to creativity (Lage-Gómez & Ros, 2024).

Disciplinary Integration

There is no agreement on how many disciplines should be included to consider a project or activity to be truly STEM or STEAM. In fact, Roehrig et al. (2021) state that initially, STEM was concerned only with integrating the science and mathematics disciplines, and it was not until the inclusion of engineering concepts and practices in the US national science standards around 2012 that this integration began to expand. Several STEM curriculum models define STEM as primarily focused on a single subject, while others define it as encompassing two or more disciplines. These diverse conceptions are also found in surveys of teachers from different countries (Ritz & Fan, 2015). Moore et al. (2014) defined STEM education as "an effort to combine some or all of the four disciplines of science, technology, engineering, and mathematics into one class, unit, or lesson that is based on connections between the subjects and real-world problems" (p. 38). Moreover, a recent systematic review of STEM publications shows that more than 17% focus on a single subject area, although most consider all four areas (Li et al., 2020).

In addition, there is no agreement on the best method of integrating the different disciplines (Martín-Páez et al., 2018; Thibaut et al., 2018). In their review of 60 articles published between 2020 and 2022, Larkin & Lowrie (2023) analyse the level of integration in STEM/STEAM education. Many studies approach integration superficially, either through disciplinary projects (where only a single subject is truly involved) or multidisciplinary projects (where a problem is examined from multiple perspectives but without actual integration). As a result, fewer than 10% achieve high levels of integration. These high levels could be classified as: "Integrated STEM", in which various STEM disciplines are combined, either by emphasising one over the others (Sanders, 2015) or by treating them as a cohesive entity (Kelley & Knowles, 2016) (this approach extends to "Integrated STEAM" with the inclusion of A (Quigley & Herro, 2016)); interdisciplinary, which refers to the ability to tackle complex problems by integrating tools and theories from multiple disciplines, actively seeking connections between them; and transdisciplinary, where disciplinary boundaries dissolve, allowing for a holistic approach to problem-solving.

STEAM researchers usually advocate for transdisciplinary approaches (Costantino, 2018), for example, by using the concept of Big Ideas to develop their projects (Lage-Gómez & Ros, 2021). In any case, greater consideration of the pedagogical and curricular implications of a trans/interdisciplinary approach is recommended (Colucci-Gray et al., 2017).

Creativity

The inclusion of creativity is a key aspect of development and learning, and it is understood as essential for advancement and innovation (Perignat & Katz-Buonincontro, 2019). A thorough revision of the approach to creativity in education has been underway since the beginning of the 21st century (Hernández-Torrano & Ibrayeva, 2020). Several models with different dimensions have been proposed, as well as adaptations to the field of education (Glaveanu & Beghetto, 2020; Craft, 2001). Beyond its conception, the measurement and evaluation of creativity are also complex issues.

A systematic review conducted over the decade 2010-2020 on creativity in STEM and STEAM (Aguilera & Ortiz-Revilla, 2021) found that: the interventions have contradictory forms, both in theory and practice; that there is diversity in the measurement tools used; and that while STEM focuses more on the products created by learners, STEAM interventions pay greater attention to the context and the learning process, as well as the development of personal creativity. In relation to STEAM specifically, another systematic review found that the theme of "creativity" is a common thread in research on STEAM Education (Marín-Marín et al., 2021). Several studies show that the inclusion of the arts fosters creativity and self-efficacy, generating positive emotions and innovation (Conradty et al., 2020; Allina, 2018). Others highlight the positive interaction between creativity, motivation, and transdisciplinary integration (Lage-Gómez & Ros, 2023).

Equity and Vocations

From its inception, STEM education has been seen as an opportunity to encourage all students to be more engaged in their scientific and technological learning while also fostering interest in these fields. The concept of STEAM was introduced to better include girls, given their generally positive attitudes towards the arts. Girls tend to enjoy art more, exhibit greater confidence in their artistic abilities, and place greater value on art than boys (Pavlou & Kambouri, 2007). STEAM aims to address the well-documented decline in interest in science, particularly among girls and members of non-dominant cultures, during the middle school years (Baram-Tsabari & Yarden, 2011). Various recommendations have been made to promote equity within STEAM, such as fostering community engagement in STEAM learning environments, prioritising inclusive mentorship, integrating identity into maker pedagogies, advocating for the development of multi-institutional networks, and prioritising assessment plans that capture complexities, among others (Castek et al., 2019). As an example, Palid et al. (2023) show that interventions that focus on the successes of minoritised students represent a promising step towards diversity, equity, and inclusion in STEM. Although a systematic review found that gender equity and related topics are key drivers and themes in STEAM research (Marín-Marín et al., 2021), the role STEM/STEAM should play in addressing inequalities remains open to discussion. In addition, special attention is demanded not only when considering gender but also other minorities (Bruijnzeel et al., 2022).

Difficulties of Application

STEM and STEAM instruction in actual classrooms is still quite rare. After a systematic literature review, Margot & Kettler (2019) found that teachers reported barriers including pedagogical, curricular, and structural challenges, as well as a lack of teacher support. Furthermore, difficulties exist in selecting appropriate topics, developing educational materials (Hong, 2017), and assessing learning across multiple processes, instruments, and agents (Portillo-Blanco et al., 2024). Finally, there is a lack of knowledge about the content itself, about the pedagogical content knowledge related to it, and the competencies about the different disciplines that make up STEAM (Toma & Greca, 2018). These difficulties also appear in the meta-analysis by Wan et al. (2023). Additionally, there is a wide variety of methodological strategies for implementation (see the next section), many of which are not well known to teachers, who acknowledge having limited procedural knowledge (Haddad et al., 2022).

STEM education is on the educational agenda in many countries, but little action has been taken to appropriately modify educational systems (Ritz & Fan, 2015). In other countries, there is no national effort to implement STEM/STEAM. Instead, there are various programmes at the regional level or initiatives led by researchers, individual schools, or teachers. Consequently, the appropriateness and validity of many resources and materials labelled as STEM or STEAM are questionable, particularly at the pre- and school stages, where engineering, technology, and design are easily misunderstood and misrepresented (Bagiati et al., 2015). Furthermore, these STEAM activities are not usually well connected to curricular content, so they are often seen as extracurricular, and their assessment is of little relevance to teachers and students.

STEM and STEAM Methodologies

There are many methodological approaches for STEM, as already noted in the literature (NAS, 2014; Thibaut et al., 2018; Larkin & Lowrie, 2023; Portillo-Blanco et al., 2024). In addition, we found that the projects published under the STEAM framework are diverse and adopt different methodologies too. To better understand this complex reality, a classification is presented in Table 2 according to the pedagogical tradition from which they originate: science education, technology and engineering education, arts education, and others. A brief description, along with its strengths and benefits for STEM/STEAM projects, is included. The "Others" section includes additional methodologies considered relevant and/or proposed for more specific purposes, without aiming to be exhaustive.

As can be observed, no section on methodologies in mathematics education is included. Other studies already indicate that mathematics is less often considered within STEM and is sometimes used merely as a tool (Portillo-Blanco et al., 2024; Forde et al., 2023; Jumini et al., 2022). Few studies choose mathematics as the "backbone" of their projects (Martín-Páez et al., 2018) or as the axis of their methodological approach (Marín- Marín et al., 2021).

Table 2

Categorization of methodologies in STEM/STEAM education

	Description	Strengths
Methodologies from Science Education		
Inquiry and the 5E Instructional Model for STEM (Bybee, 2019; Leung, 2020; Conradty & Bogner, 2019; Bush, Cook et al., 2016; Toma & Greca, 2018)	The inquiry focuses on developing scientific research processes in the classroom, with an emphasis on promoting conceptual change. 5E has 5 phases with specific functions: engage-(preconceptions and motivation), explore (manipulation and inquiry), explain (new concepts and guided learning), elaborate (extend to a new challenge), and evaluate.	• One of the most widely used methodologies in Science Education • Strong support that enhances mastery of the subject and scientific reasoning, even long-term benefits on conceptual knowledge. Also fosters interest in science • Already adapted to STEM projects
Project-Based Learning (Capraro et al., 2013; Tseng et al., 2013; Lu et al., 2021; Han et al., 2015).	Learners construct knowledge through teamwork and problem-solving using scientific methods within a constructivist framework, creating a creative artefact.	• Widespread in Science and Engineering Education. In fact, it facilitates the connection between the two disciplines • Connected to real-world problems fosters positive attitudes to Science and Technology • Probably the most common methodology in STEM • Benefits for low-performing pupils.
Methodologies from Technology and Engineering Education		
Design Thinking and Design-Based Learning (Henriksen, 2017; Hynes et al., 2011; Chin et al., 2019).	A collaborative process to develop and test solutions to real problems. Typically follows an iterative process: defining problems, forming ideas, conducting research, creating prototypes, and testing solutions.	• Clear connection to real-world problems. • Address Engineering problems through design. • Emphasises learners' communication and collaboration. • Improve problem-solving even among lower-achieving pupils.
6E Learning byDeSIGN™	Proposed by the International	• Emphasise problem-based learning,

(Burke, 2014)	Technology and Engineering Educators Association, replaces the "elaborate" phase of the 5E model with "engineering" and "enrichment."	designing solutions to real problems. • Potentially share the benefits of the 5E methodology
Computational pedagogy (Psycharis et al., 2020; Chen et al., 2023)	Address real computational problems by using computers or unplugged activities.	• Fosters computational thinking and computational content knowledge • Develops modelling thinking
Digital game-based learning (Gui et al., 2023)	Creates an engaging learning environment that allows learners to interact with game mechanics in a virtual world and provides a meaningful gaming experience.	• Enhances learning motivation. • Learners practice problem-solving skills, develop critical thinking, and foster STEM literacy.
Methodologies from Arts Education		
Transdisciplinary integration (Costantino 2018; De la Garza & Travis, 2019)	The key concept is the usefulness of art in breaking down disciplinary barriers	• Integration of more disciplines. • Specific development of artistic creativities • Correlation between students' involvement in the arts and their performance in maths and science • A strong push from the STEAM movement
Experiential learning (Smith, 2006)	Construct meaning from lived experience	
Lincoln Center model (Holzer, 2005)	Focus on aesthetic education, inquiry and the imagination	
Artful Learning Model™ (LBC, 2008)	Arts are the central ingredient to learning, and using the arts across all disciplines	
Art and Design (Bequette & Bequette, 2012; Keane & Keane, 2016).	Connected to Design Thinking, but to foster creative artistic processes inside STEM, especially through visual solutions using design, and highlighting the value of aesthetics.	
Some other methodologies		
Situated STEM Learning (Kelley & Knowles, 2016)	Grounded within the situated cognition theory, with its key elements being scientific enquiry and engineering design	• Connected to real-world problems. • Potentially share the benefits of design and inquiry methodologies
Equity-oriented STEAM Framework (Jackson et al., 2021; Castek et al., 2019)	Equity is the central axis of the projects.	• Especially concerned with cultural and ethnic diversity. • Draw out relationships around identity in the design of the projects.
iSTEAM (Tsai et al., 2017)	Introduce imagination in the design thinking methodology.	• Try to foster creativity and design skills

The STEAM-5E framework

In the previous review, synthesised in Table 1, five categories of debated aspects in STEM/STEAM education have been identified. Additionally, the strengths of the most commonly used methodologies have been analysed (see Table 2). Based on these findings, this section develops a methodological model, STEAM-5E, that aims to provide a coherent framework aligned with the objectives of STEAM education and to address ongoing debates in the field.

First, the methodological foundation guiding the proposed framework is introduced: the 5E model. The subsequent sections address the debates and topics outlined in Table 1, specifically how STEAM-5E responds to key issues such as the conceptualization of STEAM, disciplinary integration, creativity, and equity—pillars of our framework. Regarding the final category of debate—difficulties of application—specific sections address the design and implementation of educational projects within the STEAM-5E framework. Additionally, guidelines and tools are provided for student assessment and for evaluating projects implemented under this framework from both student and teacher perspectives.

Altogether, this constitutes a coherent and comprehensive methodological proposal that has not been previously developed in STEAM education. An example of a STEAM-5E project designed for primary education is presented. However, it is important to stress that this framework is not limited to this educational stage; we believe it is equally applicable to secondary education.

Methodological Foundation of STEAM-5E

The 5E Instructional Model (Bybee et al., 2006), originating from Science Education in the 1980s, serves as the methodological foundation of this proposal. The model follows five phases: Engage (activating prior knowledge and stimulating interest), Explore (facilitating conceptual change through activities), Explain (constructing explanations), Elaborate (deepening understanding through new experiences), and Evaluate (assessing comprehension).

The 5E model was chosen due to its strong theoretical and empirical support: it is rooted in cognitive theories of memory and learning (NRC, 1999), emphasises motivation and prior conceptions (Bybee et al., 2006), and integrates manipulative and inquiry-based activities essential for science learning (NRC, 2006). The Explore-before-Explain approach promotes meaningful learning and conceptual change in science and mathematics (Sinha & Kapur, 2021), while the Elaborate phase enhances knowledge transfer (Hattie & Yates, 2013). Additionally, the model provides clear instructional guidelines and, despite its origins in science education, is easily adaptable to mathematics education, sharing features with the Singapore method (Yoong & Hoe, 2009).

Empirical studies confirm the effectiveness of the 5E model across multiple domains, including enhancing subject mastery, improving standardized test performance, developing scientific reasoning, fostering interest in science, strengthening understanding of the Nature of Science, and helping teachers implement more effective instructional practices (Bybee et al., 2006). Recent studies provide strong evidence of the long-term positive effects on conceptual learning (Garcia I Grau et al., 2021).

We consider inquiry-based learning the most appropriate methodology during the Explore and Explain phases, especially in science and mathematics disciplines (Crawford, 2000; Bybee, 2006). In contrast, Project-Based Learning and Design Thinking are particularly interesting when teaching Technology and Engineering. This is also considered an appropriate method for developing the arts (Graham, 2021; Henriksen, 2017). Therefore, in STEAM-5E, we propose developing the project for the Elaborate phase using these methodologies. In this phase, we also propose collaborative learning, in agreement with Jolly (2014), who states that STEM focuses more on teamwork and STEAM on collaboration, with the latter being a process with greater benefits for learners who can extend their critical thinking and reasoning skills by being involved in collaborative activities (Veldman & Kostons, 2019).

Finally, in accordance with a transversal perspective on arts, the use of Visual Thinking is proposed to create maps and graphical learning diaries (Rohde, 2013; Megías, 2018). This is an effective way to deepen metacognition through the processes of synthesising, organising, and linking information, and to connect with more emotional learning (Megías, 2020). In addition, the maps and diaries arising from this approach can also serve as an assessment tool, understood as a creative research process (Megías, 2020).

STEAM Conceptualisation in STEAM-5E

STEAM-5E strongly supports the inclusion of A within STEM, understanding A in a broad sense. This includes considering all the arts as valuable in Education (visual arts, architecture, music, performing arts, dance, etc.) but also expanding A in a globalising sense that leads to the consideration of the Humanities in the search for holistic and integrative learning.

Regarding the role of the Arts and Humanities, we view them as equal to the other STEM areas. We value both their own disciplinary sense and their integrative and cross-disciplinary potential. Root-Bernstein (2015) reports a strong correlation between interest in artistic, musical, literary, or craft areas and success in STEM fields.

Regarding technology and engineering, both must be included in STEAM-5E projects. Studies have shown that engineering is rarely addressed in STEM (Bagiati et al., 2015). One possible cause is that in many countries, engineering is not included in curricula, especially at the primary level. Therefore, we propose using the National Assessment of Educational Progress (NAEP) standards for Technology and Engineering Literacy as a guide (National Assessment of Educational Progress [NAEP], 2018).

Disciplinary Integration in STEAM-5E

We propose a progressive approach to disciplinary integration, starting at the discipline-specific level, progressing to interdisciplinary connections, and finally to transdisciplinary integration. Beginning with the Explore and Explain phases in each discipline enables learning to advance across subjects. It is necessary to respect the content, methods, and concepts of the individual disciplines (Kelley & Knowles, 2016). Research indicates that conceptual learning in mathematics benefits from a multidisciplinary approach, where each discipline is purposefully emphasized within a unit and aligned with explicit student learning outcomes (Baldinger et al., 2021). Later, it becomes possible to establish strong relationships between different disciplines, which must be explicitly addressed. In the elaboration phase, transdisciplinary integration is achieved, fostering collaboration between scientific-technological and artistic fields (Chapell et al., 2019) and approaching solutions to complex problems through creative thinking (Costantino, 2018). This progression of complexity and level of integration is supported by cognitive learning theory (Salden et al., 2006).

Creativity in STEAM-5E

As mentioned above, several models address creativity in education, and discussions within the STEAM community address its implementation. Among them, in STEAM-5E, we highlight two key aspects to consider about creativity in the design, development, and implementation of a STEAM project (Figure 2):

I. Creative Domain: Glaveanu (2018) proposes the existence of three creative domains based on a historical review of different models and constructs on creativity. These domains are artistic, scientific, and craft creativity. The main traits of each dimension are shown in Figure 2. This conceptual framework aligns with the STEAM-5E model, which necessarily includes arts, science, and engineering. Thus, creativity from all disciplines is demanded by several authors (Graham, 2021).

II. Creative person or group: the person or creative group is analysed considering both cognitive and conative traits following Lubart & Thornhill-Miller (2019). In this way, the dual analysis of creativity from individual and distributed (group) perspectives relates to the conception of the school as a social space.

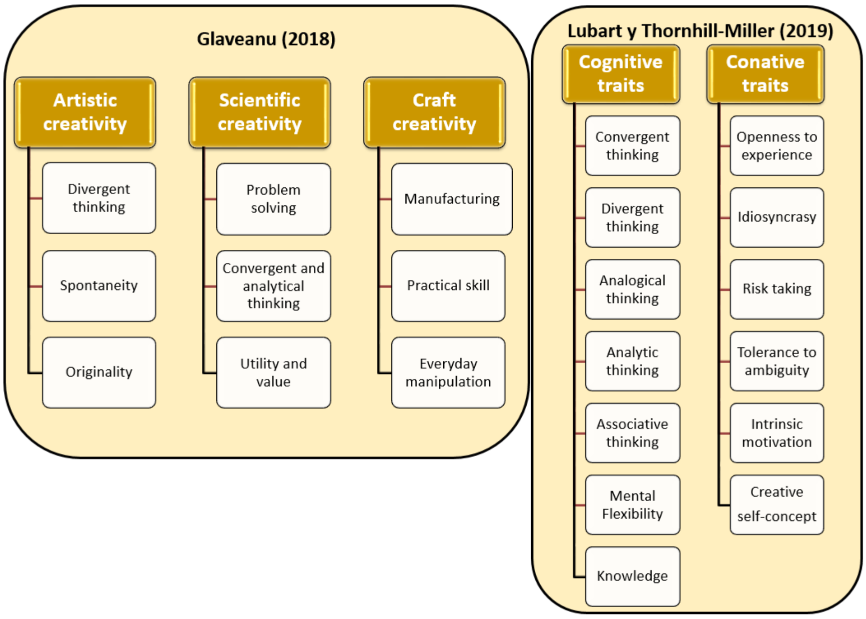
This conceptual framework has already been recognised for analysing creativity across various STEAM projects, both by examining how different disciplines contribute to distinct traits of creativity and by studying the interrelationships between them (Lage-Gómez & Ros, 2024).

Equity in STEAM-5E

In the STEAM-5E framework, equity is a fundamental pillar, as it should be a primary goal of education in the 21st century. Several recent studies note that these aspects of equity and diversity are not sufficiently addressed in current projects (Bruijnzeel et al., 2022; Palid et al. 2023). Therefore, any STEAM-5E project must explicitly include activities, discussions, and attitudes that demonstrate a commitment to equity, particularly gender equity. Research such as that done by Bian et al. (2017) demonstrates that gender stereotypes about intellectual abilities arise during childhood and impact the later interests of boys and girls. It is therefore essential for a STEAM project to create opportunities and visibility for the work of women scientists, mathematicians, and engineers to encourage girls' interest in experimental science and engineering.

Figure 2

Conceptual framework for creativity in STEAM-5E



Design and Implementation of a STEAM-5E Project

There are many difficulties in implementing a STEAM project as discussed previously. From the STEAM-5E perspective, we propose the Design-Based Research (DBR) approach as a guide for the design and implementation of STEAM-5E projects.

Design-Based Research (Design-Based Research Collective [DBRC], 2003) is a design and research methodology that guides the educational research process, aiming to connect major theories of teaching and learning with specific conceptual challenges in real-world contexts. Its goal is to bridge the gap between research and practice. DBR places significant importance on involving teachers in the research, fostering communities of practitioners, and promoting partnerships between university researchers and schoolteachers. Essentially, DBR proposes a design phase that considers theoretical evidence, followed by an iterative implementation phase for refinement.

In the STEAM-5E model, projects should be led by teams of researchers specialising in the relevant educational fields. This ensures that the projects are designed with adequate pedagogical content knowledge of each discipline. These researchers also serve as guides for teachers, helping them correctly apply the methodology. It is recommended to organise coordination meetings and training courses that allow teachers to expand their conceptual and pedagogical knowledge and strategies. This helps them overcome the challenges raised by various authors (Quigley & Herro, 2016; Toma & García-Carmona, 2021).

Teachers bring deep knowledge of the classroom and curriculum requirements, and collaborate with researchers in the essential process of translating content into teaching materials. They ensure the sequencing and appropriate cognitive and procedural levels of the content, ensuring coherence (Roehrig et al., 2021). This collaboration results in valid materials that can be used in other contexts. Establishing this relationship from the beginning of the process also ensures the indispensable collaboration of schoolteachers and the management team in terms of using appropriate spaces and adapting schedules, which may be necessary to carry out the project.

Assessment

Figure 3 summarises the assessment approach in STEAM-5E, which is based on continuous, processual, and formative assessment. Feedback and metacognition play a central role in dialogical interactions among students and between students and teachers. Feedback should go beyond the task itself to include the process, metacognitive strategies, and students' approach to learning (Martín, 2020). Qualitative feedback is preferred over quantitative assessment (Martín, 2020).

Metacognition is developed throughout the project via discussions, group debates, and guided questioning, allowing learners to reflect on their learning. The Visual Thinking methodology is implemented at the end of each subject's activities (after the Explain phase) and at project completion (during the Evaluate phase). During the Elaborate phase, pupils engage in metacognitive processes such as planning tasks, selecting strategies, executing plans, monitoring progress, and making adjustments (Martín, 2020).

Regarding what to assess, STEAM-5E projects align with educational curricula, enabling teachers to use their standard tools (e.g., observations, written tests, assignments, and presentations) to evaluate both conceptual and procedural learning. A marking key (see Supplementary Material) is proposed in the Elaborate phase to assess group performance (e.g., project planning, design, construction, and communication) and individual contributions (e.g., motivation, participation, and teamwork). A dual individual and group evaluation approach is recommended as the most suitable and complementary method for assessing complex STEM projects (Han et al., 2021).

Finally, a crucial aspect of assessment is the development of positive attitudes, including enjoyment, interest, self-efficacy, and expectations toward the disciplines involved. Attitudes play a key role in fostering future vocations (Archer et al., 2020) and in preventing early dropout (Vázquez & Manassero, 2008). We propose using three statistically validated questionnaires from the literature to assess the impact of STEAM-5E projects on learners' attitudes (see Table 3). These questionnaires are validated for similar age groups and use a consistent scale, ensuring a uniform and reliable analysis.

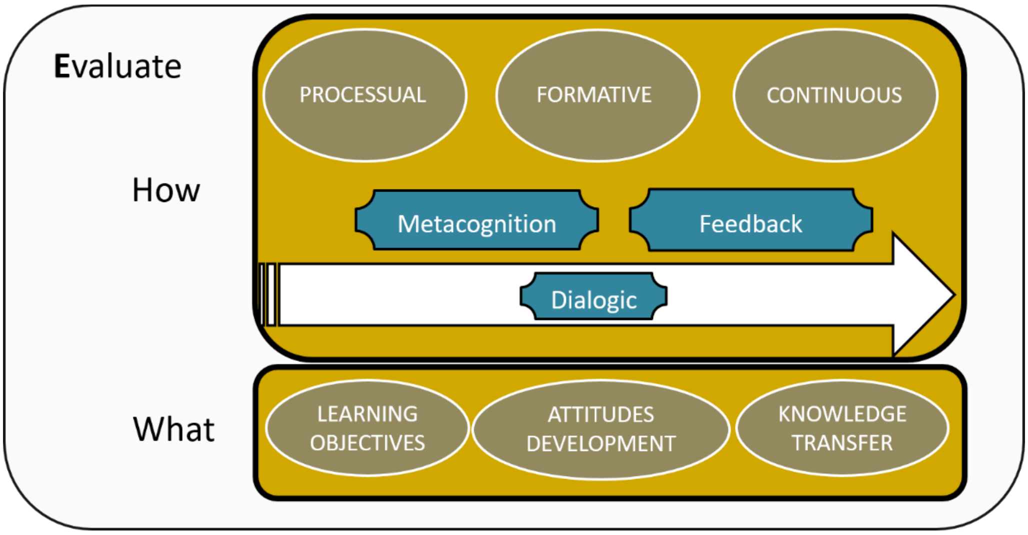
Table 3

Questionnaires are needed to assess the development of attitudes towards STEAM areas.

Questionnaire	Dimensions	Comments
S-STEM questionnaire (Unfried et al., 2014)	Attitudes towards STEM areas (Science, Mathematics, Engineering, and Technology)	• It focuses on self-efficacy and utility • Two versions: one for primary school (4-5th grade) and the other for high School (6-12th grade) with little differences • 26 items (8 for maths, 9 for science, 9 for engineering) • 1-5 Likert scale • Also includes 13 items about 21st-century skills
Students' attitudes towards art teaching in primary school (Pavlou & Kambouri, 2007).	Enjoyment, confidence, usefulness, and support are needed	• We consider here only the first three dimensions • 34 items (9 for enjoyment, 8 for confidence, 10 for usefulness, and 7 for support needed). • 1-5 Likert scale • We think it could also be appropriate for junior high school
Pupils' attitudes to school and music at the start of secondary school (Kokotsaki, 2016).	Liking music and making music	• We think it could also be appropriate for the last years of primary school • 13 items (7 for liking music and 6 for making music) • 1-5 Likert scale

Figure 3

Assessment in STEAM-5E



Evaluation of the STEAM-5E Project by Students, Teachers, and Researchers

The evaluation of the project itself is an essential element in STEAM-5E. The way it is carried out must necessarily be the product of joint reflection by teachers and researchers, again in accordance with the spirit of the DBR, and must include the students' perspective. Two questionnaires have been designed for this evaluation: one to collect students' perspectives (Appendix 2) and the other for the teachers involved in the implementation (Appendix 3). A description of the dimensions and items of both questionnaires is given in Table 4.

Table 4

Description of the questionnaires designed to evaluate STEAM-5E projects

Questionnaire for students (see Appendix 2 in supplementary material)	
Dimension	Number of items
Self-regulation (Metacognition, emotions, and motivation)	9
Disciplinary integration	6
Creativity	7
Contextualisation and transfer of knowledge	4
Working groups	4
Global assessment	7
Questionnaire for teachers (see Appendix 3 in supplementary material)	
Dimension	Number of items
Motivation	5
Disciplinary integration	3
Creativity	16
Collaboration	3
Competences and contents	13
21^{st} century skills	18
Methodology	9
Timing and Resources	7
Support and relationship of the researchers and schoolteachers	11

As can be seen, both questionnaires are multidimensional and address the fundamental pillars that these projects aim to develop (self-regulation, motivation, creativity, and disciplinary integration) and include an in-depth evaluation by the teachers on the methodology, the compliance of the curriculum, and other aspects related to the implementation (spaces, schedules, relationship with the researchers. Both questionnaires use a 4-point Likert scale, so there is no 'neutral' option. The content validation of the questionnaires followed a structured process:

1. Expert Self-Assessment (Cruz Ramírez & Martínez Cepena, 2012): Experts' competence coefficient (ranging from 0 to 1) was determined based on their self-reported knowledge of the research problem and the sources supporting their evaluation criteria. A minimum threshold of 0.75 was required for inclusion in the validation process, resulting in the exclusion of three of the nine pre-selected experts.
2. Item Review: Experts were invited to provide comments on each item, which facilitated minor revisions for improved clarity.
3. Content Validity (Escobar-Pérez & Cuervo-Martínez, 2008): The selected experts rated each item on a 1-to-4 scale across four dimensions: clarity, sufficiency, relevance, and coherence. The Content Validity Index (CVI) was calculated as the ratio of the total points obtained to the maximum possible score. A CVI above 0.80 indicates a high level of agreement (Sangoseni et al., 2013). Only three items narrowly fell below this threshold. However, given their minor deviations and the need to maintain questionnaire completeness for reliability purposes, these items were retained with slight wording modifications.

Finally, we recommend that researchers conduct interviews with several groups of pupils and teachers after analysing the questionnaires. Qualitative information is highly valuable for improving the project in future implementations, as it helps to understand the quantitative results better and evaluate the processes developed during project implementation.

STEAM-5E at a Glance

Figure 4 summarises the core principles of the model, where all STEAM disciplines are considered equally, and the A represents the potential inclusion of all disciplines. The methodological foundation is the 5E model, with Project-Based Learning (PBL) and Design Thinking (DT) incorporated into the Elaborate phase. Activities should primarily be manipulative and guided by inquiry-based learning, supplemented with collaborative work, visual thinking tools, and dialogic processes to foster student motivation, metacognition, and meaningful learning.

For disciplinary integration, the model begins with a disciplinary approach, progressing to interdisciplinary connections in the Explore and Explain phases, and culminating in transdisciplinary integration in the Elaborate phase. The development of STEAM-5E projects should adhere to Design-Based Research (DBR) principles to ensure rigorous design, implementation, and evaluation.

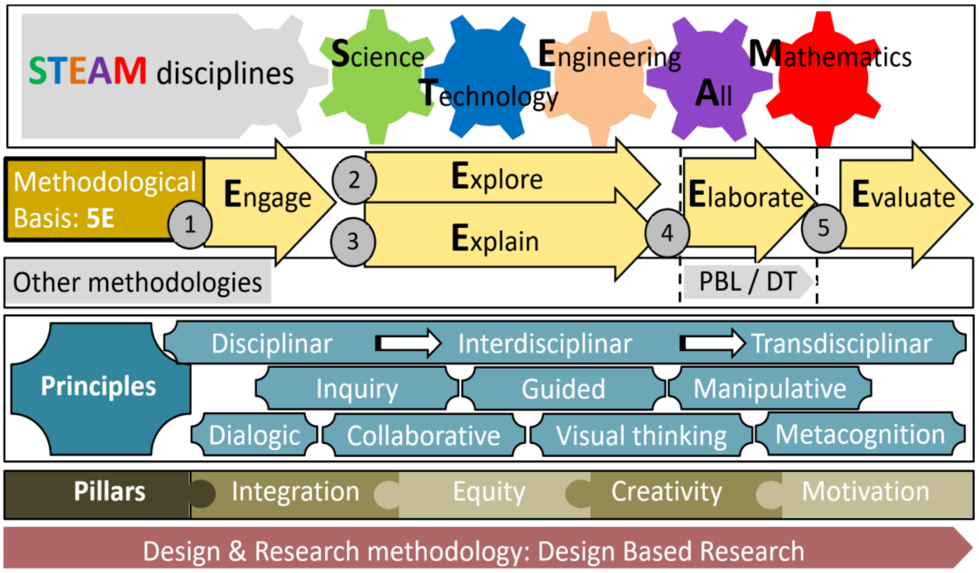
This approach aims to fulfil the core objectives of STEAM education, including effective disciplinary integration, fostering diverse forms of creativity, promoting equity, and cultivating positive attitudes toward learning.

A STEAM-5E Project for Elementary Education – "Machining" in Ancient Egypt

This section presents "Machining in Ancient Egypt," a STEAM-5E project designed for pupils aged 9-11. Developed by specialists in mathematics, science, music, arts, engineering, and technology education—alongside an expert in educational psychology—the project also involved collaboration with three primary school teachers. To facilitate implementation, video tutorials and worksheets for both teachers and students have been created (https://youtube.com/GRUPO-ICC-UAH, see list "Maquinando en el Antiguo Egipto"), ensuring accessibility for other schools.

Figure 4

The STEAM-5E methodological framework



The project spans around 50 one-hour lessons over 7-8 weeks, following the 5E instructional model (see Figure 5):

- ✓ Engage (2 hours): A gymkhana activity introduces key concepts through card games and manipulative materials, fostering motivation. Themes such as the plundering of Egyptian heritage and the role of female pharaohs are introduced.
- ✓ Explore & Explain (30 hours): Each subject covers specific content aligned with the official syllabus, including simple machines (Science), fractions and decimals (Maths), and musical instruments, voices, and qualities of sound (Music). A digital music score reader is created using a Microbit card and MakeCode, integrating programming and electronics. Inquiry-based, hands-on, and interdisciplinary activities reinforce learning.
- ✓ Elaborate (10 hours): Following Project-Based Learning (PBL) principles, pupils collaboratively reconstruct Abu Simbel using educational materials, applying knowledge from previous phases. The project emphasises teamwork, planning, and organisation while revisiting cultural heritage and gender roles in Ancient Egypt.
- ✓ Evaluate (8 hours): Pupils create a visual notebook and a collaborative visual map based on Visual Thinking principles. Traditional assessments, along with rubrics and questionnaires, measure knowledge transfer, attitude development, and overall project effectiveness.

This project was implemented in two schools during the 2021–22 academic year. Previously, activities related to simple machines and the digital music score reader were tested, reassessed, and redesigned following the Design-Based Research process. As a result, one article has already been published (Ros et al., 2022) and another is currently under development. Additionally, another publication has analysed pupils' self-regulation processes within this project using the instruments outlined in previous sections (López-Carrillo et al., 2024). Furthermore, aspects such as creativity, disciplinary integration, the associations between these dimensions, and the evaluation by participating teachers have been analysed and presented preliminarily at several national and international conferences (Ros et al., 2022, Ros et al., 2023). Several articles on these topics are currently being prepared for submission.

Conclusions and Implications

Given the diversity of definitions, goals, objectives, methodologies, and proposals within the STEM and STEAM paradigms, and given the demand for coherence within the community, this paper analyzes the main issues currently under debate in these paradigms, as well as the methodologies proposed. The analysis is conducted through a narrative and critical review of the literature following the qualitative content analysis approach. Other reviews have recently been conducted in the STEM field (Potillo-Blanco, 2024; Aguilera et al., 2024; Wan et al., 2023; Larkin & Lowrie, 2023). However, this work delves into the STEAM approach, incorporating a broader, more critical perspective that enables categorization and deeper exploration of the current points under discussion within the scientific community. Thus, this work sheds light not only on the complex landscape of STEM and STEAM education but also on their essential components.

First, we identify several key points of debate within the community: i) conceptualization, including the diversity of conceptual interpretations of STEM and STEAM, the discussion on the role of the Arts, the possible inclusion of the Humanities, and the conception of Engineering and Technology; ii) the disciplines included and their different modes of curricular integration (multi-, inter-, and transdisciplinary); iii) how to understand and address creativity; iv) how to promote equity; and v) difficulties in implementation, including challenges related to student assessment and project evaluation.

Second, we classify methodologies by educational tradition and summarize their strengths. We distinguish between those coming from Science Education (Inquiry, 5E, PBL), Engineering Education (Design Thinking, Design Learning, 6E Learning by Design, Computational Pedagogy, Digital game-based learning), those focused on arts (Transdisciplinary approaches, Experiential Learning, Arts and Design, the Lincoln Center Model and the Artful Learning Model), and some other approaches.

Third, a new methodological model is proposed to address the issues discussed and to bring together the benefits of the methodologies analysed. Essentially, it is based on the 5E methodology adapted to STEAM, with the real integration of all STEAM disciplines in a broad sense, the development of creativity from its multiple facets, special consideration for equity, and the search for student motivation through inquiry, manipulative activities, and collaborative work. All of this is guided through metacognition and dialogic processes. We propose the Design-Based Research methodology guide as a tool for designing educational projects under this model and for subsequent research analysis. Additionally, a project developed within the STEAM-5E model and implemented in primary education is presented, along with references to the results.

The study presents some methodological limitations. As with any narrative review, it is not exhaustive and may be subject to author bias, although we have detailed the criteria and procedures used to minimise such bias. Furthermore, the analysis is not intended to be generalizable; however, the rigorous process and the comparison with recent meta-analyses help ensure a certain level of consensus.

This work contributes to educators and researchers by providing a model for developing both teaching practices and educational research. In the first case, the model serves as a guide for creating educational materials and projects, including criteria and a rubric for students' assessment. We believe it is also sufficiently flexible to adapt to both primary and first-year students in secondary education, despite differences in teacher training and the organisational structures of their institutions.

Figure 5

Pictures of the STEAM-5E Prosubject "Machining" in ancient Egypt

In the second case, the model proposes a methodological research process based on DBR, offering tools (validated questionnaires for teachers and students) to evaluate the success of projects in various aspects that are currently hot topics in educational research, such as curriculum integration, the development of creativity, and the promotion of positive attitudes towards the diverse areas of STEAM. Moreover, several results from the implementation of a project under the STEAM-5E model have already been published, with others in progress, underscoring the feasibility and validity of the proposed model.

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Appendix 1

Rubric for the Elaborate Phase

PHASE	Can be improved	Satisfactory	Excellent
Group Evaluation			
A) Approach, planning, and design	1. They understand the problem posed with help. 2. Identify necessary tasks and order them with assistance. 3. Establish some criteria for success with help.	1. They understand with little help the problem posed. 2. Identify necessary tasks and order them with little assistance. 3. Establish some criteria for success.	1. Understands without help the problem posed and/or can support other classmates who have more difficulties. 2. Identify and correctly order the necessary tasks. 3. They establish valid and sufficient success criteria. 4. They can perceive and raise
B) Information search	1. They consult a single source of information. 2. They have difficulties in selecting the most relevant information.	1. They consult a few sources of information. 2. They select the most relevant information.	1. They consult various sources of information. 2. They select very relevant information. 3. They value the information
C) Construction	1. They have difficulties applying what they have learned in the project for the construction of the temple. 2. There is no logical order in the construction of your section. 3. The division of tasks has not been clear.	1. They apply in part what they have learned in the project for the construction of the temple. 2. They follow a logical order in the construction according to the established stages most of the time. 3. The distribution of tasks is valid but can be optimized. 4. Errors have been corrected, but with little foresight.	1. They apply what they have learned correctly in the construction of the temple. 2. They follow a logical order in the construction according to the established stages. 3. They carry out an adequate distribution of tasks and use of time. 4. Evaluate the process to correct mistakes and make new decisions.

D) Evaluation	1. The result of your template section is correct, but very improvable. 2. They check the result and correct some mistakes promptly. 3. They collaborate in a not very active way with the rest of the groups in the construction of the temple. 4. The result is technically and artistically valid	. The result of your temple section is adequate. 2. They check the result and correct some mistakes. 3. They collaborate with the rest of the groups in the construction of the temple. 4. The result is technically and artistically adequate.	1. The result of your section of the tem999ple is entirely satisfactory. 2. They check the result, re-evaluate, and correct errors satisfactorily. 3. They collaborate optimally with the rest of the groups in the construction of the temple. 4. The result is optimal from the technical and artistic point of view.
E) Communication	1. They consult the source of the information provided. 2. They have an idea to answer the question posed. 3. They have some idea about the conclusions of the project.	1. They consult the source of the information provided and know how to explain it adequately. 2. They have several ideas to answer the question posed and discuss them. 3. They have several ideas about the conclusions of the project and discuss them.	1. They consult the source of information provided and other additional information and know how to explain it adequately. 2. They have several ideas to answer the question posed, discuss them, and decide on the most relevant ones. 3. They have several ideas about the conclusions of the project, discuss them, and decide on the

Individual Evaluation	
1. Show interest in the project. 2. Helps the group to achieve the objectives. 3. Collaborate with peers.	1. Shows a high level of interest in the project. 2. Strives to achieve goals. 3. Promotes interest among peers. 4. Argue based on acquired knowledge
1. Takes responsibility for the work assigned to them and carries it out appropriately. 2. Participates in group discussions and decision-making. 3. Supports your peers.	1. Takes responsibility for the work assigned to them and performs it to the best of their ability. 2. Actively participates in group discussions and decision-making. 3. Supports peers and exercises some leadership in the group.
1. Adequate participation in a small group. 2. Appropriate large group participation. 3. Collaborate in class discussion.	1. Active participation in a small group. 2. Active participation in a large group. 3. Collaborate in class discussion by expressing ideas with fluency and rationale.

Note: the teacher must assign a level of achievement by assessing the aspects indicated, considering which level is closest, i.e., it is not necessary to 5 meet all the items of the "excellent" level to achieve that assessment.

	Motivation Transfer	1. Shows moderate interest in the project. 2. Moderately helps the group to achieve the objectives. 3. Does not collaborate actively with
	Teamwork	1. Takes partial responsibility for the work assigned to them. 2. Participates little in group discussions and decision-making. 3. Little support for their teammates.
	Participation	1. Little participation in a small group. 2. Little participation in a large group.

Appendix 2

Questionnaire on STEAM-5E Projects for Students

Likert scale. 1 means minimum agreement, and 4 means maximum agreement (except questions V2 to V7 as indicated).
Name:
Class:
Gender:
Indicate your degree of agreement with the following statements related to the project:

Code	Item	CVI
1) SELF-REGULATION (Metacognition, emotions, and motivation) During the activities:		
A1	I was aware of what was clear and what was not	.91
A2	I noticed the mistakes I made and tried to fix them	.90
A3	I think I learn more by working this way than the usual way	.85
A4	I found the project very attractive	.84
A5	I had fun and enjoyed the proposed activities	.85
A6	I have felt capable of carrying out the proposed tasks	.88
A7	I believe that what I have learned will be useful to me in the future	1
A8	I have been able to make choices when doing the activities	.81
A9	I felt guided by the teachers	.92
2) DISCIPLINARY INTEGRATION		
I1	We have related content from different areas (Mathematics, Science, Plastic Arts, Music, Engineering, and Technology).	.79
I2	I have enjoyed working on Mathematics, Science, Art, Music, Engineering, and Technology in the same project.	.95
I3	This way of working has helped me better understand the content.	.90
I4	In the final project, we have applied what we have learned during the previous project classes	.85
I5	In the final project, we have extended what we have learned during the previous project classes	.85

I6	In the final Visual Thinking, we have represented what we have learned in the whole project	.97
3) CREATIVITY		
C1	During the project, I have acted as an engineer (designing, constructing, and testing)	1
C2	During the project, I have acted as a scientist (experimenting, formulating hypotheses, and drawing conclusions).	.86
C3	During the project, I have acted as a mathematician (working with numbers and representing data).	.89
C4	During the project, I have acted as an artist using various art forms	.88
C5	What I have learned has allowed me to do something new.	.89
C6	I felt free to propose ideas and solutions	.84
C7	I enjoyed creating things with my hands and seeing them work	.78
4) CONTEXTUALIZATION AND TRANSFER OF KNOWLEDGE		
CT1	The project has included elements that connect to real-world situations or problems.	.85
CT2	I think I can apply what I have learned to other similar situations	.99
CT3	Now it is clearer to me what engineering is and what it does.	.97
CT4	I think what I have learned will be useful in the future.	.88
5) WORKING GROUPS		
G1	I enjoyed working on individual tasks on my own.	.97
G2	I enjoyed working as part of a team with my colleagues.	.98
G3	I enjoyed solving problems as part of a team.	.95
G4	I felt part of the team in the group work.	.99
6) GLOBAL ASSESSMENT		
V1	I would like to continue learning in this way in the future	.99
V2	I have felt guided by the teachers.	.98
V3	I found the project fun.	.92
V4	I found the project easy.	.88
V5	I found the project original.	.89
V6	I found the project useful.	.93
V7	I found the project innovative.	.99

Appendix 3

Questionnaire on STEAM-5E Projects for Teachers

Likert scale. 1 means minimum agreement, and 4 means maximum agreement.
Age:
Gender:
Years of teaching experience:
Civil servant/interim/employee:
Indicate the subject(s) you teach at the school:
Number of years in the school:
Type of centre where you work (public, private):

1. Assessment of the project from the teachers' own perspective

Code	Item	CVI
1) MOTIVATION		
Mot1	I find the project stimulating as a teacher	.96
Mot2	It motivates me to work in this way	.82
Mot3	It has given me a feeling of satisfaction	.87
Mot4	This way of working has brought new elements to my teaching practice	.88
Mot5	My expectations have been largely fulfilled	.76
2) DISCIPLINARY INTEGRATION		
I1	An inter/transdisciplinary integration has been achieved in the project	1
I2	The different areas have been worked on in a balanced way	1
I3	A holistic approach has been used in the project.	.97
3) CREATIVITY		
CR1	The project has provided the right environment for the proposal of ideas	.99
CR2	Students have been able to develop divergent thinking strategies.	.97
CR3	Problem solving strategies have been applied.	.97
CR4	There have been several creative processes throughout the project.	1
CR5	Students have been able to develop analogical thinking strategies (seeing and using structural, logical or symbolic parallels or similarities between ideas or systems).	.97

CR6	Students have been able to develop convergent thinking strategies (identifying the best solution among possible solutions).	1
CR7	Students have been able to develop analytical thinking strategies (examining information and evaluating its strengths and weaknesses).	.97
CR8	Students have been able to develop associative thinking strategies (making connections between ideas or areas).	.95
CR9	Students have been able to develop cognitive skills such as flexibility (diversity of perspectives) and the ability to adjust their thinking to new information.	.95
CR10	Students have been able to develop cognitive skills such as using their own knowledge (to understand a problem and synthesize a solution).	.94
CR11	The project has encouraged students to interact with the world around them in new ways.	1
CR12	The project has fostered a taste for new experiences and stimuli.	1
CR13	The project has encouraged a taste for risk in the face of a new challenge.	.99
CR14	The project has fostered tolerance of ambiguity (with experiences that could be relatively uncertain).	.99
CR15	The project has fostered the development of intrinsic motivation (e.g., satisfaction with achievements or generating interest in certain topics).	1
CR16	The project has fostered a high creative self-concept (the student has felt creative, in general or in a specific domain).	1
4) COLLABORATION		
Co1	Collaborative situations between students have been encouraged	.98
Co2	Teamwork skills have been fostered.	.99
Co3	The development of positive values among the students has been encouraged	.95
5) COMPETENCES and CONTENTS		
CC1	The project adequately covered many of the curricular evaluable learning standards established for the course, term, and subjects included in the project.	.9
CC2	The fact that this project is embedded in the curriculum is a very important positive element	.8
CC3	The conceptual contents (knowledge) have been worked satisfactorily	1
CC4	The procedural content (know-how) has been satisfactorily worked on.	1
CC5	Attitudinal contents (knowing how to be) have been worked satisfactorily.	1
CC6	Technology and engineering content have been successfully incorporated.	.94
CC7	The key competence of *learning to learn (LL)* has been satisfactorily developed	1
CC8	The key competences in *mathematics and basic competences in science and technology (CM)* have been satisfactorily developed.	1
CC9	The key competency of *cultural awareness and expression (CC) has been* satisfactorily developed.	1
CC10	The key competences, *social and civic competences (CS),* have been satisfactorily developed.	1
CC11	The key competence of *sense of initiative and entrepreneurship (SI)* has been satisfactorily developed	1
CC12	The key competence, *linguistic and communicative competence (CL),* has been satisfactorily developed.	1
CC13	The key competence, *digital competence (CD),* has been satisfactorily developed	1
6) 21st CENTURY SKILLS: Assesses whether the project has developed the following skills in students:		
S1	Curiosity	1
S2	Critical thinking	.92
S3	Troubleshooting	.92
S4	Quantitative Reasoning	1
S5	Logical thinking	.97
S6	Innovation ability	.97
S7	Apply and create technology	.98
S8	Decision-making and autonomy	1
S9	Initiative and entrepreneurship	.99
S10	Communication skills	.95
S11	Organizational skills	.87
S12	Empathy	1
S13	Adaptability	1
S14	Leadership	1
S15	Acceptance of diversity	.95
S16	Social, cultural, and environmental responsibility	.80
S17	Scientific, numerical, technological, and cultural language.	.86
S18	Gender equality	.97
7) METHODOLOGY		
Me1	The methodological framework of the project (5E) seemed to me to be the right one.	1
Me2	The approach of the project encourages students to learn the contents in a meaningful way	1
Me3	The methodological techniques and tools were appropriate to each type of activity	1
Me4	Activities have been carried out in which the students are the main subject of their learning	1

Me5	Students have developed experimentation and manipulation skills	.94
Me6	Students have developed logical and mathematical reasoning skills	.94
Me7	Students have developed artistic and musical expression skills	.94
Me8	The project has enabled adaptation to students' different skills and abilities.	1
Me9	The project has been adapted to the different learning rhythms of the students	1
8) TIMING AND RESOURCES		
TR1	The timing of the project has been adequate	.99
TR2	Working in the proposed way has not meant spending much more time in class to develop the syllabus as usual.	.97
TR3	The resources (materials, digital, personal, and spaces) used for the project have been adequate.	1
TR4	The worksheets and materials designed for the project have been appropriate for the level	1
TR5	The worksheets and materials designed for the project have been attractive	1
TR6	The worksheets and materials designed for the project have been coherent	.99
TR7	The cards and materials designed for the project have been original	.92
2. Assessment of the support and relationship of the researchers to schoolteachers		
Code	**Item**	**CVI**
SR1	Throughout the project's development, teachers have been involved in decision-making.	1
SR2	The opinions and suggestions of the teachers and the school have been included.	1
SR3	The project as a whole has been an enrichment for my professional work.	1
SR4	The project has been well adapted to the needs of the school	1
SR5	I believe that it has been a project of mutual collaboration between the school and the University	.99
SR6	The interrelation between the University researchers and the teachers has been very fruitful.	1
SR7	The involvement of the University researchers has been high.	1
SR8	The training courses have been very fruitful	1
SR9	The help of the University researchers during the lectures has been a great support	1
SR10	I would recommend that other schools implement this project.	1
SR11	I feel able to do the project on my own in the future.	.99

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Enhancing science process skills: problem-based learning in salt hydrolysis for metacognition growth

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ABSTRACT
The demands of today's workforce for knowledge and flexible, cross-disciplinary skills have changed. Through problem-based learning, students can develop the skills necessary for a range of careers. This kind of research employs a pretest-posttest control-group design and is a quasi-experiment. One hundred and twenty-nine students from SMA Negeri 1 South Dampal XI MIPA class made up the study population. Simple random sampling was used to produce the sample. Thirty-two students from class XI MIPA 1 made up the experimental group, while 32 students from class XI MIPA 4 made up the control group. Students using the problem-based learning implementation model exhibited science process abilities with an effect size of 8.92 (M=71.84, SD=7.956), whereas those using the discovery learning model had an effect size of 8.33 (M=72.34, SD=7.872). For both the problem-based learning implementation model (M = 77.03, SD = 3.961) and the discovery learning model (M = 77.62, SD = 2.738), the effect size value of students' metacognitive awareness was 5.56. An independent-samples t-test indicated that the difference between the two groups was not statistically significant ($t(62) = 0.67$, $p > 0.05$). As a result of the problem-based learning approach, students' science process skills in the salt hydrolysis material improved significantly. Their metacognitive awareness of the material was affected, and there is a positive correlation between students' science process skills and their metacognitive awareness.

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Introduction

The primary and secondary school curricula for 2013 were intended to adjust to the demands of the increasingly globalised world. The emphasis on student-centred learning highlights the importance of fostering active involvement and overall development. A well-rounded education is important, as evidenced by the integration of emotive, cognitive, and psychomotor elements (Hodza et al., 2021). Learners' critical thinking abilities are greatly influenced by metacognition, as the curriculum emphasises (Mohseni et al., 2020). The importance of metacognition in learning cannot be overstated; it is a critical component in determining students' academic achievement. The term "metacognition awareness" describes a person's conscious knowledge of and management of their cognitive processes (Asy'ari et al., 2019). The curriculum aims to equip pupils with the tools to digest complex material, integrate new information with what they already know, and adapt to changing conditions by encouraging them to reflect on their thinking (Liu et al., 2021). By enhancing metacognitive capacities, learners are better prepared to tackle challenges, find solutions, and develop higher-order cognitive skills**.** This strategy demonstrates a dedication to fostering higher-order cognitive abilities necessary for success in the contemporary world, alongside procedural and factual knowledge. The curriculum's emphasis on metacognition acknowledges that it can enable pupils to become self-reliant learners who can evaluate, modify, and apply their knowledge throughout their lives (Lamb et al., 2017). The inclusion of metacognition in the curriculum is a forward-thinking approach that equips learners with the skills they need to navigate the challenges of a changing global education landscape.

Academic achievement is consistently higher among those with strong metacognitive skills than among those with weaker metacognition (Abdelrahman, 2020). In this setting, the cultivation of metacognitive awareness is essential, as it helps learners effectively organise, monitor, and regulate their cognitive processes. This significantly enhances the efficacy and efficiency of thinking and learning. Their ability to overcome obstacles, understand difficult ideas, and maximise their general cognitive functioning improves as they get acclimated to these metacognitive processes, all of which support their academic achievement (Alam, 2020; Antonio & Prudente, 2021).

The incorporation of science process skills is imperative for the implementation of the 2013 curriculum, particularly when utilising a scientifically based learning paradigm. The scientific method aims to achieve learning objectives in a variety of domains, such as attitudes, skills, and knowledge, by involving students in scientific thinking and processes (Kyere, 2017). This method encourages pupils to take an active and participatory part in their education, which develops their critical thinking, curiosity, and practical skills. This method represents a modern view of education, recognizing the need for critical thinking and practical skills in preparing them for the demands of the current world (Hyun et al., 2017).

Scientific thinking and metacognitive ability are two significant qualities that contribute to student learning. They aid in the cognitive and skill development of pupils in the context of scientific study. Students' capacity to observe, develop questions, gather data, make predictions, test hypotheses, and draw conclusions based on evidence or information obtained is part of the science thinking process. Students with strong scientific thinking abilities may gain a thorough understanding of scientific topics, discover cause-and-effect relationships, and apply their knowledge across a variety of settings. Students' knowledge and grasp of their own thought processes are examples of metacognitive skills. It entails the ability to plan, monitor, and evaluate one's own learning development. Students with strong metacognitive abilities may organize their learning processes, recognize difficulty in grasping the subject, and take efforts to overcome these obstacles. They can also assess whether or not they have met the learning goals.

Contemporary methods of teaching science, especially in chemistry and, by extension, in other disciplines such as physics and biology, offer unique opportunities for student engagement. Chemistry provides a unique opportunity for students to engage in inquiry and develop important skills, including reasoning, thinking, problem-solving, experimentation, observation, data analysis, and scientific reasoning (Stammen et al., 2018). Beyond only imparting theoretical information, the purpose of teaching chemistry in schools is to enable pupils to use the scientific method in practical experiments. This hands-on method develops critical scientific process skills while improving students' comprehension of chemical principles.

In the context of chemistry education, active engagement in practical exercises is essential. Teachers provide an atmosphere that promotes curiosity, discovery, and the development of practical skills by immersing students in experiments and hands-on activities (Papanastasiou et al., 2019). Students improve their comprehension of chemical concepts and acquire critical thinking, problem-solving, and scientific method application skills by practising science process skills via hands-on activities. These abilities help students not just in their future academic endeavors but also in a variety of real-world opportunities and problems (Sutaphan & Yuenyong, 2019; Mulyenı et al., 2019). In conclusion, it is critical to place a strong focus on active participation in real-world activities during the chemical learning process.

One of the most important aspects of scientific education is the training and development of science process skills. Through practical exercises, laboratory work, and inquiry-based learning, teachers want to foster these abilities in their students during the learning process (Ulger, 2021). This method not only improves their comprehension of scientific ideas but also develops their capacity for critical analysis and problem-solving (Akuma & Callaghan, 2019). Measurement of learning in science process skills is largely dependent on assessment and evaluation. Instructors assess students' competency in using these abilities through a variety of assessment techniques, including hands-on experiments, written assignments, and presentations. Both students and teachers need to use this feedback loop to monitor their progress and pinpoint areas for development (Koomson et al., 2024; Sholahuddın et al., 2020).

Given that salt hydrolysis is an analytical process, a problem-based learning (PBL) strategy could be highly effective. Learners might be given tasks to solve in real-world circumstances involving salt hydrolysis, which encourages critical thinking and the application of theoretical ideas. Students' comprehension of salt hydrolysis may be enhanced and their viewpoints shared by encouraging inquiry-based learning and collaborative activities (Verawati et al., 2020). Students may also use this as a chance to connect the subject matter to real-world situations. Learning can be improved by using simulations, virtual experiments, or multimedia materials, particularly when learning abstract ideas and doing mathematical computations. Incorporating case studies about salt hydrolysis in various contexts can provide students with a comprehensive understanding of its applications and implications. Teachers can select instructional approaches that support greater comprehension of the subject matter while also accommodating a variety of learning styles by considering the mathematical and practical components of salt hydrolysis (Heliawati & Rubini, 2020). This method supports the objective of helping students become more adept at connecting academic knowledge to practical situations.

The convergence of learning models, past knowledge, metacognitive awareness, and problem-solving abilities within the framework of a problem-based learning strategy for salt hydrolysis content. Understanding how learning models, prior knowledge, metacognitive awareness, and problem-solving abilities converge within the PBL framework for salt hydrolysis content is essential. This recognises that the instructional strategy selected may affect how students reflect on and manage their mental processes, thereby influencing their problem-solving capacity and overall learning outcomes. The relationship identified by Moser et al. (2017) between students' prior knowledge and metacognition underscores the importance of accounting for individual variation when designing a learning process. Optimising the development of metacognition and, consequently, problem-solving abilities requires addressing these disparities.

Notably, the problem-based learning paradigm is beneficial in improving students' science process abilities. This bolsters the theory that the development of practical abilities in science is greatly aided by active involvement, inquiry-based learning, and problem-solving scenarios. Giving readers a clear understanding of the manuscript's goal gives them direction. The research will have a defined direction thanks to your focus on defining how applying a problem-based learning model to salt hydrolysis material affects science process abilities and metacognitive awareness in Class XI MIPA students at SMA Negeri 1 Dampal Selatan.

Problem-Based Learning in Salt Hydrolysis for Metacognition Growth

The 2013 curriculum in Indonesia places a strong emphasis on a learner-centred methodology to support learners' overall development. The curriculum emphasizes moving away from conventional teacher-centred methods toward student-centred ones. This entails motivating critical thinking, fostering autonomous inquiry, and actively involving students in the learning process—the 2013 curriculum centres on the acquisition of competencies, including skills, knowledge, and attitudes. In addition to imparting factual knowledge, the goal is to equip students with useful skills and positive attitudes towards learning (Amolloh et al., 2018).

The integration of a scientific approach across topics is one of the key features of the 2013 curriculum. Students are encouraged to use inquiry-based learning, observation, experimentation, and analysis to think and operate like scientists. Beyond scholastic achievement, the curriculum also prioritizes character education, aiming to instill moral principles, social awareness, and positive values to support students' holistic development into responsible members of society. While these aspects are not directly connected to specific subject content, such as the Periodic Table, they form part of the broader educational objectives outlined in the curriculum. This entails using ICT resources to improve education, advance digital literacy, and prepare pupils for the challenges of the contemporary world (Moreno-Marcos et al., 2020).

To effectively teach and succeed with the Problem-Based Learning (PBL) paradigm, one must comprehend its tenets, how to apply them, and how they could affect student performance (Scott, 2017). Problem-based learning is an educational strategy centred on real-world challenges. Students collaborate to understand the issue, identify relevant ideas, and use their expertise to solve it (Misnasanti et al., 2017). Problem-based learning (PBL) is a student-centred approach that engages learners through active involvement, inquiry, and collaboration. It emphasises applying knowledge to real-world situations while fostering problem-solving and critical thinking skills.

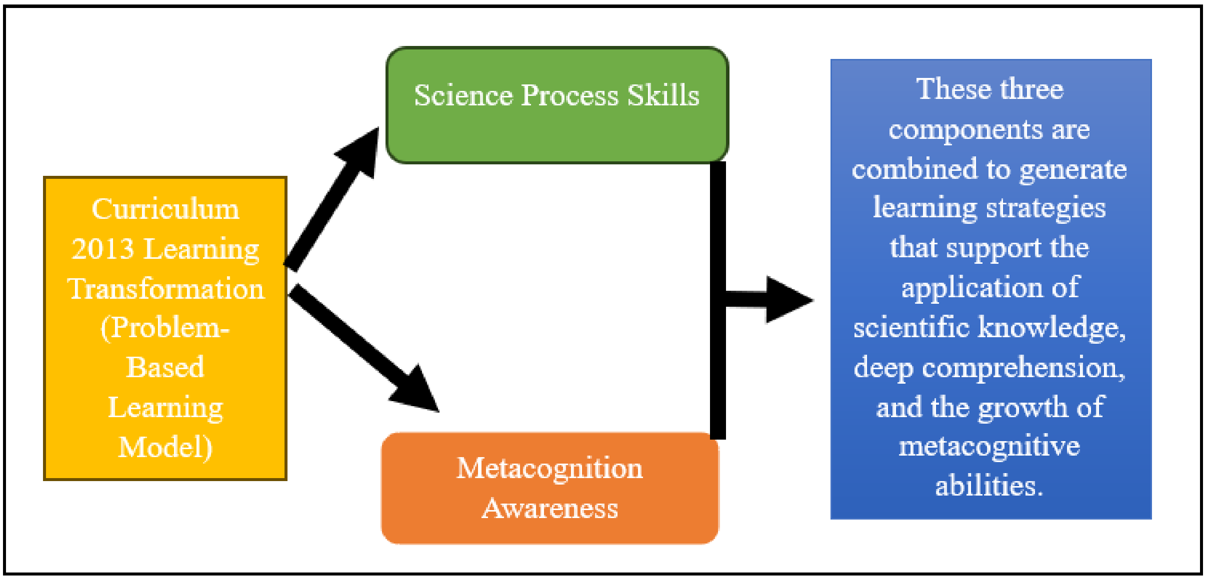
The teacher's role shifts from delivering content to facilitating and guiding students' learning. PBL frequently involves cooperative group projects that foster interpersonal, communication, and collaboration skills (Crespí et al., 2022). PBL helps students develop their critical thinking abilities by having them synthesise, evaluate, and apply knowledge to tackle challenging issues (Ali et al., 2019). Students are naturally motivated and interested in solving real-world challenges, which leads to a deeper understanding of the material. PBL emphasizes applying knowledge in real-world contexts to prepare students for the obstacles they may face. Additional time and material resources may be needed for PBL implementation (Vasiliene et al., 2020). Teachers might need training to guide student inquiry and facilitate PBL sessions. The development of metacognitive skills, which allow students to evaluate their own methods and approaches to learning, is a key component of success (Kasuga et al., 2022). Understanding the tenets, elements, advantages, difficulties, and success metrics of the problem-based learning approach is necessary before delving into it (Smith et al., 2022). PBL implementation requires meticulous planning, facilitation, and evaluation techniques to optimize student engagement, learning, and knowledge application. Interactive demonstrations, simulations, or multimedia materials can effectively illustrate salt hydrolysis processes. Visual aids can enhance understanding and retention.

Students should make concept maps that illustrate the connections between the various elements of salt hydrolysis. This facilitates information organization and understanding of processes. Encourage students to express their knowledge, concerns, and difficulties about salt hydrolysis during class discussions. Promote a cooperative learning atmosphere. In teaching salt hydrolysis, connecting the fundamental concepts to practical applications across various fields and everyday contexts can enhance relevance and student engagement. The use of technology, such as interactive simulations or virtual laboratories, can provide dynamic learning experiences. At the same time, exposure to complex scenarios that require applying salt hydrolysis principles can foster deeper conceptual understanding and strengthen problem-solving abilities (Seskir et al., 2022).

Metacognitive awareness entails reflecting on one's thought processes, including monitoring comprehension, controlling cognitive processes, and being conscious of how one learns. Metacognition enables individuals to actively regulate and enhance their cognitive processes, making it an essential component of learning and problem-solving (Tachie, 2019). being aware of the problem-solving process, keeping an eye on developments, and modifying tactics to overcome roadblocks. transferring information or abilities from one setting to another. Figure 1 shows the linkage of the 2013 Curriculum learning transformation in relation to problem-based learning, science process skills, and metacognition awareness.

Figure 1

Linkage of the 2013 curriculum learning transformation in relation to problem-based learning, science process skills, and metacognition awareness



In the domain of scientific learning, there is a strong relationship between the science thinking process, metacognition, and Problem-Based Learning (PBL) (Kuvac & Koc, 2019). The process of thinking scientifically involves observing events, developing hypotheses, carrying out experiments, analyzing data, and drawing conclusions. To solve issues or provide answers, scientific concepts must be used. Understanding and managing one's cognitive processes is a key component of metacognition (Cho & Linderman, 2019). It entails being aware of the cognitive techniques used, measuring comprehension, and being able to self-regulate to meet learning objectives. PBL is a teaching method in which pupils are presented with real issues and collaborate to find solutions. It promotes the use of information, critical thinking, and metacognition in the development and assessment of problem-solving techniques (Medina et al., 2017). These three components are combined to generate learning strategies that support the application of scientific knowledge, deep comprehension, and the growth of metacognitive abilities.

Methodology

A pretest-posttest control group is part of the quasi-experimental design used in this study's research methodology. While there are some parallels between experimental and quasi-experimental research, full randomisation of individuals to treatment and control groups is absent in the former. This lack of randomisation can introduce potential biases, such as selection bias, which may affect the results (Appelbaum et al., 2018). Based on initial observations, students' academic performance was relatively homogeneous, helping ensure comparable groups at the outset. To further address these limitations, efforts were made to match participants in the experimental and control groups based on key demographic and academic variables to control for potential confounding variables. In this design, the treatment and control groups have their dependent variables measured before and after the intervention.

Table 1

Tabulation of class characteristics data

Classes characteristics	Class XI MIPA 1	Class XI MIPA 4
Class Group	As an experimental class	As a control class
Number of Students	The class comprises 32 students.	Class XI MIPA 4 also consists of 32 students.
Gender Distribution	Within this class, there are 11 boys and 21 girls.	Similar to Class XI MIPA 1, this class includes 11 boys and 21 girls.
Age Range	The students in Class XI MIPA 1 range in age from 16 to 18 years.	The students in Class XI MIPA 4 range in age from 16 to 19 years.

Both classes are homogeneous in terms of student type distribution. This supports the internal validity of the research because both groups’ subjective characteristics, such as motivation to learn, interest in science, and preferred learning styles, are similar.

The experimental group received an intervention consisting of implementing HOTS-based LKPD using problem-based learning models. This intervention included a series of structured problem-solving activities designed to enhance critical thinking and science processing skills. The control group, on the other hand, used a discovery learning model with integration of HOTS-based LKPD. Both groups took a pretest to assess their initial knowledge and skills, followed by a posttest after the intervention to measure any changes in their performance. This design enabled a direct comparison of the effectiveness of the HOTS-based LKPD in improving students' critical thinking and science processing skills. Table 2 presents the pretest-posttest control-group design used in the study.

Table 2

Pretest-posttest control group design

Class	Pretest	Treatment	Posttest
Experiment	T	X	T
Control	T	Y	T

The study’s population consisted of 129 students from class XI MIPA at SMA Negeri Dampal Selatan. From this population, two classes were randomly selected as samples: class XI MIPA 1 (experimental group, 32 students) and class XI MIPA 4 (control group, 32 students). Simple random sampling was used to minimise selection bias and ensure each student had an equal chance of being selected, thereby supporting the external validity of the study.

Instruments

The instruments used in this study included: (1) a test of science process skills consisting of six open-ended questions, and (2) a metacognitive awareness inventory.

The science process skills test measured students’ abilities in observing, classifying, predicting, measuring, concluding, and communicating (Nurhayati et al., 2021). Each skill was assessed using specific open-ended questions designed to elicit responses that demonstrate students’ proficiency in that area. For example, observing was evaluated by asking students to describe phenomena they witnessed during experiments, while predicting required them to hypothesize outcomes based on given scenarios.

The metacognitive awareness inventory assessed students’ awareness and regulation of their own learning processes, providing insight into how they plan, monitor, and evaluate their learning strategies.

The Metacognitive Awareness Inventory (MAI) is the measure used by the metacognitive awareness tool. Fifty-two statements, comprising metacognitive knowledge (knowledge about cognition) and control of cognition with eight indications of metacognitive awareness, make up this inventory or questionnaire, which is used to assess students' metacognitive awareness. Declarative knowledge, procedural knowledge, and conditional knowledge are the three indicators that make up metacognition knowledge, or understanding of cognition. Planning, information management strategy, comprehension monitoring, strategic debugging, and assessment methods are the five indicators that make up the regulation of cognition. The MAI has been widely used in previous studies to assess metacognitive awareness, demonstrating good reliability and validity. For instance, studies by Schraw and Dennison (1994) reported high internal consistency with a Cronbach's alpha of 0.90, indicating strong reliability. Furthermore, the validity of the MAI has been supported by factor analysis, which confirms the inventory’s ability to measure distinct aspects of metacognitive awareness.

Experts' construction validity tests were employed as the validity test in this study. From a technical standpoint, an instrument grid, also known as an instrument development matrix, can help in construction validity testing. Indicators serve as benchmarks in this grid, and question item numbers are derived from them. This instrument grid makes validity testing simple and methodical. An expert validator who certified that the science process skills test instrument and the metacognition awareness questionnaire were suitable for data collection provided validity evidence for this instrument (Snyman & Kruger, 2019).

Validity

The validity of the science process skills test instrument and the metacognitive awareness questionnaire was confirmed by an expert validator, who certified that both instruments were appropriate for data collection (Snyman & Kruger, 2019).

Data Analysis

Data were analysed using both descriptive and inferential statistics. Descriptive statistics (mean, standard deviation) were used to summarise the data for each variable. Independent samples t-tests were conducted to determine whether there were significant differences between the experimental and control groups in science process skills and metacognitive awareness. Effect size (Cohen's d) was also calculated to assess the magnitude of these differences. All analyses were performed using SPSS version XX, with a significance level set at $p < 0.05$.

Findings/Results

The students' classical science process abilities in the experimental and control classes may be noticed in the pretest scores provided at the start of the session and the posttest scores collected at the end of the course. Table 3 shows the statistics on the experimental and control class students' science process skills.

Table 3

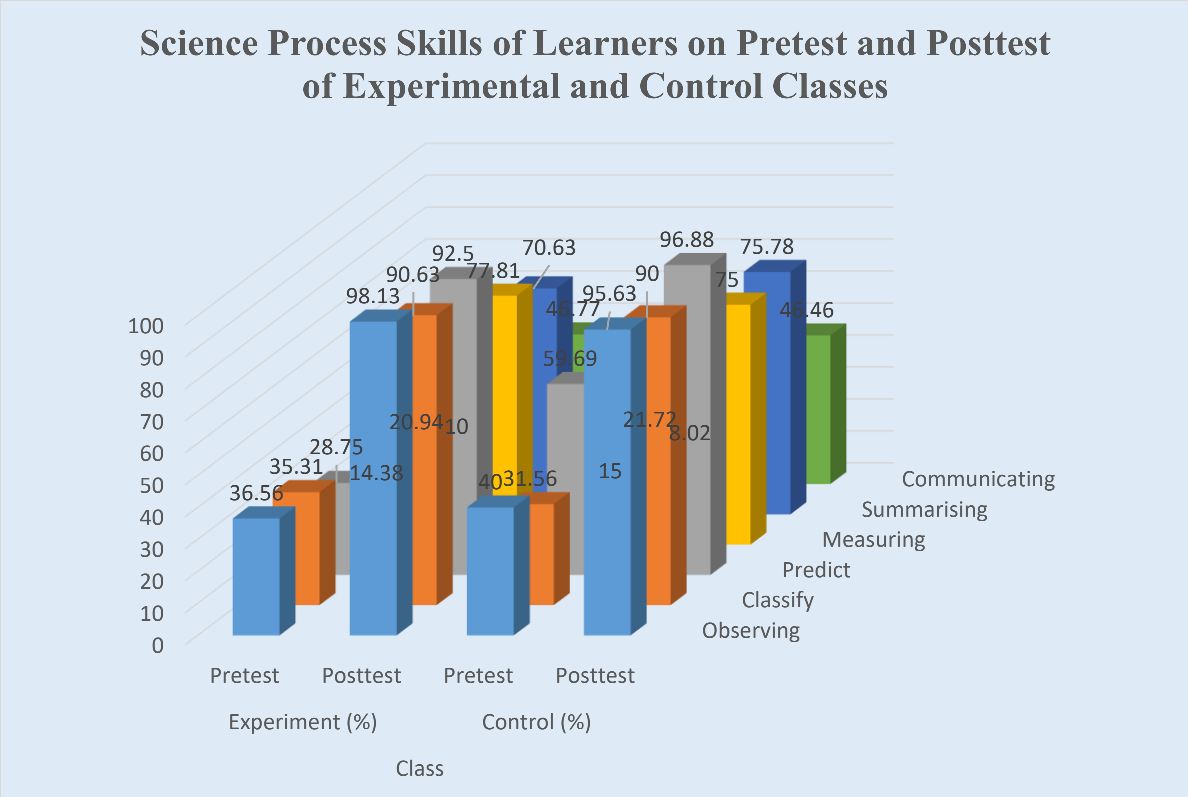
The value of the results of the pretest and posttest of the classical science process skills

Experiment Class			Control Class		
Description	Pre-Test	Post Test	Description	Pre-Test	Post Test
Sample	32	32	Sample	32	32
Lowest Score	16	58	Lowest Score	17	56
Highest Score	25	96	Highest Score	30	90
Average Score	20.13	71.84	Average Score	22.88	72.34
Standard Deviation	1.99	7.95	Standard Deviation	2.91	7.87

The increase in posttest scores for both research classes, particularly the experimental class's average score, is a strong signal that the intervention or learning approach used may have a favorable effect on students' capacity for science thinking. This finding is confirmed by statistical test results, specifically a *t*-test, which demonstrates considerable progress (p-value < 0.05) and indicates that the intervention was successful in enhancing students' capacity to think scientifically. The increase in posttest scores in both courses demonstrates that students in both the experimental and control classes improved after the intervention. The rise in scores following treatment in both classrooms demonstrates that both discovery learning (control class) and problem-based learning (experimental class) have a favorable effect on average student scores. Despite the increase in both groups, the control class's mean score (72.34) was greater than the experimental class's (71.84). This might imply that, in this unique situation, discovery learning outperformed problem-based learning in improving students' test results. This nuanced finding prompts a deeper analysis of why discovery learning might unexpectedly outperform PBL in certain metrics, which could be explored further in subsequent research.

Figure 2

Science process skills measurement results



The findings revealed that using problem-based learning (experimental class) and discovery learning (control class) models improved students' science process abilities in the context of studying salt hydrolysis.

This suggests that using problem-based learning to improve students' understanding and abilities in the context of salt hydrolysis may be more beneficial (QomariYah, 2019). The improvement in each criterion demonstrates that the applied learning approach was successful in enhancing students' science process abilities (Simamora et al., 2018). However, further research may be undertaken to understand better the precise components that contribute to the effectiveness of each learning model and the amount to which such variances may alter learning outcomes.

Table 4

Effect size of science process skills indicators for experimental and control class learners

	Experiment Class		Control Class	
Science Process Skills Indicators	Effect Size	Category	Effect Size	Category
Observing	7.00	Very large	5.56	Very large
Classifying	4.65	Very large	5.22	Very large
Predicting	7.01	Very large	2.82	Very large
Measuring	6.22	Very large	4.53	Very large
Concluding	5.40	Very large	5.35	Very large
Communicating	2.66	Very large	3.25	Very large

The findings revealed that using learning models in both experimental (problem-based learning) and control (discovery learning) classrooms had a significant impact on all markers of science process abilities. Further analysis found an intriguing contrast between the two groups, revealing the influence of each learning model as assessed by the effect size for each indicator. Both problem-based learning and discovery learning have a considerable positive influence on learners' science process abilities. The effect sizes observed in this study were consistently classified as very large, indicating meaningful practical significance in the classroom. For example, the very large effect size for observing suggests that students improved substantially in making detailed observations, a skill essential for conducting scientific investigations and experiments. Such improvements are likely to enhance students’ overall scientific reasoning and problem-solving abilities in real-world contexts.

Table 5

The value of the results of the pretest and posttest of the classical science process skills

Parameters	Class	
	Experiment	Control
M Pretest	20,13	22,88
M Posttest	71,84	72,34
Std. Deviation Pretest	1,996	2,915
Std. Deviation Posttest	7,956	7,872
Effect Size (d)	8,92	8,33
Criteria	Very large	Very large

The traditional data analysis indicates that the effect of using a problem-based learning strategy to increase students' science process abilities in salt hydrolysis material is extremely substantial. The same thing happened in the control class, which used the discovery learning approach and had a significant impact on strengthening students’ science process abilities on salt hydrolysis. Traditionally, the discovery learning approach has been used to encourage active participation, conceptual understanding, and inquiry-based exploration in science subjects, including chemistry. However, the experimental class had a larger effect size than the control class, suggesting that, compared to the discovery learning model, the problem-based learning approach is more effective at enhancing students’ science process abilities for the salt hydrolysis material.

Table 6

Dimensions of metacognition awareness level of experimental and control classes

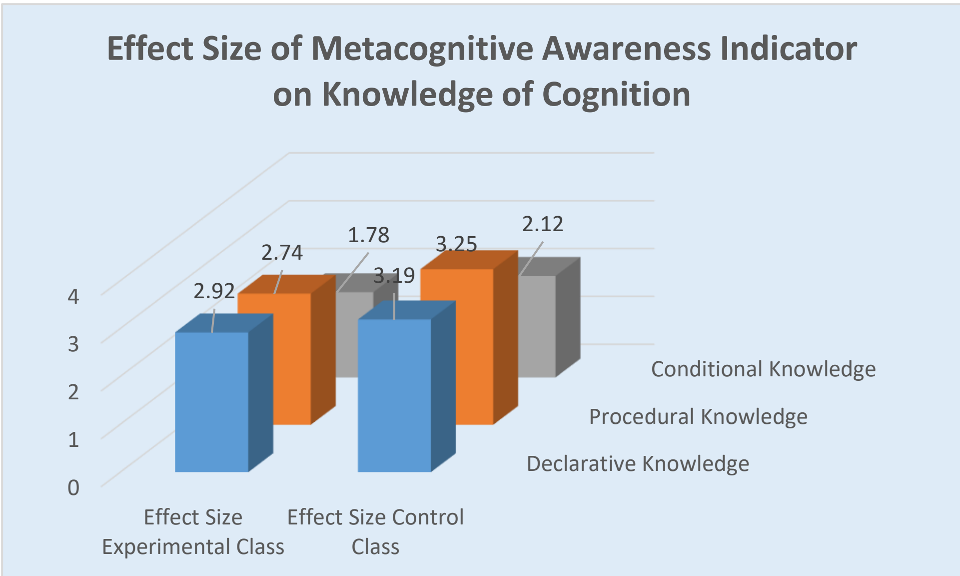
Metacognitive Awareness Indicator	Experiment Class				Control Class			
	Pretest		Posttest		Pretest		Posttest	
	Score (%)	Category	Score (%)	Category	Score (%)	Category	Score (%)	Category
Knowledge of Cognition								
Declarative Knowledge	55.18	Sufficient	79.69	High	56,93	Sufficient	79,20	High
Procedural Knowledge	56.35	Sufficient	77.93	High	56,25	Sufficient	78,71	High
Conditional Knowledge	52.81	Low	72.03	High	55,47	Sufficient	74,84	High

Average	54.78	Low	76.55	High	56,22	Sufficient	77,58	High
				Regulation of Cognition				
Planning	52,79	Low	72,66	High	53,01	Low	74,11	High
Information management strategies	54,06	Low	80,70	Very High	54,69	Low	80,08	Very High
Stabilisation of understanding	52,23	Low	76,00	High	53,79	Low	76,00	High
Improvement strategy	48,28	Low	80,47	Very High	50,00	Low	77,19	High
Evaluation	53,52	Low	77,31	High	54,82	Low	80,86	Very High
Average	52,18	Low	77,02	High	53,26	Low	77,65	High
Average Metacognitive Awareness	53,48	Low	76,79	High	54,74	Low	77,62	High

To see the effect size of students' metacognition awareness, calculate the effect size for each indicator. The effect size for metacognition awareness for each indicator is shown in Figure 2.

Figure 4

Effect size of indicators of metacognition awareness of experimental class and control class learners on cognition regulation



The findings revealed that using the learning model in both the experimental (problem-based learning) and the control (discovery learning) classes had a significant impact on all indices of metacognitive awareness. The problem-based learning approach has a significant impact on metacognition awareness, particularly the component of knowing about cognitive processes. The declarative knowledge indicator has the maximum impact size value of 2.92 in the dimension of knowledge about cognition. The indicator of stability of understanding had the maximum impact size value of 4.78 in the dimension of control of cognition. The discovery learning approach has a significant impact on all aspects and measures of metacognition awareness. The indicator of procedural knowledge has the maximum impact size value of 3.25 in the dimension of knowledge about cognition. The indicator of repair method has the largest impact size in the cognitive control dimension, at 5.83. On the metacognition awareness indicator, the control class showed a larger effect size than the experimental class. Discovery learning appears to have a greater influence on metacognition awareness than problem-based learning in this scenario.

Table 7

Hypothesis testing results of the relationship between science process skills and metacognition awareness

Variables	N	Sig (2-tailed)	Pearson Correlation
Science Process Skills	32	0,003	0,505
Metacognitive Awareness	32	0,004	0,506

The correlation analysis findings show a significance value of $p = 0.003$, which is below the 0.05 threshold, indicating a statistically significant relationship between science process abilities and metacognition awareness. The correlation coefficient ($r = 0.50$) explains approximately 25% of the variance shared between the two variables, suggesting that other factors account for the remaining variation. This association does not imply any direction of causality, but rather that students with higher levels of one tend also to have higher levels of the other.

Discussion

The problem-based learning (PBL) methodology is particularly appropriate for salt hydrolysis content because it encourages learners to become adept at addressing real-world situations (Zinsli, 2021). The PBL paradigm, for example, allows learners to actively engage in problem solving and grasp ideas in detail by answering questions such as "How do I know the nature of salt?" or "Why can salt lower the pH of the soil?" The PBL model is appropriate for salt hydrolysis material because it emphasizes solving real-world issues, such as investigating the effects of using fertilizers as a source of plant nutrients and the effects of salt decomposition on soil pH. This provides learners with a relevant context and makes learning more engaging (Kizilcec et al., 2017). Following the introduction of the PBL paradigm, observations revealed that learners' activities and interactions increased. This strategy allows for conversation, cooperation, and concept development, enhancing learners' interest in learning. The teacher's role is diminished in PBL, as students are encouraged to solve their own problems (Phungsuk et al., 2017). The instructor serves as a facilitator, directing and supporting the learning process. This allows students to improve their independence and problem-solving abilities (Robinson & Persky, 2020). PBL enables students to identify and solve issues on their own or in groups. This technique can help them connect theory to practical applications, such as salt hydrolysis. The relationship between PBL and students' increased engagement and understanding of salt hydrolysis material highlights the importance of problem-based learning approaches in science education. By guiding students to actively engage in solving real-world problems, PBL not only enhances conceptual understanding but also prepares students to apply their knowledge in real-life situations. This aligns with constructivist theory, where students build their understanding through interaction with the real world and through hands-on experiences.

The use of problem-based learning (PBL) in teaching salt hydrolysis has several notable benefits. The PBL paradigm begins with learners being introduced to the provided challenge. In this setting, the teacher poses a pertinent problem and encourages students to consider the nature of the salt produced by the neutralisation reaction. This technique gives learners a meaningful context and a clear aim (Roach et al., 2018). Learners may observe, identify required resources, and design problem-solving solutions.

Problem orientation is the first stage in adopting the problem-based learning (PBL) approach to salt hydrolysis material. This stage includes numerous critical goals, including assessing learners' understanding of required content and establishing challenging scenarios that might entice and inspire them to engage in investigative activities. The problem-orientation stage allows the instructor to assess learners' mastery of key preparatory information. This helps determine their initial level of comprehension before engaging with the salt hydrolysis content. The instructor creates a troublesome scenario by presenting an issue related to the nature of the salt produced by the neutralisation process. This boosts learners' attention and motivation. The challenge provides a real-world setting that can serve as a focus for study and problem-solving. Learners are encouraged to participate actively in observation. They can learn about the nature of salt solutions formed when acids and bases are combined by seeing them. The initial stage in acquiring and improving science process abilities is observation. Observation skills are not only important for understanding the nature of salt solutions, but they also serve as a springboard for the development of future science process skills.

Learners can improve analytical skills, data interpretation, and scientific judgment by witnessing events or experiments. As a result, the issue orientation step of PBL lays the groundwork for deep learning. It not only gives an early review of learners' learning, but it also increases their interest and motivation by presenting difficult problems from everyday life. Furthermore, learners' participation in observation allows for the development of critical scientific process abilities. The significant correlation between metacognitive awareness and science process skills in the experimental class suggests that PBL not only enhances conceptual understanding but also promotes metacognitive development. Metacognitive awareness enables students to plan, monitor, and evaluate their learning processes, thereby strengthening their abilities in scientific processes such as observation, data interpretation, and decision-making. The important implication of this finding is that integrating metacognitive exercises into the science curriculum can further enhance students' science process skills, which are crucial for their success in scientific fields.

Observation is an important part of problem-based learning (PBL). Learners are expected to engage in assessing what they know and recognizing their needs from the start to progress to the next stage of learning. In this case, observation is accomplished by asking questions about instances of salt compounds encountered in ordinary life. Learners are invited to think about and respond to questions concerning real-life examples of salt compounds. Learners' initial understanding of salt compounds is reflected in their responses, which include noting table salt (NaCl), NH_4Cl, and CH_3COONa. The instructor then randomly divides the class into groups. This group divide can encourage learners to collaborate, improve their learning through cooperation, and spark different viewpoints that can be used in issue-solving. A Learner Worksheet (LKPD) is distributed to each group, which acts as a problem or job to be completed during problem-based learning. The LKPD becomes the focal point of group activity to study further and address the difficulties presented. For learners to build problem-solving techniques, LKPD serves as a guide or starting point. Learners are required to plan the following steps, beginning with more observations and experiments and ending with the creation of solutions, by comprehending the issues specified in the LKPD. Learners actively participate in the observation and inquiry stages by responding to the questions and focusing on the LKPD. This offers a learner-centered environment where learners can build their own knowledge and problem-solving skills. Learners can also supplement one another's knowledge and expertise by working in groups.

In the second level of the problem-based learning (PBL) approach, learners are organized to learn actively and cooperatively. This stage aims to encourage students to seek information from diverse sources regarding the difficulties identified in the first phase. Learners are tasked with locating information about the highlighted problem. Textbooks, scientific journals, internet sources, and related experiments can all be used to get information. Learners are encouraged to take an active role in researching a wide range of relevant sources of knowledge. Although PBL has proven effective in enhancing understanding and science process skills, this study's methodology has certain limitations. For instance, the non-randomisation of groups in this study may introduce selection bias, potentially affecting the internal validity of the results. Additionally, external variables such as differences in teacher quality or student motivation, which were not controlled, may influence the outcomes. A critical reflection on these limitations is important for informing the interpretation of the results and the design of future studies.

Conducting individual or group investigations is the third phase in the problem-based learning (PBL) methodology. At this step, learners are tasked with planning and conducting an inquiry to test a previously formulated hypothesis. The use of the PBL approach helps students to identify solutions to challenges on their own. Teachers may monitor learners' capacity to identify, test, and record the outcomes of experiments in this setting, which are signs of success in scientific inquiry (Orhan Göksün & Gürsoy, 2019). Based on these findings, it is possible to infer that using the PBL paradigm effectively inspires learners to actively participate in the study while also developing their scientific and analytical skills.

The fourth phase of the problem-based learning (PBL) methodology is to create and showcase learners' work. At this step, students collaborate in groups to present their research findings and solutions. Data interpretation and communication skills are two parts of the science process abilities that are gained at this level. By the end of this level, learners have mastered not only data interpretation and communication skills but also the process of generating scientific findings and presenting information effectively. During this stage, the PBL approach assists learners in connecting their newly acquired knowledge and abilities to real-world situations by linking theoretical concepts with practical applications through tangible presentations (Ballesteros et al., 2019). Given the findings that discovery learning has shown superiority in certain aspects over PBL, future research could focus on the specific conditions under which each teaching method excels. For instance, comparative studies investigating how learning context, student characteristics, or the type of learning content influence the effectiveness of PBL and discovery learning could provide educators with further insights for selecting appropriate teaching strategies for specific situations.

The fifth phase in the problem-based learning (PBL) paradigm includes learners analysing and assessing their problem-solving process. At this step, learners provide feedback on other groups' work to determine each group's strengths and weaknesses. After receiving feedback and development ideas from the teacher and other groups, learners determine the best problem-solving strategy to use. Communication abilities are among the science process skills gained at this level. This level promotes interpersonal communication skills, the capacity to provide and receive constructive criticism, and the ability to think critically about ideas and solutions presented by other groups by integrating learners in peer review (Vong & Kaewurai, 2017). It also promotes a reflective mindset, which can help learners consistently improve their quality. The practical implications of these findings are significant for educators seeking to implement PBL in science teaching. Teachers can apply PBL to enhance student engagement and develop their science process skills by providing relevant contexts and encouraging active exploration. Challenges that may arise include the need for additional teacher training to adopt the role of facilitator, as well as the need to design PBL tasks that genuinely reflect real-world problems. However, the benefits of deep learning and the development of critical thinking and problem-solving skills make PBL a valuable approach in science education.

The findings of the experimental class's pretest and posttest, which showed an improvement in average score from 20.13 (pretest) to 71.84 (posttest), demonstrated the usefulness of the problem-based learning (PBL) learning model in boosting students' comprehension and knowledge. Some of the contributing variables highlighted in the description are: The adoption of the PBL model through defined stages lays the groundwork for learners to be actively involved in the learning process. PBL encourages learners to engage in exploration and problem-solving rather than simply receiving knowledge passively (Y. Liu & Pásztor, 2022).

The teacher's straightforward presentation of the idea of salt hydrolysis, supplemented by instructional resources in the form of LKPD and modules, provides students with clear direction and a solid framework for understanding. Teachers employ LKPD and modules built on the PBL paradigm, which provide practical, meaningful contexts for salt hydrolysis. The first meeting's observation and problem-solving exercises on the nature of salt provide an introduction to the notion of acid-base solutions as necessary material. This helps learners connect known concepts to the new content they are learning. The instructor employs a contextual learning strategy by connecting the information to real-life circumstances. However, further research might focus on the longitudinal effects of PBL on students' learning outcomes. It would be beneficial to investigate how sustained use of PBL impacts students' ability to apply scientific concepts over time, particularly in different learning environments or across diverse student populations.

According to the results of the study in Table 7, there was a high link between science process abilities and students' metacognition awareness in the experimental class that used the problem-based learning paradigm. That is, there is a strong positive association between the experimental class's level of metacognition awareness and science process abilities. This suggests that learners with a high level of metacognitive awareness also have stronger science process abilities. In other words, excellent metacognitive awareness can aid in the development of scientific process abilities. Meanwhile, the Pearson correlation coefficient was 0.505 in the control class using the discovery learning model. According to the correlation test criteria in Table 7, this result indicates a strong association between science process abilities and students' metacognition awareness in the control class. Although not as strong as in the experimental class, the control class shows a substantial positive relationship between metacognition awareness and students' science process abilities. As a result, it is possible to conclude that there is a favourable relationship between metacognitive awareness and students' science process abilities in both experimental and control classrooms. However, the experimental class showed a stronger correlation than the control class, suggesting that the problem-based learning paradigm has the potential to strengthen the link between the two variables. The findings suggest that educators might consider integrating more metacognitive strategies into their PBL approaches to enhance students' science process skills further. This could include activities that promote self-reflection, goal-setting, and self-assessment, helping students become more aware of their own learning processes and develop stronger scientific inquiry skills.

Conclusion

Several significant themes may be drawn from the study and discussion outcomes. The use of the problem-based learning (PBL) paradigm improves students' science process skills in the context of salt hydrolysis. This is evident in the extremely large effect sizes for both the experimental (8.92) and control (8.33) classes. This suggests that PBL can significantly improve students' abilities in the scientific process. The use of a problem-based learning strategy improves students' metacognition awareness of salt hydrolysis information. The experimental class had an effect size of 5.56 (very big), whereas the control class had an effect size of 6.46 (extremely large). This demonstrates that using PBL may dramatically increase students' metacognition awareness. On salt hydrolysis material, there is a positive association between science process abilities and students' metacognition awareness. The Pearson correlation coefficient of 0.772 in the experimental class indicates a substantial relationship between the two variables. In the control class, the Pearson correlation coefficient of 0.505 indicates a moderate relationship, accounting for approximately 25% of the shared variance, with the remainder attributable to other factors. This suggests that pupils with strong science process abilities have more metacognition awareness, and vice versa. Thus, the findings revealed that using a problem-based learning approach not only had a good influence on students' science process abilities and metacognition awareness, but also demonstrated a positive association between the two variables.

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The potential of the integrated project-based and 4C-scaffolding (Pj4CS) learning model to increase prospective biology teachers' global 4C skills

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ABSTRACT
Research on identifying 4C skills using the Pj4CS model remains limited, especially in biology education. Preliminary studies indicate that the 4C skills of prospective biology teachers still need improvement and optimal utilization in classroom learning. This study aims to analyze the potential of the Integrated Project-Based and 4C-Scaffolding (Pj4CS) model to increase global 4C skills (Critical Thinking, Communication, Collaboration, and Creativity). This research type is a quasi-experiment. The research instrument was valid and reliable before data collection. The research results showed differences in 4C skills between the pretest and posttest in the Pj4CS model. The *t*-test results showed significance at the 0.000 level for critical thinking, communication, collaboration, and creativity. A significance value of less than 0.05 indicated that the Pj4CS model effectively improved students' critical thinking, communication, collaboration, and creativity. Providing appropriate scaffolding in project-based learning helps students produce more creative project products. The Pj4CS model has been shown to positively impact improving aspects of critical thinking, communication skills, collaboration skills, and creativity, which are important life skills that must be developed in today's learning. Students are trained to develop critical thinking and communication skills through collaborative project design. The syntax of the Pj4CS model positively empowers 4C skills in biology learning. The research concludes that the Pj4CS model can improve 4C global skills (critical thinking, communication, collaboration, and creativity).

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Introduction

The rapid development of the digital era presents challenges for universities in preparing globally competitive graduates with 21st-century skills (Asrizal et al., 2022; Haviz et al., 2020; Hrechanyk et al., 2023). Education in the 21st century aims to build students' intelligence competencies to learn and overcome surrounding problems and the challenges of the Industrial Revolution 4.0 (Asrizal et al., 2025; Effendi et al., 2020; Le et al., 2022; Proud & Potter, 2020). Intelligence in the real world is not only about what prospective teachers know, but also about their ability to solve problems in meaningful, contextual ways (Desgamalia & Syamsurizal, 2019; Van Laar et al., 2017; Villena Taranilla et al., 2019). Critical thinking, communication, collaboration, and creativity are soft skills needed in a career and in the future (Hunaidah et al., 2018; P21 (Partnership for 21st Century Skills), 2011; Tang et al., 2020; Triana et al., 2020). Students need comprehensive knowledge, skills, and attitudes to think and act appropriately (Abaniel, 2018; Ang, 2018; Kubitskyi et al., 2023; Malik, 2018). This can strengthen prospective biology teachers' global competence in facing the 21st-century challenges. Educators must consistently develop learning designs that accommodate 4C skills in delivering material in class (Jalinus et al., 2023; Sipayung et al., 2018; Teo, 2019).

In the principles of 21st-century learning, learning must be student-centered, collaborative, connected to the real world, and integrated with society (Asrizal et al., 2019; Supriyono & Prabowo, 2021; Wulandari et al., 2016). Communication and collaboration skills enable prospective biology teachers to interact competently and respectfully with others from various cultures, social backgrounds, and communities in the global era (Amin, Adiansyah, et al., 2023; Erdoğan, 2019). Collaboration and communication skills are essential for workplace success (Indrawati, 2021; Rosen et al., 2020). Authentic, real projects are crucial for providing opportunities to develop the skills needed in the job market (Arwizet & Saputra, 2019; Miller & Grooms, 2018). Through project implementation, prospective biology teachers can build knowledge and skills through inquiry. Integrating project-based strategies makes this learning method adaptable to students from various backgrounds, ages, and education levels (Nasir & Andrew, 2022). Effective learning should be designed to match graduates' capacity to apply knowledge in the workplace.

Job opportunities in the technology sector are currently increasing on an industrial scale. However, there remains a gap between job seekers' skills and the industry's competencies (Widarti et al., 2020). The low critical thinking skills of prospective biology teachers are caused by the learning process, which has not developed their reasoning skills (Amin & Adiansyah, 2023; Supena et al., 2021). The verbal and nonverbal communication skills of prospective biology teachers are still relatively low (Amin et al., 2022). Problems that occur in the learning process for prospective biology teachers include a lack of participation in asking questions and discussions, low courage to ask questions, low communication skills both verbally and in writing, and low problem-solving skills (Amin et al., 2020; Hastuti et al., 2022). Critical thinking skills do not develop automatically as they age and grow (Amin, Karmila, et al., 2023). This issue has widened the gap between the quality of graduates and the workforce's demand for 4C global competencies.

Mastering the 4C global skills (critical thinking, communication, collaboration, creativity) is necessary for students to develop the qualities needed for success in college, in their careers, and in citizenship in the 21st century. To direct learning towards 21st-century skills, educators must choose a learning model that involves students in teaching and learning to help them master the 4C skills. Educators must also design fun, creative, and innovative learning experiences and foster students' learning independence by integrating the 4C global skills into classroom instruction. Prospective teachers must compete and contribute to learning to achieve goals and success (All et al., 2021; Hwang, 2023; Li et al., 2021; Tapingkae et al., 2020). Project-based learning has been reported to contribute to deeper understanding and to the improvement of scientific attitudes in the classroom (Markula & Aksela, 2022). However, the Project-Based Learning model is not without its limitations. Several studies have identified various weaknesses in its implementation within classroom settings. For instance, prospective biology teachers often require extended time to plan and develop their projects (Grant, 2002). During Project-Based Learning, students frequently struggle to generate innovative ideas, collaborate effectively to develop them, and resolve intragroup conflicts through negotiation (Sumarni, 2015). To address these limitations, students can be guided toward greater independence by employing a modified project-based learning model that incorporates simplified learning stages while still fostering the development of 4C global competencies. This approach is embodied in the Pj4CS model.

Pj4CS is a new learning model designed to facilitate critical thinking, communication, collaboration, and creativity by providing scaffolding for students' needs. There has not been much research on applying Pj4CS in biology learning. The Pj4CS model is expected to provide a new color in learning that is more independent, meaningful, and in line with the needs of 21st-century learning. In this learning model, educators serve primarily as facilitators and directors, while each collaborative group generates the project design and ideas. When students encounter difficulties, educators provide scaffolding tailored to individual needs. This support includes technical guidance on using digital tools such as Canva, Mendeley, AI applications, and other relevant technologies to enhance the creativity, structure, and visual quality of students' final products. The learning environment is intentionally structured to enable students to manage their own learning processes as they work toward completing their projects. This approach fosters student autonomy and supports the development of individuals who are not only academically capable but also adaptive, creative, and responsible (Amin & Karmila, 2024).

This result can contribute to science education in instructional learning, especially regarding new learning models. In biology education, this research can strengthen students' 4C skills by enhancing their biological scientific literacy. Apart from that, this research also enriches the theoretical repertoire regarding educators' (teachers and lecturers') professional skills in addressing the global challenges of the Industry 4.0 and Society 5.0 era. At the practical level, research can serve as a basis for designing new learning designs and for further research on implementing learning models in the classroom. This study aims to analyze the potential of the Integrated Project-Based and 4C-Scaffolding (Pj4CS) model to increase global 4C skills (Critical Thinking, Communication, Collaboration, and Creativity).

To guide our research, we propose the following research questions.

1. How does the Integrated Project-Based and 4C-Scaffolding (Pj4CS) model influence the critical thinking of pre-service biology students?
2. How does the Integrated Project-Based and 4C-Scaffolding (Pj4CS) model influence the communication skills of pre-service biology students?
3. How does the Integrated Project-Based and 4C-Scaffolding (Pj4CS) model influence collaboration skills among pre-service biology students?
4. How does the Integrated Project-Based and 4C-Scaffolding (Pj4CS) model promote creativity in pre-service biology students?

Literature Review

Critical thinking skills direct students to formulate, identify, and solve problems by providing logical arguments (Lestari et al., 2021; Novitra et al., 2021; M. A. Samsudin et al., 2020; Utaminingsih et al., 2024). The project-based learning model, integrated with 21st-century skills, guides prospective biology teachers to collaborate and form teams to complete planned projects (Anazifa & Djukri, 2017; Raiyn, 2016). Applying project-based learning integrated with 21st-century skills can improve higher-order thinking skills (Hujjatusnaini et al., 2022; Suryandari et al., 2021). The project-based learning model can train thinking skills, make them more critical of each problem, and help them analyze it based on their experience (Asman et al., 2022; Pratama et al., 2018).

To accommodate the needs for 4C skill development, project-based learning can be applied. Critical thinking skills are important for encouraging student independence and training their ability to solve scientific problems. Project-based learning can develop higher-order thinking skills by having students express ideas and arguments related to the project they work on (Choi et al., 2019; Rati et al., 2023; Szalay et al., 2024). The problems that arise prompt students to develop their projects and to formulate related basic questions (Bhakti et al., 2020; Kokotsaki et al., 2016). Students in project-based learning are trained to explore, analyze, interpret, synthesize, and evaluate information to improve thinking skills and learning success (Astra et al., 2019; Somphol et al., 2022).

Previous studies indicate that the Pj4CS learning model significantly enhances pupils' critical thinking skills (Hama & Amin, 2025). For instance, in experimental classes, the critical reading phase trained prospective biology teachers to engage actively and critically with the learning materials, such as e-books and handouts. This engagement fostered teachers' perspectives on collecting, processing, analyzing, and evaluating information critically (González-Cespón et al., 2024). In the study, critical thinking enabled the students to identify and select valid, relevant, high-quality, and verified sources of information.

The advantage of project-based learning combined with 4Cs skills is that it can motivate students to engage in critical thinking actively (Efendi et al., 2020; Listiqowati et al., 2022). Regional potential-based project learning has improved students' 4C skills (Syahril et al., 2022). Integrating project-based learning into science instruction has the advantage of improving critical thinking skills and of assessing biology teachers' perspectives (Maryuningsih et al., 2019).

In addition, the Pj4CS model has been shown to impact digital literacy positively (Amin et al., 2025). Scaffolding in the form of structured guidance, such as training in using digital tools like Canva and artificial intelligence applications, helped students enhance the quality and creativity of their project work. Students responded enthusiastically to these digital tools, especially when they were contextualized within biology learning. Furthermore, the Pj4CS model has proven effective in strengthening analytical thinking and communication-argumentation skills (Amin et al., 2025).

The Pj4CS model encourages prospective biology teachers to get involved in learning activities, thereby enhancing overall learning effectiveness. It has also been found to reduce biological misconceptions (Amin & Karmila, 2024). One of its core components, the *collaborative participation* phase, aims to foster a cooperative learning environment conducive to successful project development. During this phase, prospective biology teachers engage in activities such as observing, associating, experimenting, discussing, and exchanging ideas related to the project. Educators play a supportive role by facilitating group collaboration and guiding the effective use of digital tools and media to ensure the success of the project design (Amin & Karmila, 2024).

Research on the Pj4CS model remains limited, as it is a relatively new instructional approach developed by scholars. However, numerous studies have explored the integration of Project-Based Learning (PjBL) with various other instructional strategies. For example, combining prospective teachers' advanced thinking abilities can significantly improve their cognitive learning outcomes (Liline et al., 2024). Similarly, the use of science project-based learning modules can strengthen students' problem-solving skills in a collaborative learning environment, thereby fostering critical thinking, promoting teamwork, and improving academic performance (Ghazali et al., 2025).

Methods

Research Design

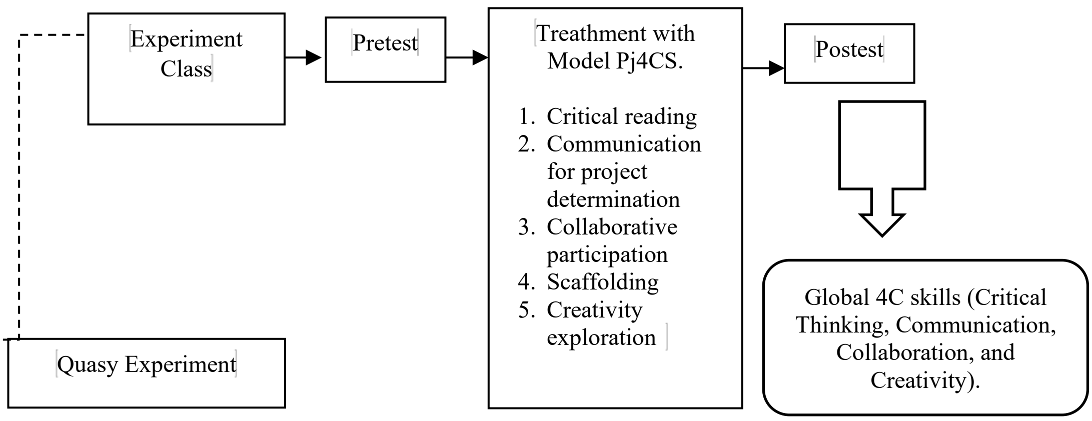
This research type is a quasi-experiment (Creswell & Clark, 2011). The experimental design used was a one-group pretest-posttest. The research sample was 22 prospective biology teachers. A pretest was conducted before learning to determine students' initial skills (Wisdom & Creswell, 2013).

Research Procedure

The experimental class was taught using the Pj4CS model. The steps of the Pj4CS learning model consist of critical reading, communication for project determination, collaborative participation, scaffolding, and creative exploration. At the critical reading stage, lecturers assigned students to read and analyze essential concepts/material, checked and identified their critical reading results, and provided reflections on essential concepts/material. During the project determination stage, the lecturer organized students into project groups and asked them to communicate internally to determine which project to design. At the collaborative participation stage, the lecturer assigned each project group to collaborate on implementing the project design and to search for project concepts and supporting materials online. At the scaffolding stage, the lecturer provided guidance and support for using media/ICT relevant to the group's needs. Guidance from lecturers took the form of using Canva, Mendeley, e-library, and other media applications. At the creativity exploration stage, the lecturer allowed each group to create products using the given material and display their results to the class. Lecturers rewarded each project group's achievements (Amin & Karmila, 2024). This Pj4CS learning syntax is applied to lectures on human body anatomy and physiology, covering the musculoskeletal, integumentary, nervous, endocrine, urinary, lymphatic, respiratory, digestive, circulatory, and reproductive systems. The research flowchart is shown in Figure 1 below.

Figure 1

Research flowchart



Research data are collected through several activities. The first activity was a pretest. The test used an essay question type. Questionnaires were also used to determine students' motivation. Students' initial critical thinking, communication, collaboration, and creativity skills were measured using tests. Measurement of these variables was conducted on 22 prospective biology teachers. After the pretest, the researcher conducted lectures using the Pj4CS learning syntax. Observations were conducted during lectures to collect data on the implementation of learning syntax and communication skills. At the critical reading stage, students are assigned e-books, e-modules, and journal articles on research findings to support learning in human anatomy and physiology. During the project-determination stage, students are grouped into five teams and assigned tasks to design projects related to human anatomy and physiology. At the collaborative participation stage, each group collaborates to realize their project design and conducts monitoring, including managing time and resources, finding and using learning resources, taking responsibility for each task, and maintaining consistency in implementing project stages according to plan. At the creativity exploration stage, each group presents the project's creative products and contributes to the class exhibition. One partner lecturer and two observers observe the Pj4CS learning process to review the implementation of the Pj4CS learning stages.

The researcher administered a posttest consisting of a questionnaire and an essay at the last meeting. Questionnaires were used to determine students' motivation. The student learning motivation questionnaire comprises 52 statement items, both positive and negative, covering aspects of attention, relevance, confidence, and satisfaction. This motivation questionnaire used a Likert scale.

Students' final critical thinking, communication, collaboration, and creativity skills were measured using tests. The next activity was to provide student response questionnaires on implementing the Integrated Project-Based and 4C-Scaffolding (Pj4CS) learning model. The series of activities closed with a learning reflection. Reflection aims to analyze prospective biology teachers' responses to the applied learning model and to evaluate the potential and shortcomings of the Pj4CS model. Table 1 presents the steps (syntax) of the Pj4CS learning model, outlining the specific activities carried out by both the lecturer and the students.

Table 1

Pj4CS syntax/learning stages

Syntax	Learning Activities	
	Lecturer	Students
Step 1. *Critical Reading*	1. Assigns students to read and analyze essential concepts/materials. 2. Checks and identifies the results of students' critical reading process and provides reflection on essential concepts/materials.	1. Read and analyze essential concepts/materials. 2. Clarify the identification results from the critical reading process.
Step 2. *Communication for project determination*	1. Organizes students into project groups 2. Asks students to communicate with each other within their respective groups to determine the project	1. Students sit in groups 2. Communicate project design ideas in their respective groups
Step 3. *Collaborative participation*	1. Assign students to collaborate in groups and complete the assigned project tasks. 2. Asks each group to search for concepts/material to support the project on the internet	1. Students work together in groups and collaborate to complete pre-designed project assignments. 2. Search for concepts/supporting project materials via the internet.
Step 4. *Scaffolding*	1. Provides scaffolding according to the needs of each project group. 2. Guides the use of media/ICT, AI applications that are relevant to the needs of the group. Guidance can take the form of showing students how to use Canva, Mendeley, the e-library, AI, and other media.	1. Follow the scaffolding provided by the lecturer. 2. Ask for the lecturer's guidance that is relevant to the group's needs.

Syntax	Learning Activities	
	Lecturer	Students
Step 5. *Creativity Exploration*	1. Offers each group the opportunity to be creative in producing products after understanding the material. 2. Asks each group to display their products in front of the class and award each group's achievements.	1. Each group explores its creativity to produce projects such as learning posters, e-modules, brochures, learning videos, and others. 2. Display the products in front of the class.

Research Instrument

The research instruments measured critical thinking, communication, collaboration, and creativity skills. Data on critical thinking skill scores are obtained through an essay test. Critical thinking skills scores were obtained using the critical thinking skills scoring guide developed by Zubaidah et al. (2015 which is an adaptation of the Illinois Critical Thinking Essay Test and Scoring Guidelines. The assessment consists of 5 scales (0-5). Communication skills data are collected through observation sheets during the discussion and presentation. The guide was an adaptation of NEA and P21, which includes four indicators: speaking, listening, writing, and non-verbal (NEA, 2012; P21 (Partnership for 21st Century Skills), 2011).

Collaboration skill data refers to indicators of responsibility, respect for others, contributions, ability to organize work, and working as a team. Meanwhile, creativity data refers to indicators of originality, fluency, flexibility, elaboration, and risk-taking. The assessment was carried out through questions and observation sheets. The prepared questions are high-level reasoning essay questions that assess originality, fluency, flexibility, elaboration, and risk-taking in the material on human anatomy and physiology. Previously, a question grid was prepared that referenced the creativity indicators, learning objective achievement, and the cognitive level of the questions. Meanwhile, the observation sheet is used to assess the project process and product which is reflected by the originality indicators (new and unique ideas generated during the project assignment), elaboration (the ability used in working on the project and producing project products), fluency (the number of creative and innovative ideas that are relevant to the project assignment problem), flexibility (the ability to change the approach used if the problem requires a new approach in completing the project task), risk taking (willing to try new things in completing the project task on time). The creativity observation sheet is conducted throughout the learning process, with assistance from partner lecturers and two observers.

The research instrument underwent expert and empirical validation. Three biology education lecturers carried out expert validation. The following summarizes the average expert validation scores.

Table 2

The average scores of expert validation

Research Instrument	Average Score of Expert Validation	Category
Critical Thinking	3.63	Valid
Communication	3.75	Valid
Collaboration	3,68	Valid
Creativity	3,71	Valid

The validity test of the research instrument was conducted by correlating each item score with the total score using the Pearson product-moment correlation coefficient. The test criterion is that if the correlation coefficient exceeds the Product-Moment r-table, the questionnaire items are valid data-collection instruments. From the validity test with a sample size of n = 21 and a significance level ∝ = 0.05, the r-table value is 0.433. Questionnaire reliability was assessed using the Alpha-Cronbach formula. The test criteria state that the questionnaire items are reliable if the Cronbach's alpha is greater than 0.6. The following summarizes the research instrument's empirical validation and reliability test results.

Table 3

Results of the empirical validity and reliability test of the research instrument

Research Instrument	Validity Test Result	Reliability Test Result
Critical Thinking	0.626 (all items are valid)	0.774 (all items are consistent or reliable)
Communication	0.613 (all items are valid)	0.974 (all items are consistent or reliable)
Collaboration	0.585 (all items are valid)	0.939 (all items are consistent or reliable)
Creativity	0.518 (all items are valid)	0.945 (all items are consistent or reliable)

Data Analysis

Research data are analyzed descriptively and inferentially. Descriptive analysis provided a profile description of critical thinking, communication, collaboration, and creativity skills. The inferential analysis tested the influence of the Pj4CS model on critical thinking, communication, collaboration, and creativity, to assess its potential as a predictor of the dependent variable. Data were analyzed using a paired *t*-test with a significance level of 5%.

Findings

The following presents the average scores for the 4C skills (critical thinking, communication, collaboration, and creativity).

Table 4

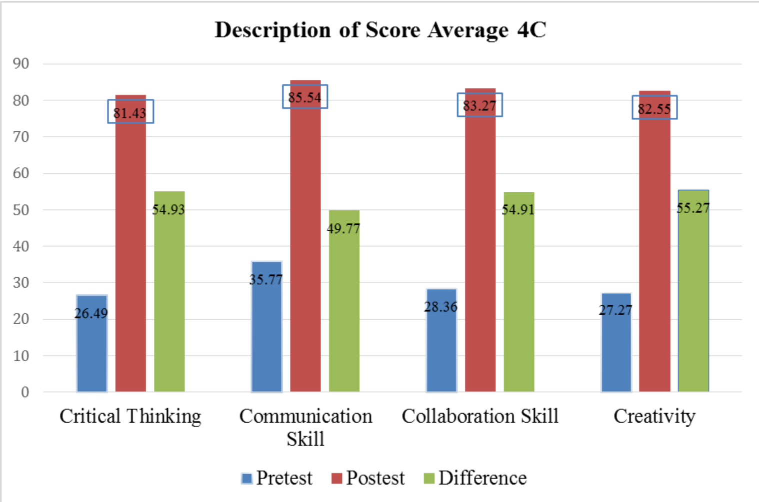
The average scores of 4C skills

Variable	Average			t count	P value	N Gain
	Pretest	Postest	Difference			
Critical Thinking	26.49	81.43	54.93	42.657	0.000	0.747
Communication	35.77	85.54	49.77	179.208	0.000	0.774
Collaboration	28.36	83.27	54.91	36.219	0.000	0.766
Creativity	27.27	82.55	55.27	34.698	0.000	0.760

Based on Table 4, students' 4C skills (critical thinking, communication, collaboration, and creativity) have increased after implementing the Pj4CS model. The difference obtained for the critical thinking skills is 54.93, the communication skills are 49.77, the collaboration skills are 54.91, and the creativity is 55.27. Before the hypothesis test, prerequisite tests, namely the normality and homogeneity-of-variance tests, were conducted. Based on the results of the normality test using the Kolmogorov-Smirnov test and the decision-making criteria with α = 0.05, the significance values (p-values) for the pretest and posttest on all variables were greater than 0.05 (p>0.05). This shows that the data on critical thinking, communication, collaboration, and creativity are normally distributed. Meanwhile, the homogeneity test produced a significance value (p-value) for the Levene test greater than 0.05 (p>0.05), so the pretest and posttest data for critical thinking, communication, collaboration, and creativity have homogeneous values. All variables had a significance of 0.000, which is less than 0.05. Therefore, H_0, which states that there is no difference between the pretest and posttest scores on 4C skills in the Pj4CS Model, is rejected. Thus, the research hypothesis is accepted. The comparison of average 4C skills after implementing the Pj4CS model is shown in the following figure.

Figure 2

The comparison of the score average 4C Skills after applying the Pj4CS learning model



Based on Figure 2, the highest post-test score was in communication, and the largest increase in difference was in creativity.

Discussion

The syntax of the Pj4CS learning model is proven to stimulate students' 4C skills. The critical reading stage in Pj4CS learning changes students' thinking skills. This opportunity affects students' classroom readiness. They have adequate prior knowledge to contribute actively to the next stage of Pj4CS learning. Students with critical thinking skills can write something essential and substantive because they can clearly and critically express various ideas (Cossu et al., 2024; Saad et al., 2024; Suteja & Setiawan, 2022). Critical thinking skills play an important role in analyzing decision-making and in making quality arguments to defend opinions, so that, in the future, students can survive in the working world (Islamiyati et al., 2023; Susilo et al., 2023). Students with strong reading skills also tend to have better reasoning skills (Zulyusri et al., 2023). Critical thinking must continue to be empowered in learning because it is the core of scientific development (Isra & Mufit, 2023). The development of cognitive skills is important for students' future academic and professional growth (Suryawati et al., 2024). Students' prior knowledge is increasingly recognized as a determining factor in science learning (A. Samsudin et al., 2024). The stages of the Pj4CS model have demonstrated effectiveness in stimulating students' critical thinking skills (Hama & Amin, 2025).

Educators in the second activity of the Pj4CS model, communication for project determination, act as facilitators and supervisors. Educators ensure that each group communicates internally during project design. The groups formed were heterogeneous, consisting of students with high, medium, and low prior academic knowledge. Excellent and effective communication skills will enable students to build strong relationships with others and the world (Fitriati et al., 2023; Omodan, 2023; Rati et al., 2023). One can quickly enter new situations using knowledge and good communication skills (Afikah et al., 2023; Alawamleh et al., 2022). If others cannot receive, understand, and listen to the message, communication cannot occur (Ilinitska et al., 2023; Munthe et al., 2023; Rahaman & Luczynski, 2024). Communication skills can only be achieved when discussion and confrontation of ideas among learners are promoted, with the need to convince themselves and others of the truth of their statements grounded in quality arguments (Rico et al., 2023). Prospective teachers need to be encouraged to develop scientific and communication skills so that future learning can be of higher quality and globally competitive (Baigabylov et al., 2025; Silverio et al., 2024). Understanding scientific concepts is one indicator of success in science learning (Winarni et al., 2024). Students with strong information and communication literacy skills exhibit greater capacity to access, assess, and use relevant information effectively (Akhtar et al., 2024; Nuraini et al., 2025). Research has demonstrated the effectiveness of the Pj4CS model in enhancing students' information processing and digital literacy, thereby fostering greater autonomy in project design (Amin et al., 2025).

Educators in this activity guide each group in building active collaboration and utilizing media and IT resources to support the design's success. This activity has been proven to increase group members' cooperation. Students in the experimental class are trained to observe, associate, compare, discuss, and communicate essential things that support project design. 21st-century learning requires students to be literate in developing and advancing information and communication technology and 4C skills (Muliyati et al., 2023; Pramasdyahsari et al., 2023; Siebers & Cobley, 2024). Project-based learning provides both independent and direct learning experiences for students, enabling them to develop 4C skills (Chang et al., 2024; Imansari et al., 2022; Shukor et al., 2023). Students' active collaboration and participation in learning can be seen in effective work activities, productivity, collaborative participation, and successful learning strategies (Ajani, 2023; Kuhlmann et al., 2023; Nahar et al., 2022). Student collaboration and active participation in learning can be seen in effective work activities, productivity, evaluation, and role-sharing and collaboration (Nahar et al., 2022). Fostering active student engagement and facilitating knowledge acquisition at higher cognitive levels necessitate complex interactions, often driven by significant innovations in instructional practices (Chohan et al., 2024; Labak et al., 2024).

In scaffolding activities within the Pj4CS model, educators guide each project group based on needs. Each group in the experimental class communicates the progress of their design and the obstacles they face in realizing it. Educators can also guide IT on project design and product needs, such as using the Canva application for designing project product presentations, citation management with Mendeley, e-library access, Artificial Intelligence (AI), and other structured guidance. High-performing learners generally demonstrate higher cognitive abilities in acquiring, integrating, and applying knowledge to projects (Mou, 2023; Tian et al., 2023). Students' performance is evaluated from five aspects: cognitive load, learning attitude, learning engagement, level of scientific knowledge, and skills (Kocsis & Molnár, 2024; Shaninah & Mohd Noor, 2024; Zhong et al., 2024). Prospective teachers must develop content knowledge and pedagogical strategies during their pre-professional practice, which is essential for their future teaching practice (Hernandez & Barrera, 2024). The use of IT in learning plays a very important role in the effectiveness of access to information and in the development of science skills (Rusdiyana et al., 2024). The syntax of the Pj4CS model can accommodate these learning needs.

The final activity, creativity exploration, in the Pj4CS model has been shown to stimulate and increase the creativity of students in experimental classes. At this stage, educators explore each student's potential so they can actively contribute creative ideas when designing products for their group projects. During project design discussions, students in each group express creative ideas and communicate with their group members to determine the project design. The project learning model stimulates students to produce creative and critical ideas and increases team collaboration to solve problems effectively (Crawford et al., 2024; Sugiharto et al., 2024; Syahril et al., 2022). Students require sufficient time to engage in the design and development of innovations and to navigate the challenges encountered throughout the project design process (Jituafua, 2024). The final phase of the Pj4CS model offers learners the opportunity to showcase their creativity and innovation by producing final outputs (Amin & Karmila, 2024).

The findings in the research are that the Pj4CS model positively influences critical thinking, communication, collaboration, and creativity, which are life skills that are important to cultivate in current learning. Implementing the Pj4CS model requires a fast adaptation pattern and adequate cognitive accommodation capabilities for students. The challenge for educators today is how to move from old learning patterns towards independent learning. The Pj4CS model has the advantage of having specific scaffolding stages at the learning stage. Educators and students must work together to achieve holistic, independent, and globally competitive learning success. Successful programs combine active learning, collaboration, and reflection, are often longitudinal and comprehensive, and impact student attitudes, knowledge, self-efficacy, and skills (Almonacid-Fierro et al., 2023; Langelaan et al., 2024; Nguyen et al., 2024). Improving students' critical thinking, communication, and argumentation skills can be achieved in a meaningful way when students' and educators' beliefs and motivations are integrated (Mavuru, 2024). Biological knowledge and pedagogical competence are essential for prospective biology teachers to develop effective teaching plans (Parmin et al., 2024). Learners can actively develop their understanding by engaging in real-world problems and achieving their goals through social interaction and sharing (Özkan et al., 2024). The Pj4CS model is well-suited to support these learning needs.

The Pj4CS model can serve as a learning model that accommodates 21st-century learning needs. Implementing the Pj4CS model development design can contribute to the development of classroom teaching and learning strategies. The Pj4CS learning model can improve aspects of life, such as science and technology. Learning syntax can strengthen students' scientific, digital, and life skills. The integration of critical thinking, communication, collaboration, and creativity aligns with the application of biology learning principles, enabling students to develop independence and a more vital scientific process attitude as they construct their knowledge and understanding. This research also contributes to previous findings on the role of scaffolding in students' development. Scaffolding affects students cognitively and emotionally; it impacts not only their skills and knowledge but also their motivation and confidence when undertaking project tasks. The application of the Pj4CS model is reviewed to support project-based learning and appropriate scaffolding. The application of this model can, in theory, contribute to education, especially by strengthening Vygotsky's learning theory and instructional practice. In practice, research results inform the development of applied research in biology education. The Pj4CS model can also serve as an alternative learning approach to support the development of digital literacy in secondary schools and universities (Amin et al., 2025).

Conclusion and Implications

The research hypothesis is accepted based on the research results and data analysis. The Integrated Project-Based and 4C-Scaffolding (Pj4CS) learning model significantly increases critical thinking, communication, collaboration, and creativity. Activities in Pj4CS learning can improve 4C skills. Students in biology education have more robust literacy, increased learning activities, and greater creativity and collaboration, fostering positive social attitudes that support learning success. The application of this model can, in theory, contribute to education, especially by strengthening Vygotsky's learning theory and instructional practice. At the practical level, this research can serve as a reference and basis for designing new learning designs and for supporting further research on implementing learning models in the classroom. It is hoped that the Pj4CS model can be implemented widely on a larger, more global scale. The Pj4CS model can serve as an alternative for educators across countries to address the gap between students' global skills and the needs of careers in the Industry 4.0 and Society 5.0 era. Future researchers can conduct studies using moderator variables to evaluate the potential of the Pj4CS model, such as gender, academic ability, and multiculturalism.

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Declaration of Interest

No conflict of interest.

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Appendix

Lesson Plan (Pj4CS Model)

Course Name	Human Anatomy and Physiology
Credit Hours/Semester	2 SKS/ VI
Course Description	*Human Anatomy and Physiology* is a compulsory 2-credit course offered in the even semester. It provides an in-depth study of the structural and functional organization of the human body. Key topics include levels of biological organization, anatomical and physiological terminology, homeostasis and feedback mechanisms, and the structure and function of major body systems. The course covers the nervous system (including neurons, neuroglia, central, peripheral, and autonomic components), special senses, integumentary, skeletal, muscular, and endocrine systems. Emphasis is placed on the anatomy and hormonal mechanisms of major endocrine glands, including the hypothalamus, pituitary, thyroid, parathyroid, pineal, thymus, pancreas, adrenal glands, and gonads.
Study Program Objectives	S1: Students are devoted to God Almighty and able to demonstrate a religious attitude. S9: Students demonstrate a responsible attitude towards work in their field of expertise independently. P10: The study program facilitates the development of students' biological science potential optimally KU 1: Students are able to apply logical, critical, systematic, and innovative thinking in developing or implementing science and technology that pays attention to and applies humanities values that are in accordance with their field of expertise. KU 2: Students are able to demonstrate independent, quality, and measurable performance. KU9: Students are able to document, store, secure, and rediscover data to ensure validity and avoid plagiarism. KK4: The study program facilitates the development of students' biological sciences to actualize their abilities and skills in the field of biology in real life at school/*madrasah* and in society.
Course Objectives	*CPMK* (Graduate Learning Outcomes Assigned to Courses) By the end of this course, students will be able to:

	1. Explain the levels of biological organization and apply anatomical and physiological terminology to describe the human body comprehensively. 2. Describe the principles of homeostasis and the mechanisms of feedback regulation. 3. Analyze the anatomy of neurons and neuroglia and explain the physiological basis of neural activity. 4. Identify and describe the normal anatomy and physiology of the central nervous system. 5. Identify and describe the anatomy and physiology of the peripheral nervous system. 6. Explain the structure and function of the autonomic nervous system. 7. Describe the anatomy and physiology of the special sensory organs. 8. Identify the structure and function of the integumentary system. 9. Describe the anatomical structure and physiological roles of the skeletal system. 10. Explain the anatomy and physiology of the muscular system. 11. Differentiate between endocrine and exocrine glands and explain the mechanisms of hormone action. 12. Identify the anatomy of the hypothalamus and pituitary glands and explain the hormonal regulation mechanisms involved. 13. Describe the anatomical structures of the thyroid, parathyroid, pineal, and thymus glands and the functional mechanisms of their respective hormones. 14. Examine the anatomy of the pancreas, adrenal glands, and gonads, and explain the mechanisms of action of the hormones they produce.
Learning Materials	1. Levels of organization in living organisms; terminology related to human anatomy and physiology. 2. Principles of homeostasis and feedback mechanisms. 3. Anatomy of neurons and neuroglia; mechanisms of neural activity. 4. Normal anatomy and physiology of the central nervous system. 5. Anatomy and physiology of the peripheral nervous system. 6. Anatomy and physiology of the autonomic nervous system. 7. Anatomy and physiology of the special senses. 8. Anatomy and physiology of the integumentary system. 9. Anatomy and physiology of the skeletal system. 10. Anatomy and physiology of the muscular system. 11. Structure and function of endocrine and exocrine glands; mechanisms of hormone action, with emphasis on the pancreas. 12. Anatomy of the hypothalamus and pituitary glands; hormonal regulation and mechanisms of hormone action. 13. Anatomy of the thyroid, parathyroid, pineal, and thymus glands; mechanisms of hormone production and function. 14. Anatomy of the pancreas, adrenal glands, and gonads; mechanisms of hormone production and action.
Learning Model	Pj4CS Model
Learning Methods	1. Question and answer method. 2. Integrated lecture method 3. Exploration method. 4. Problem-solving method. 5. Argumentative discussion method

Learning Media	**Software**: *PowerPoint files, animations, and learning videos related to human anatomy and physiology materials, biology learning charts, and* learning posters. **Hardware:** LCD & projector.
References	1. Tortora, Gerrard J., & Derrickson, B. (2013). *Principles of Anatomy and Physiology, 14th edition*. Wiley 2. Martini, F. H., E. F., Bartholomew, J. L., & Nath. (2017). *Fundamentals of Anatomy & Physiology*, 11th edition. Pearson. 3. Sherwood, L. (2014). Fisiologi Manusia dari Sel ke Sistem, Edisi 8. Penerbit EGC. 4. Campbell, *et.al.* 2008. *Biologi Jilid 3 Edisi Kedelapan.* Erlangga: Jakarta 5. Research journals related to human anatomy and physiology.

Learning Activities for the Integrated Project-Based Learning and 4C Global Competence-Scaffolding (Pj4CS)

No	Learning Activities (Syntax)	Lecturer's Activities	Student's Activities
	Warm-up Activities		
	Opening	1. Opens the lesson with greetings, a prayer, student attendance, and an apperception activity to activate prior knowledge. 2. Provides motivation by presenting animations relevant to the lecture material. 3. Communicates the learning objectives and explains the assessment methods to be used.	1. Listen to and follow the lecturer's instructions during the opening activities, including greetings, prayer, attendance, and apperception. 2. Pay attention to the motivational remarks and introductory statements delivered by the lecturer. 3. Listen to the explanation of learning objectives and assessment techniques.
	Main Activities		
	Step 1. *Critical Reading*	1. Assigns students to read and analyze essential concepts/materials. 2. Checks and identifies the results of students' critical reading process. 3. Provides reflection on essential concepts/materials.	1. Read and analyze essential concepts/materials. 2. Clarify the identification results from the critical reading process. 3. Listen to the reflection of essential concepts/materials carried out by the lecturer.

No	Learning Activities (Syntax)	Lecturer's Activities	Student's Activities
	Step 2. *Communication for project determination*	1. Organizes students into project groups. 2. Asks students to communicate with each other within their respective groups to determine the project	1. Listen to the lecturer while s/he forms the groups. 2. Communicate project design ideas in their respective groups
	Step 3. *Collaborative participation*	1. Assigns students to collaborate to realize the project's design 2. Asks each group to search for concepts/material to support the project on the internet	1. Collaborate to realize the previously determined project design. 2. Search for concepts/supporting project materials via the internet.
	Step 4. *Scaffolding*	1. Provides scaffolding according to the needs of each project group. 2. Provides guidance on the use of media/ICT, AI applications that are relevant to the needs of the group. Guidance can be in the form of showing students how to use the Canva application, Mendeley, e-library, AI, and other media.	1. Follow the scaffolding provided by the lecturer. 2. Ask for the lecturer's guidance that is relevant to the group's needs.
	Step 5. *Creativity Exploration*	1. Offers each group the opportunity to be creative in producing products after understanding the material. 2. Asks each group to display their products in front of the class. 3. Gives rewards for the group achievement.	1. Produce creative biology-related products. 2. Display the products in front of the class. 3. Appreciate the rewards given by the lecturer.
	Wrapping Up		
	Closing	Coincludes the lecture by assigning tasks, encouraging students, and offering closing remarks	Listen attentively as the lecturer provides homework assignments, offers motivational messages, and concludes the session with closing remarks.

Assessment Rubric

No	Evaluated Elements	Maximum Score	Assessment
	Assessment of the critical reading process		
1	Students engage in careful reading of the assigned lecture materials.	**10**	
2	Students complete all required materials as instructed.	**10**	
3	Students make an effort to critically analyze the reading materials	**10**	
	Assessment of the questions asked		
1	The questions are constructed using proper and correct Indonesian.	**10**	
2	Each question is clearly worded and avoids ambiguity	**10**	
3	The questions are rational.	**10**	
4	The questions are selective.	**10**	
5	The questions reflect a comprehensive understanding of the subject matter.	**10**	
6	The questions demonstrate appropriate reasoning and cognitive skills.	**10**	
7	The validity of the reasoning is evident, supporting the formulation of further questions.	**10**	
8	The questions reflect cognitive levels: C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6 ☐	**10**	
	Assessment of the answers submitted.		
.1	Answers are written in proper and correct Indonesian.	**10**	
2	Answers are relevant to the questions.	**10**	
3	Answers demonstrate concepts clearly and accurately.	**10**	
4	The structure of the answers is coherent, systematic, and logically organized.	**10**	
5	Answers demonstrate a thorough understanding of the material being studied.	**10**	
6	Arguments provided are strong, well-reasoned, and clearly articulated.	**10**	
7	Answers reflect appropriate and accurate thinking skills.	**10**	
8	Answers demonstrate an integrated, reflective, and well-developed thought process.	**10**	
9	Answers reflect cognitive levels: C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6 ☐	**10**	

No	Evaluated Elements	Maximum Score	Assessment
	Assessment of Group Discussions		
1	Students actively discuss in groups.	**10**	
2	Students respect differences of opinion in group discussions.	**10**	
3	Students are willing to accept opinions and criticism in group discussions.	**10**	
4	Students note important things obtained from group discussions.	**10**	
5	Students are willing to provide explanations if there are still group members who do not understand the discussion topic.	**10**	
	Assessment of Argumentative Production		
1	The argumentative discourse is written using proper and correct Indonesian.	**10**	
2	Sentences are clearly structured, avoiding ambiguity or multiple interpretations.	**10**	
3	The discourse is representative, supported by strong arguments.	**10**	
4	The discourse demonstrates a logical and integrated thought process.	**10**	
5	Answers reflect cognitive levels: C1 ☐ C2 ☐ C3 ☐ C4 ☐ C5 ☐ C6 ☐	**10**	
Total Score			

Critical Thinking Skills Questions
Questions:

1. Considering the control role of negative feedback and the function of the respiratory system, what changes in respiratory rate and depth would you expect in response to decreased levels of carbon dioxide in the internal environment?
2. Body temperature is maintained through homeostatic regulation around a set point. Based on your understanding of negative feedback and thermoregulation, would you expect cutaneous blood vessels to constrict or dilate during vigorous physical activity? Explain your reasoning.
3. Given that the olfactory receptor cells are not directly affected by the common cold, why is the sense of smell typically diminished during such an illness?
4. Why does regular aerobic exercise offer more substantial cardiovascular benefits compared to resistance training?
5. Why do you think air enters the lungs during inspiration and exits during expiration?
6. Why is it recommended that patients with stomach cancer or severe gastric disturbances consume small, frequent meals rather than follow the typical pattern of three larger meals per day?
7. How do you think vomiting occurs? What are the causes and consequences of vomiting, diarrhea, and constipation?

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The moderating role of conservation education in the effect of climate change awareness and pro-environmental behavior on students' sustainable lifestyle

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ABSTRACT
This study examines the role of conservation education in moderating the relationship between pro-environmental behavior and sustainable lifestyles among students at Semarang State University, Indonesia. The findings indicate that conservation education does not significantly moderate this relationship, suggesting that while students develop pro-environmental behavior, it does not necessarily lead to a sustainable lifestyle. The R-Square test results show that the model explains 45.7% of the variance in sustainable lifestyles, while external factors influence 54.3%. Discriminant validity analysis confirms that the constructs used meet the necessary validity criteria. Several factors may contribute to the limited moderating effect of conservation education, including curriculum limitations, insufficient behavioral interventions, and students' pre-existing environmental attitudes. While environmental education increases knowledge about sustainability, it does not automatically translate into behavioral change. To enhance its effectiveness, conservation education should incorporate experiential learning, hands-on activities, and social reinforcement mechanisms. Universities can implement service-learning projects, eco-campus initiatives, and internships with environmental organizations to bridge the gap between knowledge and action. This study highlights the need for a multi-dimensional approach to sustainability education. Future research should explore longitudinal studies to assess long-term behavioral changes and examine additional institutional and social factors that influence sustainable lifestyles. These findings contribute to the ongoing discourse on sustainability education by emphasizing the importance of integrating theoretical knowledge with practical applications to foster meaningful environmental behavior change.

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Introduction

Semarang State University is recognized as a conservation-oriented university that integrates environmental values into its academic and community activities. It plays an important role in preparing students to develop strong environmental knowledge and awareness so that, after graduation, they can apply conservation principles such as protection, preservation, and the sustainable use of natural resources, human resources, the environment, arts, and culture in their daily lives and professions. The existence of conservation-based character education at Semarang State University is expected to produce people who can develop themselves, their communities, and their country sustainably. A person's character is formed indirectly through the learning and education they undergo, rather than something they are born with, through the shaping of their environment and the influence of the people around them (Tang et al., 2023). In general, the character of conservation is reflected in concrete human actions, as 'conservation' itself is a social construct that can be observed in the sustainable management and use of natural resources for the benefit of present and future generations. The conservation-based values developed at Semarang State University encompass 11 core principles: honesty, religiosity, intelligence, justice, responsibility, tolerance, care for others, democracy, patriotism, politeness, and resilience (Wibowo et al., 2017). These values explain Semarang State University's vision: "University with a World Reputation and Pioneer of Excellence in Education with a Conservation Insight". The character values to be developed by students in each faculty include honesty, fairness, inspiration, respect for human dignity, compassion, innovation, creativity, and teamwork. Through this character development, it is hoped that students can make a real contribution to the development of a dignified national identity amidst the challenges of the global world. The primary means of implementing conservation character education is through the general course Conservation Education.

Conservation education aims to increase people's knowledge, skills, and awareness of environmental values and issues, thereby fostering positive changes in attitudes and behavior. Conservation education is a learning process to change the mindset from using natural resources for the benefit of the present without thinking about the future of future generations, to using natural resources wisely for the sake of the sustainability of environmental functions and the sustainability of the future for the next generation (Huda & Feriandi, 2018). Through the conservation education process, it is hoped that students, as members of society, will develop awareness and sensitivity towards the environment. There are 3 important aspects of conservation education learning: cognitive, affective, and psychomotor. The cognitive aspect involves understanding the scientific principles that govern ecosystem functions and the strategies required to sustain environmental equilibrium. Affective aspects that can be applied in conservation education include the values, attitudes, and commitment needed to build a sustainable society. The psychomotor aspect of conservation education concerns students' behavior and skills for managing the surrounding environment. Through conservation education, students are expected to be able to solve problems in their surrounding environment, both the physical and social environments (Wibowo et al., 2017). The focus of conservation education is to develop communities that can understand, appreciate, and implement sustainable, pro-environmental behavior (Potter, 2009).

While prior studies confirm the direct relationship between environmental awareness and pro-environmental behavior (Cardenas Morales et al., 2025; Mkumbachi et al., 2020), few examine structured conservation education programs as a moderating variable. Existing research has primarily focused on environmental education, which emphasizes developing knowledge and skills related to environmental issues, and moral education, which seeks to cultivate values and ethical reasoning that guide pro-environmental behavior (Begum et al., 2021). However, these approaches are often treated separately and lack specificity regarding how formal conservation-centric curricula can amplify the impact of climate change awareness and behavior on sustainable lifestyles.

Current literature highlights short-term behavioral outcomes (e.g., recycling, energy conservation) but rarely explores how conservation education fosters enduring sustainable lifestyles (Piao & Managi, 2023). There is a gap in understanding the pedagogical strategies (e.g., experiential learning, community projects) that translate awareness into lifelong habits.

According to the Theory of Planned Behavior, various factors contribute to behavioral change, both directly and indirectly. Attitudes, subjective norms, and perceived behavioral control are interconnected elements that indirectly shape an individual's behavior. These three factors directly influence a person's intention to change, which, in turn, leads to actual behavioral change. Attitude reflects an individual's positive or negative evaluation of a particular behavior. Meanwhile, subjective norms refer to the social pressure one experiences regarding whether to engage in or refrain from a specific action or behavior (Ajzen, 1991).

This study aims to examine the mediating role of conservation education in the relationship between climate change awareness, pro-environmental behavior, and students' sustainable lifestyles. Specifically, it investigates how conservation education not only enhances students' environmental awareness but also strengthens their perceived behavioral control and collective responsibility, ultimately fostering long-term sustainable practices.

The community-oriented nature of conservation education suggests that its impact extends beyond individual knowledge acquisition to the cultivation of shared responsibility and sustained behavioral change. This aligns with the Theory of Planned Behavior, which posits that subjective norms and perceived behavioral control influence individuals' intentions and actions. Within this framework, conservation education may serve as a crucial mechanism for translating environmental awareness into tangible, sustainable behavior. The problem formulation that can be drawn from the research background is as follows: (1) does climate change awareness affect students' sustainable lifestyle?; (2) does pro-environmental behavior influence students' sustainable lifestyle; (3) does conservation education play a mediating role in the influence of climate change awareness on students' sustainable lifestyles; (4) does conservation education play a mediating role in the influence of pro-environmental behavior on students' sustainable lifestyle; (5) Does climate change awareness and pro-environmental behavior influence students' sustainable lifestyle through conservation education?

Climate change is a pressing issue that significantly impacts the younger generation (Jürkenbeck, Spiller, and Schulze 2021). Students must be aware of their level of climate change awareness. Social media campaigns have played a key role in educating the public and raising awareness about climate change in Indonesia, leading to lifestyle changes among its people (Turpyn & Adwitiya, 2021). Understanding the extent of public awareness regarding climate change is essential for formulating appropriate policies to mitigate its risks, especially in highly vulnerable countries such as Indonesia (Nggole, Tyas, and Pradoto 2019). However, studies indicate that Indonesians generally have low awareness and concern about climate change issues (Lee et al., 2015). On the other hand, social media has proven to be an effective tool in educating Generation Z and increasing their awareness of climate change challenges (Ariestya, Paramitha, and Elmada 2022).

The existing literature shows that environmental education plays an important role in shaping students' environmental attitudes and behaviors. Specifically, research has shown that environmental education can help students integrate environmental concerns into their future professional contexts, ensuring the continuation of sustainability efforts long after graduation. Additionally, students' pro-environmental willingness was significantly correlated with their participation in environmental associations and their academic majors, highlighting the importance of integrating environmental education across all disciplines. While studies link environmental education to pro-environmental behaviors, the specific moderating role of conservation education remains underexplored (Piao & Managi, 2023). Research often broadly defines environmental education, neglecting conservation education's unique focus on resource protection and direct engagement (Prayogo et al., 2022). Furthermore, contextual factors, long-term lifestyle changes, and moderating capacity are often overlooked. The influence of subjective norms and perceived behavioral control is also frequently omitted; conservation education's impact likely hinges on perceived community support and individual capabilities (Xu et al., 2022). Existing literature thus inadequately elucidates conservation education's distinct role in fostering sustainable lifestyles, leaving a crucial gap to be addressed.

Human behavior plays a significant role in shaping environmental quality, and as future leaders, students hold a crucial responsibility in environmental conservation (Shafiei & Maleksaeidi, 2020). Pro-environmental behavior reflects an individual's awareness and commitment to minimizing negative environmental impacts through daily activities (Dono, Webb, and Richardson 2010). However, students' engagement in environmental concerns still requires attention. Previous studies have found that students in Indonesia generally exhibit a moderate level of pro-environmental behavior (Dewi, 2018). Universities, as students' second home, have a vital role in fostering sustainable environments (Siregar et al., 2022). Research also suggests that Indonesians still display relatively low levels of pro-environmental behavior in their daily routines (Djuwita & Benyamin, 2019).

To mitigate climate change, adopting a sustainable lifestyle is essential. This involves engaging in environmentally friendly practices across various aspects of life, including energy consumption at home, mobility, food consumption, and product usage. However, studies reveal that individuals do not always consistently apply pro-environmental behaviors across these different domains (Dreijerink, Handgraaf, and Antonides 2022). Encouraging sustainable lifestyles within communities requires a focus on behavioral patterns and ingrained habits.

Previous research has demonstrated that conservation education significantly enhances knowledge and attitudes toward environmental protection, effectively strengthening the link between awareness and pro-environmental behavior (Ma et al., 2023). Other studies have highlighted the role of environmental education in bridging environmental knowledge and pro-environmental intentions, emphasising its importance in fostering sustainable behaviors (Ozbey et al., 2024). At Semarang State University, conservation education is integrated into the curriculum as a general subject, aligning with the university's vision to help students adopt sustainable lifestyles. Furthermore, this initiative contributes to broader public education efforts, promoting economic development and cooperative human behavior to safeguard environmental sustainability (Piao & Managi, 2023).

Methods

This study employs a quantitative research approach, focusing on collecting numerical data and using statistical techniques to examine relationships among variables and test the proposed hypotheses. Specifically, this study employs a descriptive research method, which aims to present an accurate and systematic depiction of the phenomenon under investigation based on collected data. This approach is valuable for identifying patterns, characteristics, and relationships that can inform subsequent analysis and interpretation (Sugiyono, 2020). This study adopts a descriptive–confirmatory design: it first provides a systematic overview of the variables under study and then tests specific hypotheses to examine their relationships. To achieve this, the study applies Partial Least Squares Structural Equation Modeling (PLS-SEM), a method well-suited for exploratory research and predictive modeling (Hair & Alamer, 2022).

Data Collection

Data for this study were obtained through a structured questionnaire designed to assess participants' perceptions, attitudes, and self-reported behaviors. It is acknowledged, however, that self-reported measures may not fully reflect actual behavior due to potential biases such as social desirability and respondents' awareness of expected answers. It was distributed to students at Semarang State University enrolled in conservation education courses. The population in this study was Semarang State University students who had completed Conservation Education courses. Conservation Education is a compulsory course designed to instill the values of environmental sustainability and local wisdom, in line with the university's identity as a Conservation University. The course is typically offered in the second semester of undergraduate programs across all faculties. The course carries 2 credit units (2 credits) and runs for approximately 16 weeks within a regular semester. Each week consists of 100 minutes of lectures, discussions, and project-based activities. The average class size is up to 200 students, depending on the study program and student intake in each academic year. The material is delivered using a combination of lectures, group discussions, case studies, field observations, and project-based learning (PjBL). This approach allows students not only to understand the theoretical concepts of conservation but also to engage directly with environmental issues in their surroundings.

To mitigate potential bias in data collection, several measures were implemented. First, a stratified sampling technique (Howell et al., 2020) was used to ensure representation across different faculties and academic levels, reducing the risk of overrepresentation from any particular group. Second, response bias was minimized by ensuring anonymity and confidentiality, and by encouraging students to provide honest answers without fear of judgment. The questionnaire was carefully designed to use neutral and clear language, avoiding leading questions that might influence responses. To further control for social desirability bias, participants were reminded that there were no right or wrong answers, and the study aimed to understand their genuine perceptions and behaviors. The sample used in SEM (Structural Equation Modeling) research is 100-200 (Hair et al., 2014). In this study, 300 respondents were included.

The questionnaire consisted of multiple sections measuring climate change awareness, pro-environmental behavior, conservation education, and sustainable lifestyles using a five-point Likert scale. To ensure validity and reliability, the instrument was tested with a small sample (30) before full-scale distribution. The questionnaire was administered online using Google Forms to maximize response rates while maintaining data accuracy. A stratified sampling technique was used to ensure representation across different faculties and academic levels. Ethical considerations, including informed consent and confidentiality, were strictly maintained. The collected data were analyzed using Partial Least Squares Structural Equation Modeling (PLS-SEM) to examine direct, indirect, and mediating effects within the proposed research model.

To measure respondents' perceptions, this study uses a Likert scale with five response categories, as presented in Table 1.

Tabel 1

Likert scale

Answer	Category	Score
Strongly Agree	Very High	5
Agree	High	4
Neutral / No Opinion	Moderate	3
More Disagree	Low	2
Strongly Disagree	Very Low	1

The research instrument was administered in Bahasa Indonesia to ensure respondents' full comprehension. The origiThe final questionnaire was developed in English and then translated into Bahasa Indonesia by a bilingual expert. A second independent translator conducted a back-translation to verify conceptual and linguistic equivalence. Any discrepancies were resolved through discussion to maintain the instrument's validity and reliability.

Climate Change Awareness

1. Climate change is the impact of the thinning of the ozone layer
2. Greenhouse gas emissions cause climate change
3. Every individual can do a lot to reduce climate change
4. Human activity is the main cause of climate change
5. Climate change is the main obstacle to efforts to sustain economic growth
6. I feel worried about consumption behavior and the environment
7. I feel embarrassed when I find that around me, no one cares about the environment

Pro-Environmental Behavior

1. I always aim to save food, water, and energy wherever I can

2. I always intend to save as many natural resources as I can
3. I always intend to choose to travel as environmentally friendly as possible
4. I always intend to sort waste and recycle as much waste as possible
5. I always intend to buy environmentally friendly products
6. I would like to spend more money on environmentally friendly products than conventional products
7. If I have the opportunity to take part in an environmentally oriented organization, I will always be ready to be an active member

Sustainable Lifestyle

1. I avoid using disposable tissue paper when in the toilet
2. I eat food without plastic packaging
3. I clean the kitchen with a cloth rather than paper towels
4. I avoid using disposable plates, spoons, forks, straws, and glasses when eating/drinking
5. I save energy by implementing energy-saving practices (turning off lights when not in use, using natural light all day, turning off the AC, and turning off the computer when not in use)
6. I turn off the tap water when brushing my teeth, soaping my body, and washing my clothes
7. I buy local and domestic products
8. I try to use biodegradable products in my daily life
9. I avoid using plastic bags for shopping
10. I avoid buying too many clothes
11. I avoid leaving food out

Conservation Education

1. I took part in reforestation activities around campus to maintain biodiversity as an assignment for a conservation education course
2. I have attended outdoor conservation education lectures
3. I have visited a place where compost or recycled products are made as a form of conservation education lecture
4. Lecture materials are linked to conservation values, namely inspirational, humanistic, caring, innovative, creative, sportsmanlike, honest, and fair
5. Conservation education lectures make me behave cleanly and healthily, in the sense of showing great concern for myself, the social environment, and the physical environment in the classroom and outside the classroom

It is acknowledged that self-reported questionnaires may not always reflect actual behaviors, as respondents may provide socially desirable answers rather than accurate accounts of their actions. This is particularly relevant for constructs such as pro-environmental behavior and conservation participation, where individuals might overstate their engagement to align with expected norms. To mitigate this limitation, the questionnaire items were designed to be specific and behavior-focused, reducing the likelihood of vague or inflated responses. Additionally, this limitation is recognized and accounted for in the interpretation of results. Although the listed conservation education activities can be completed in a short amount of time, the focus of this study is to capture students' reported exposure to conservation-related learning experiences rather than to measure the depth or intensity of their engagement. Therefore, the findings should be interpreted as indicative of participation frequency or presence, not necessarily the quality or impact of participation. Future research may complement this approach with observational or qualitative methods to gain deeper insights.

Based on the results of validity and reliability testing using Partial Least Squares Structural Equation Modeling (PLS-SEM), all measurement items in this study meet the required criteria. The outer loading values for each indicator exceeded the recommended threshold of 0.70, indicating good indicator validity. Furthermore, the values of Average Variance Extracted (AVE) for each construct were above 0.50, confirming convergent validity. Additionally, the Composite Reliability

(CR) and Cronbach's Alpha values for each latent variable were above 0.70, ensuring that the instruments have high internal consistency reliability. Discriminant validity was also achieved based on the Fornell-Larcker criterion and cross-loading analysis, confirming that each construct is distinct from the others. Therefore, it can be concluded that all instruments used in this study are valid and reliable for measuring the constructs of Climate Change Awareness, Pro-Environmental Behavior, Sustainable Lifestyle, and Conservation Education in the context of PLS-SEM analysis.

Data Analysis

Data analysis in this research uses Partial Least Squares (PLS). PLS is a component or variant-based Structural Equation Modeling (SEM) model. PLS is an alternative to covariance-based SEM that shifts to a variance-based SEM. Covariance-based SEM generally tests causal hypotheses or theories, while PLS is more of a predictive model. PLS is a powerful analysis method because it is not based on many assumptions. The purpose of using PLS is to help researchers for prediction purposes (Putu Gede Subhaktiyasa, 2024). The formal model conceptualizes a latent variable as a linear combination of its observed indicators. The weight estimates used to construct latent variable scores are derived from the specification of both the inner model, or the structural relationships among latent variables, and the outer model, or the measurement relationships between indicators and their corresponding constructs (Hair et al., 2017). Conservation education as a structured intervention remains an emerging area, requiring a method that allows for theory development while handling complex relationships. Unlike covariance-based SEM, which focuses on model fit, PLS-SEM prioritizes predictive accuracy, making it ideal for understanding how climate change awareness and pro-environmental behavior influence students' sustainable lifestyles through conservation education. Additionally, this study involves multiple mediation effects, which PLS-SEM effectively estimates. Given that survey data in educational research often deviates from normality, PLS-SEM is more robust as it does not require strict normality assumptions and performs well with moderate sample sizes. Furthermore, because the moderating role of conservation education is underexplored, PLS-SEM enables a flexible approach to examining indirect effects and refining theoretical frameworks. Thus, PLS-SEM is the most appropriate method for this study to generate meaningful insights.

Findings

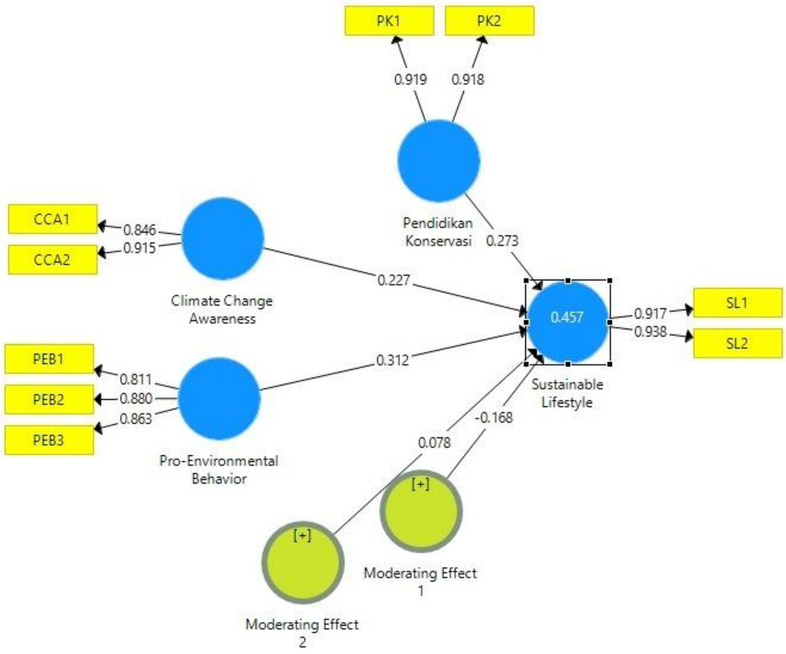
Figure 1 illustrates the structural model used in this study to examine the relationships between climate change awareness, pro-environmental behavior, conservation education, and sustainable lifestyle. The arrows represent hypothesized causal paths, with the corresponding coefficients indicating the strength of each relationship. Conservation education is positioned as a mediating variable, linking climate change awareness and pro-environmental behavior to sustainable lifestyle outcomes. The model also incorporates moderating effects to capture potential interaction influences among variables.

Partial Least Squares (PLS) Model

Hypothesis testing used Smart PLS version 3 program. Research data obtained from respondents were analyzed using SmartPLS with the Outer Model to assess construct validity and reliability. The following are the test results of the Outer Model tested:

Figure 1

Outer model



Outer Model Evaluation

The evaluation of a measurement model involves analyzing the relationship between construct variables (indicators) and their corresponding latent variables. The primary objective of this evaluation is to verify the model's validity and reliability through appropriate testing. This process ensures that the measurement instruments used provide accurate and consistent data. In this study, Structural Equation Modeling (SEM) was applied using the SEM-PLS analytical tool. Validity is assessed through two key tests: Convergent Validity and Discriminant Validity. Meanwhile, reliability is evaluated using the Composite Reliability test and Cronbach's Alpha coefficient.

According to Ghozali and Latan (2015:74), an indicator is considered to have good validity if its Outer Loading is above 0.70. The higher the value of a factor loading, the higher the role of the loading in interpreting the factor matrix. Convergent validity of a construct and its indicators can be assessed using the Average Variance Extracted (AVE), which should exceed 0.5. Apart from that, Ghozali and Latan (2015:75) stated that an AVE value of 0.50 or more indicates that the construct can explain 50% or more of the item variance. Thus, the rule of thumb for assessing convergent validity is a Loading Factor > 0.70 and an Average Variance Extracted (AVE)> 0.50. In this research, the convergent validity test is evaluated through the Outer Loading value, which is measured as follows:

Table 2

Outer loading of indicators on research variables

Variable	Indicator	Outer Loading	Taraf *Convergent Validity*	Description
Sustainable Lifestyle (Y)	SL1	0.917	0.7	Valid
	SL2	0.938	0.7	Valid
Climate Change Awareness (X1)	CCA1	0.846	0.7	Valid
	CCA2	0.915	0.7	Valid
Pro-environmental Behavior (X2)	PEB1	0.811	0.7	Valid
	PEB2	0.880	0.7	Valid

	PEB3	0.863	0.7	Valid
Conservation Education (M)	PK1	0.919	0.7	Valid
	PK2	0.918	0.7	Valid

The table above shows that the outer loading for each variable, such as sustainable lifestyle, climate change awareness, pro-environmental behavior, and conservation education, is greater than 0.7, so it can be categorised as high. These results illustrate that the indicaThe search constructs are valid and meet the requirements for convergent validity, so they can be used to measure the research variables. The next evaluation step towards convergent validity is carried out by analyzing the Average Variance Extracted (AVE) value for each variable as follows:

Table 3

Average Variance Extracted (AVE) value for each research variable

Variables	AVE Value	AVE Sig	Description
Sustainable Lifestyle (Y)	0.861	0.5	Valid
Climate Change Awareness (X1)	0.776	0.5	Valid
Pro-environmental Behavior (X2	0.726	0.5	Valid
Conservation Education (M)	0.844	0.5	Valid

The table above shows that the AVE value for each variable is > 0.5. This means that each research variable meets the rule-of-thumb criterion of AVE > 0.5, indicating that each variable is a good research construct.

The discriminant validity test aims to determine whether a reflective indicator is truly a good measure of its construct based on the principle that each indicator must be highly correlated with its construct. According to Ghozali and Latan (2015:74), the cross-loading value for each variable must be > 0.70; it is hoped that the correlation of the construct with the measurement items is greater than that of other constructs.

The second measurement is the square root of the AVE in the Fornell-Lacker Criterion. According to Fornell and Larcker (cited in Ghozali and Latan, 2015: 75), a model has good discriminant validity if each construct's AVE is greater than the correlation with other constructs. The following are the results of the Cross Loading indicators for each research variable, which can be seen in the table:

Table 4

Cross-loading results for each research variable

Indicator	Variables				Results
	CCA	PEB	SL	PK	
CCA1	0.846	0.467	0.385	0.251	Valid
CCA2	0.916	0.646	0.509	0.297	Valid
PEB1	0.566	0.811	0.467	0.363	Valid
PEB2	0.542	0.880	0.519	0.492	Valid
PEB3	0.538	0.863	0.531	0.453	Valid
SL1	0.487	0.499	0.917	0.397	Valid
SL2	0.470	0.598	0.938	0.523	Valid
PK1	0.327	0.497	0.461	0.919	Valid
PK2	0.247	0.448	0.458	0.918	Valid

The table above shows that the correlation values for each construct with its measurement items are greater than those for other constructs. For example, the correlation between the CCA1 indicator and the CCA latent variable (0.846) is greater than the correlations of the CCA1 indicator with the latent variables in the other blocks (0.467, 0.385, and 0.251). Thus, the indicator is declared valid.

The second measurement is the square root value of AVE. Below, the square root value of AVE for each research variable can be seen in the table:

Table 5

AVE square root value on the Fornell-Larcker criterion

Variables	Variable Square Root Value				Results
	CCA	PK	PEB	SL	
Climate Change Awareness	**0,881**				Valid
Conservation Education	0.313	**0,919**			Valid
Pro-environmental Behavior	0,643	0,514	**0,852**		Valid
Sustainable Lifestyle	0,515	0,500	0,594	**0.928**	Valid

The table shows that the square root of the AVE for each construct is greater than the correlation between that construct and the other constructs in the model. For example, the square root of the AVE for the CCA variable is 0.881; this value is greater than the correlations of the construct with other constructs (0.313, 0.643, 0.515). This means that all constructs in the estimated model have satisfied the rule-of-thumb criterion for discriminant validity.

In addition to being assessed using Convergent Validity and Discriminant Validity, the Outer Model can be evaluated by examining the reliability of the construct or latent variable, as indicated by Cronbach's Alpha and Composite Reliability. The construct is considered reliable if Cronbach's Alpha and Composite Reliability are both> 0.70 (Ghozali & Latan, 2015, p. 77). The following are the Cronbach's Alpha results for each research variable, which can be seen in the following table:

Table 6

Cronbach's alpha

Variable	*Cronbach's Alpha*	*Sig Cronbach's Alpha*	Results
Sustainable Lifestyle	0,839	0,7	Reliable
Climate Change Awareness	0,716	0,7	Reliable
Pro-environmental Behavior	0,811	0,7	Reliable
Conservation Education	0,815	0,7	Reliable

The table above indicates that the Cronbach's Alpha value for each variable construct is greater than 0.70. This confirms that all variables are reliable and suitable for use in research. Furthermore, the results can also be examined through Composite Reliability, as shown below:

Table 7

Composite reliability of research variables

Variable	Composite Reliability	Sig Composite Reliability	Results
Sustainable Lifestyle	0,925	0,7	Reliable
Climate Change Awareness	0,874	0,7	Reliable
Pro-environmental Behavior	0,888	0,7	Reliable
Conservation Education	0,915	0,7	Reliable

Based on the table above, it shows that Composite Reliability for each variable is declared a construct, so that each construct can be positioned as a research variable. It can be concluded that all variables exhibit adequate consistency in measuring the latent variables/constructs in a composite manner, allowing them to be used for subsequent analysis. This study iIt incorporates both the Outer Model (Measurement Model) and the Inner Model (Structural Model) in its research framework. The distinction between these two models is crucial, as each serves a specific purpose in validating the study's findings.

Ensuring the validity of both the Outer Model (Measurement Model) and the Inner Model (Structural Model) is essential for obtaining reliable and meaningful research findings. The outer model plays a crucial role in confirming that the measurement of key variables—climate change awareness, pro-environmental behavior, sustainable lifestyle, and conservation education—is accurate and consistent. Without a validated outer model, the indicators used to measure these constructs may not accurately reflect the intended concepts, leading to unreliable results. Meanwhile, the inner model is necessary to examine and interpret the relationships among these variables, enabling hypothesis testing and a deeper understanding of how climate change awareness influences pro-environmental behavior and sustainable lifestyles, with conservation education as a moderating factor. By integrating both models, this study ensures a scientifically rigorous analysis that strengthens the reliability of the findings. This approach provides valuable insights into the role of conservation education in enhancing students' environmental awareness and promoting sustainable behaviors, ultimately contributing to a greater understanding of how education can shape environmentally responsible lifestyles.

The following is the Structural Model scheme, or Inner Model scheme, used in this research, which employs Smart PLS 3.

Figure 2

Inner model

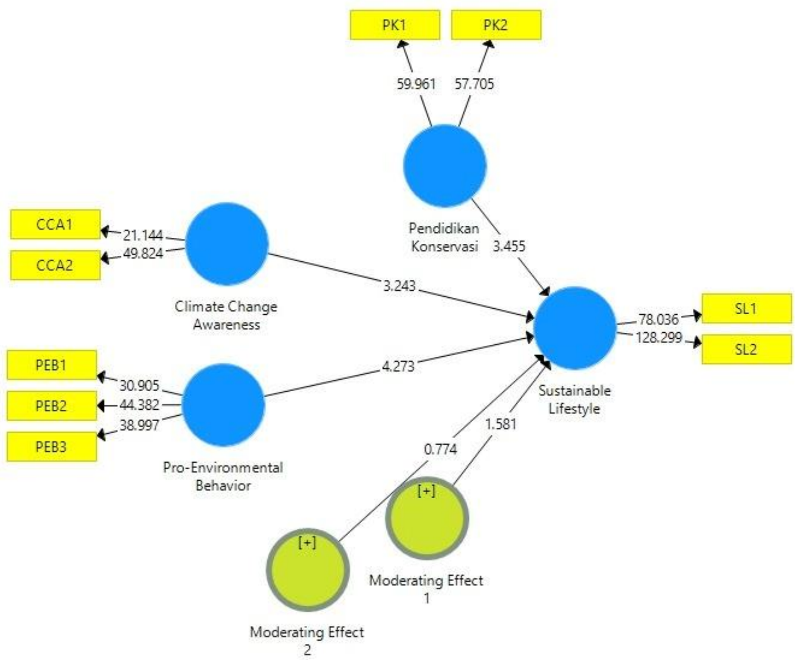


Figure 2 presents the inner model, which illustrates the structural relationships among the key latent variables examined in this study. Climate change awareness and pro-environmental behavior are hypothesized to directly influence sustainable lifestyle, while conservation education serves as a mediating variable that strengthens these relationships. The numbers on the paths represent the estimated coefficients, indicating the magnitude of the effect between constructs. Moderating effects are also included to capture potential interactions with the dependent variable.

The Structural Model, or Inner Model, is used to examine the influence of constructs. The inner model test was analyzed using R-Square, Q-Square, and statistical significance tests. The R-Square test is used to measure the level of variation in changes in exogenous variables towards endogenous variables. According to Ghozali and Latan (2015: 81), if R-Square > 0.67, the model is strong or good; if 0.68 > R-Square> 0.33, the model is fair or moderate; and if R-Square> 0.19, the model is weak. The following R Square (R2) results can be seen in the table:

Table 7

R-square test results (R2)

Variable	R-*Square*	*Adjusted R-Square*	Result
Sustainable Lifestyle	0,457	0,446	Moderates

Conservation education, climate change awareness, and pro-environmental behavior collectively explain 45.7% of the variance in sustainable lifestyle, while other unobserved factors influence the remaining 54.3%. This aligns with prior studies examining behavioral intentions and sustainability-related behavior, in which R^2 values often range from 0.30 to 0.50 in complex psychological and educational models (Ravand & Baghaei, 2016). The moderate R^2 value suggests that while the selected variables contribute significantly to sustainable lifestyle outcomes, additional factors—such as social norms, institutional policies, and personal motivations—may further explain students' engagement in sustainability practices.

A research model is considered good if the Q-Square is greater than zero. Meanwhile, if the Q-Square value is negative, the research model is not predictive. The following are the results of the Q-Square test on the sustainable lifestyle variable:

Q-Square Sustainable Lifestyle $= 1 – (1 - R1^2) (1 - R^2)$
$= 1 – (1 – 0{,}457) (1 – 0{,}446)$
$= 1 – (0{,}543) (0{,}554)$
$= 0{,}699$

Based on the calculation above, the Q-Square value for the sustainable lifestyle variable is 0.699. The figure shows > 0, indicating that the sustainable lifestyle research model has strong predictive relevance. The Q-Square value of 0.699 further reinforces the model's predictive strength, indicating that the inclusion of conservation education enhances its explanatory capacity. This is consistent with research highlighting that structured environmental education programs significantly shape long-term pro-environmental attitudes and behaviors (Burgos-Espinoza et al., 2024). However, despite the model's predictive relevance, future studies could incorporate longitudinal data to assess how sustained exposure to conservation education influences lifestyle changes over time. Additionally, integrating external moderators, such as socioeconomic background or institutional support, may refine the model's predictive accuracy. This would align with prior work emphasizing multi-dimensional influences on sustainability behaviors, ensuring a more holistic understanding of conservation education's role in shaping pro-environmental lifestyles.

The t-test was used to determine the significance and the coefficient of the structural path parameters between variables by examining the t-statistic. The stability of this estimate is evaluated if the t-statistic produced by the variable is > 1.65 at the 10% significance level, 1.96 at the 5% significance level, and 2.58 at the 1% significance level obtained through bootstrapping calculations, Ghozali and Latan (2015:81). The following are the results of the t-statistical significance test:

Table 8

T-statistic significance test results

No.	Hypothesis	Original Sample (O)	Sample Mean (M)	Standard Deviation (STDEV)	t-statistics	P-Values	Result
1.	CCA -> SL	0,227	0,244	0,073	3,113	0,002	Accepted
2.	PEB -> SL	0,312	0,323	0,074	4,244	0,000	Accepted
3.	PK -> SL	0,273	0,255	0,082	3,350	0,001	Accepted
4.	CCA -> PK -> SL	-0,168	-0,086	0,106	1,579	0,115	Rejected
5.	PEB -> PK -> SL	0,078	0,010	0,108	0,721	0,471	Rejected

Based on the data in the table above, this research examines the influence of climate change awareness and pro-environmental behavior on sustainable lifestyle as the dependent variable and tests the conservation education variable as a moderating variable, which determines whether the relationship is strengthened or weakened. The following is an explanation of the Path Coefficient results in the table above:

1) Climate change awareness has a positive and significant effect on sustainable lifestyle with a coefficient of t-statistics of 3.311 > 1.96 and a P-Value of 0.002 < 0.05.

2) Pro-environmental has a positive and significant effect on sustainable lifestyle with a coefficient of *t*-statistics of 4.244 > 1.96 and a P-Value of 0.000 < 0.05.

3) Conservation education has a positive and significant effect on sustainable lifestyle with a coefficient of t-statistics of 3.359 > 1.96 and a P-Value of 0.001 < 0.05.

4) Climate change awareness has a negative and insignificant effect on sustainable lifestyle through conservation education, with a coefficient of t-statistics of 1.579 < 1.96 and a P-Value of 0.115 < 0.05.

5) Pro-Environmental behavior has a negative and insignificant effect on sustainable lifestyle through conservation education, with a coefficient of t-statistics of 0.721 > 1.96 and a P-Value of 0.471 < 0.05.

Hypothesis testing in this research was carried out using a P-value < 0.05 at the 5% significance level. Based on Table 4.9, the P-value is 0.002 < 0.05, indicating significance at the 5% level. The original sample value is 0.227, indicating a positive influence of 22.7% on students' sustainable lifestyles from climate change awareness. The hypothesis (H1), which states that the climate change awareness variable has a positive and significant effect on sustainable lifestyles, is accepted. Based on Table 4.9, the P-value is 0.000 > 0.05, indicating that the pro-environmental behavior variable is accepted at the 5% significance level. As for the original sample value, it is 0.312, indicating a positive influence of 31.2% on students' sustainable lifestyle. The hypothesis (H2), which states that the pro-environmental behavior variable has a positive and significant effect on sustainable lifestyles, is accepted. Based on Table 4.9, the P-value is 0.001, which is greater than 0.05, indicating significance at the 5% level. The original sample value is 0.273, indicating a positive influence of 27.3% on students' sustainable lifestyles from conservation education. The hypothesis (H3), which states that the conservation education variable has a positive and significant effect on sustainable lifestyles, is accepted. Based on Table 4.9, the P-value is 0.115, which is greater than 0.05, indicating no significant difference at the 5% significance level. The original sample value is -0.168, indicating a negative influence of -16.8% and suggesting that climate change awareness does not significantly moderate its influence on students' sustainable lifestyles. The hypothesis (H4), which states that conservation education positively and significantly moderates the influence of climate change awareness on sustainable lifestyles, is rejected. This means that conservation education cannot moderate the influence of climate change awareness on students' sustainable lifestyles. These findings suggest that, within the scope of this study, students who take conservation education courses may not necessarily demonstrate a measurable change in their sustainable lifestyle associated with climate change awareness. However, the study does not provide direct evidence of behavioral change, and the results should therefore be interpreted with caution. Table 8 shows that the P-value is 0.471, which is greater than 0.05, indicating no significant difference at the 5% significance level. The original sample value is 0.078, indicating a negative influence of -7.8% and suggesting that it is not significant in moderating the effect of pro-environmental behavior on students' sustainable lifestyle. The hypothesis (H6), which states that conservation education positively and significantly moderates the influence of pro-environmental behavior on sustainable lifestyles, is rejected. This means that conservation education cannot moderate the influence of pro-environmental behavior on students' sustainable lifestyles at Semarang State University. These findings show that students who take conservation education courses do not improve their sustainable lifestyles, despite being influenced by pro-environmental behavior.

Discussion

One potential reason for the insignificant moderating effect of conservation education on the relationship between pro-environmental behavior and sustainable lifestyle could be limitations within the curriculum itself. If the course content focuses more on theoretical knowledge than on practical application, students may gain awareness but lack the behavioral reinforcement to integrate sustainability into their daily lives. Research suggests that effective conservation education requires active learning methods, such as hands-on projects and community-based initiatives, to translate environmental awareness into habitual action (Singh & Rahman, 2012).

Additionally, students' pre-existing pro-environmental attitudes could also contribute to the weak moderating effect. If students already have strong pro-environmental behaviors before taking the course, conservation education may not significantly enhance their sustainable lifestyle, as their attitudes and behaviors are already established. This aligns with Ajzen's Theory of Planned Behavior (Ajzen, 1991), which suggests that attitude formation precedes behavioral intention, meaning students with prior environmental awareness may not experience a noticeable shift through formal education alone.

Moreover, external factors, such as institutional support, social environment, and access to sustainable facilities, may also play a role in determining whether students can actively implement sustainability principles in their lives. Without structural support—such as campus-wide sustainability policies, recycling programs, or incentives for eco-friendly practices—students may find it difficult to incorporate sustainability beyond their academic setting (Uzorka et al., 2024). Future research could explore whether enhancing experiential learning, integrating sustainability-focused extracurricular activities, or institutional policy changes could strengthen the impact of conservation education in fostering a long-term sustainable lifestyle.

Awareness of climate change significantly influences sustainable lifestyles, although the relationship is complex and varies across demographics. Research shows that increased awareness can lead to behavioral changes, especially among younger generations, who are more likely to adopt climate-friendly diets (Jürkenbeck, Spiller, and Schulze 2021). University students represent an important social group within the younger population, though they do not constitute a generation in their own right. Increasing engineering students' understanding of and attitudes toward climate change is important for fostering awareness and encouraging them to integrate sustainability considerations into their future professional practice, rather than only their personal lifestyles (Shealy, Godwin, and Gardner 2017). While previous research has suggested a positive relationship between climate change awareness and pro-environmental attitudes and behaviors, this relationship may not hold uniformly across all social groups, and the degree of influence can vary depending on context and individual engagement (Ghazali et al., 2016). Higher awareness of climate change has a positive impact on demand for climate change responses, and suggests a potential relationship with the adoption of sustainable lifestyles among individuals (Venghaus, Henseleit, and Belka 2022). This is consistent with previous research indicating that students' moral obligation played a significant role in understanding their intention to engage in pro-environmental behaviors (Alshehri, 2024).

One way student behavior is formed is through the implementation of the educational curriculum. One of the courses in the tertiary education curriculum at Semarang State University is Conservation Education. This course consists of the main material, including an introduction to the environment in higher education. Conservation education courses can foster environmental awareness and encourage sustainable lifestyles among students, thereby contributing to transformative approaches to address environmental challenges and increase social responsibility (Siddiqui & Khan, 2015). Conservation education equips students with sustainable competencies, fosters awareness and practices that encourage sustainable lifestyles, thereby enhancing community resilience and environmental conservation. Conservation education at Semarang State University effectively integrates conservation values, fostering a sustainable lifestyle among students both through academic and extracurricular activities (Saddam, Zurohman, and Bahrudin 2018).

Conservation education plays an important role in shaping awareness and behavior regarding climate change. However, its effectiveness in moderating the impact of climate change awareness on sustainable lifestyles is insignificant and even unable to strengthen it. Although education can increase awareness of climate change, it does not always lead to sustainable lifestyle behaviors. Research shows that knowledge alone is not enough; behavior change requires a deeper understanding of cultural practices and engagement in society. The student demographic, which mostly lives in boarding houses, has limitations in implementing a sustainable lifestyle in society. Students, as the younger generation, actually receive knowledge about sustainable lifestyle practices more easily, for example, through participation in conservation education courses, but they often lack the skills to make informed lifestyle choices (Escobar, 2012; Lenzen & Murray, 2001). Conservation education programs need a curriculum that equips them with these skills to bridge the gap between awareness and action toward realizing a sustainable lifestyle in society. Integrated approach enriches the curriculum by providing diverse perspectives and real-world applications (Suprapto et al., 2024). The results of the research show that although environmental education, including conservation education courses, can increase knowledge of sustainable lifestyles, it cannot strengthen students' climate change awareness to improve sustainable lifestyles. This suggests that conservation education is ineffective in moderating awareness of climate change for a sustainable lifestyle (Grúňová et al., 2017). This is because having a positive attitude toward a sustainable lifestyle does not necessarily translate into concrete actions unless it is supported by psychological factors, such as personal motivation, and reinforced by social influences, such as peer norms or community support (Zaval & Cornwell, 2017).

Conservation education plays an important role in shaping pro-environmental behavior among students, but it does not sufficiently moderate the influence of such behavior on sustainable lifestyles (Tapia-Fonllem et al., 2017). The research indicates that environmental education enhances knowledge about sustainability. However, this

Knowledge does not always translate into behavior change, as individuals may lack the motivation, social reinforcement, or institutional support needed to act. One possible reason for this weak moderating effect is that conservation education curricula may focus more on cognitive learning, such as theories, policies, and ecological concepts, without incorporating practical, experiential, or community-based learning that actively shapes behavior (Ardoin et al., 2020).

Environmental education increases knowledge about sustainable lifestyles, but this does not automatically lead to behavior change, highlighting the need for a comprehensive approach that integrates education with more practical application. This shows that there are barriers to the relationship between pro-environmental behavior and sustainable lifestyles, indicating that conservation education alone is not effective in moderating this influence (Akram et al., 2023). One effort to increase conservation education's moderating influence is to develop a curriculum for learning outside the classroom and for direct practice, so that social and behavioral influences also have a slight impact on changing students' lifestyles toward a more sustainable level.

The absence of structured behavioral interventions such as eco-friendly campus initiatives, habit-tracking programs, or long-term sustainability projects may limit students' ability to integrate sustainable practices into their daily routines (Kirchner-Krath et al., 2024). Studies have shown that hands-on engagement, social modeling, and institutional reinforcement are key factors in driving long-term pro-environmental behavior change (Juma-Michilena et al., 2023). Without these components, conservation education may serve only as an informational tool rather than a transformational experience, reducing its moderating impact on sustainable lifestyles.

Despite these promising findings, it is important to recognize potential limitations. While the current assessment methods provide strong evidence of discriminant validity, future research could use multi-group analysis to assess whether discriminant validity remains consistent across demographic groups, such as gender, academic disciplines, or cultural backgrounds. Additionally, conducting longitudinal validation could help determine whether the constructs remain distinct over time, particularly in studies examining behavioral changes. Incorporating these approaches would enhance the reliability and applicability of conservation education research in promoting sustainable behavior.

Conclusion and Implications

Conservation education plays an important role in shaping pro-environmental behavior among students, but it does not moderate the influence of such behavior on sustainable lifestyles. Environmental education increases knowledge about sustainable lifestyles, but this does not automatically lead to behavior change, highlighting the need for a comprehensive approach that integrates education with more practical applications. This shows that there are barriers to the relationship between pro-environmental behavior and sustainable lifestyles, suggesting that conservation education alone is insufficient to moderate this relationship. One effort to increase conservation education's moderating influence is to develop a curriculum for learning outside the classroom and for direct practice, so that social and behavioral influences also have a slight impact on changing students' lifestyles toward a more sustainable level.

Given the limited moderating effect of conservation education on sustainable lifestyles, educational institutions must rethink and enhance the design of their conservation education programs. Traditional classroom-based environmental education, which primarily focuses on cognitive learning, should be complemented by experiential, action-oriented, and community-based learning approaches. For instance, service-learning projects, sustainability workshops, and outdoor experiential programs can provide hands-on engagement, fostering bigger behavioral change among students. Moreover, integrating behavioral interventions such as eco-campus initiatives, green competitions, carbon footprint tracking, and peer-led sustainability programs can help bridge the gap between environmental knowledge and real-world practice. Research has shown that habit formation, social reinforcement, and institutional support play crucial roles in fostering long-term pro-environmental behaviors. Universities should therefore implement structured, long-term interventions that encourage daily sustainable practices, rather than relying solely on theoretical education. Additionally, collaborations with local environmental organizations, businesses, and policy-makers can provide students with practical exposure to sustainability efforts beyond the academic setting. Internship programs, research projects addressing real-world environmental challenges, and participation in policy-making discussions can further strengthen students' commitment to sustainable living. By adopting a more holistic and applied approach, conservation education programs can move beyond knowledge transfer and actively shape students' sustainable lifestyle behaviors, ensuring that they not only understand sustainability concepts but also internalize and apply them in their everyday lives. Future curriculum development should therefore focus on integrating experiential learning, social engagement, and institutional support to enhance the overall effectiveness of conservation education in promoting sustainable lifestyles.

To enhance its effectiveness, conservation education should incorporate active learning strategies, real-world applications, and structured behavioral interventions, ensuring that students not only understand sustainability concepts but also develop habits and social norms that support a long-term lifestyle. Future research could further explore how curriculum modifications, institutional policies, and environmental incentives might strengthen the connection between pro-environmental behavior and sustainable lifestyle adoption.

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