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The role of makerspaces in advancing STEAM pedagogy: A systematic review

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ABSTRACT

The 21st century demands high-quality human resources equipped with critical, analytical, and creative thinking skills. In response to these needs, educational institutions have initiated and developed the Science, Technology, Engineering, Arts, and Mathematics (STEAM) learning approach, which emphasizes interdisciplinary learning. In parallel, several schools have implemented makerspaces to support interdisciplinary learning. This study aims to systematically review the existing scholarly literature on the potential and challenges associated with implementing makerspaces in STEAM education. This study employs a literature review method, analyzing 13 Scopus-indexed articles published between 2014 and 2024, based on established inclusion criteria. The findings reveal that makerspaces function as constructivist learning environments that support learning through a STEAM-based approach. Furthermore, makerspaces are recognized for their potential to promote inclusive and equitable education by offering culturally relevant, student-centered opportunities that reflect the diversity of learners. However, several challenges remain, including limited access to tools and infrastructure, rigid curricular frameworks, insufficient teacher training, and the absence of assessment tools capable of capturing complex and multimodal learning outcomes. In conclusion, while makerspaces hold significant potential for enriching STEAM pedagogy, their successful integration relies heavily on systemic support, inclusive design practices, and continuous professional development for educators.

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ABSTRAK

Abad ke-21 membutuhkan sumber daya manusia yang berkualitas seperti keterampilan berpikir kritis, analitik, dan kreatif. Dalam memenuhi kebutuhan tersebut, lembaga pendidikan memulai dan mengembangkan pendekatan pembelajaran Science, Technology, Engineering, Arts, and Mathematics (STEAM), dimana fokus pembelajaran interdisplinary diutamakan. Di sisi lain, beberapa sekolah menerapkan makerspace dalam mendukung pembelajaran interdisplinary. Penelitian ini bertujuan untuk melakukan tinjauan sistematis terhadap potensi dan tantangan implementasi makerspace dalam pembelajaran STEAM berdasarkan literatur ilmiah. Metode penelitian ini menggunakan studi literatur review dengan menggunakan 13 artikel terindeks Scopus dan diterbitkan antara tahun 2014 hingga 2024, berdasarkan kriteria inklusi yang telah ditetapkan. Temuan menunjukkan bahwa makerspace berperan sebagai lingkungan belajar konstruktivis yang mendorong pembelajaran berbasis pendekatan STEAM. Selain itu, makerspace juga dinilai memiliki potensi untuk mendorong pembelajaran yang inklusif dan berkeadilan melalui penyediaan peluang yang relevan secara budaya dan berpusat pada siswa, sesuai dengan keragaman peserta didik. Namun demikian, terdapat tantangan seperti keterbatasan akses terhadap alat dan infrastruktur, kerangka kurikulum yang kaku, kurangnya pelatihan bagi pendidik, serta belum tersedianya alat asesmen yang mampu mengukur hasil belajar kompleks dan multimodal. Kesimpulannya adalah makerspace memiliki potensi besar dalam memperkaya pedagogi STEAM, keberhasilan integrasinya bergantung pada dukungan sistemik, praktik desain yang inklusif, dan pengembangan profesional yang berkelanjutan bagi pendidik.

Kata Kunci: *inovasi; kompetensi; makerspaces; pendidikan STEAM; tantangan*

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INTRODUCTION

In the 21st century, the business world places increasing emphasis on the importance of higher-order cognitive and socio-emotional skills in the ever-evolving labor market. This shift is driven by the transition from Industry 4.0 to Society 5.0. Evidence from the World Economic Forum's Future of Jobs Report indicates that analytical thinking is the most sought-after skill, identified by 69% of employers as a key competency. This is closely followed by resilience, flexibility, and agility (67%), as well as leadership and social influence (61%), all of which reflect the need for adaptive and people-centered capabilities in dynamic work environments. Other highly valued skills include creative thinking (57%), motivation and self-awareness (52%), and technological literacy (51%) (link: https://www.weforum.org/publications/the-future-of-jobs-report-2023/). In response to such pressing demands, educational institutions have begun to adopt various innovative instructional approaches. One such approach is Science, Technology, Engineering, and Mathematics (STEM), which has evolved into STEAM through the inclusion of the Arts. A growing body of research suggests that STEAM education has a significant impact on the development of critical thinking and problem-solving skills, competencies that are crucial for addressing the complexities of real-world challenges.

STEAM has emerged as a comprehensive educational framework designed to foster critical thinking, creativity, and socio-emotional skills in learners. Historically, this approach emerged in response to the perceived limitations of STEM, acknowledging the importance of creativity and artistic expression in driving technological innovation (Yee-King et al., 2017). The integration of the arts into STEM encourages the development of interdisciplinary curricula that facilitate connections and applications of knowledge across domains, thus promoting deeper and more contextualized learning. Participation in STEAM-related activities has also been shown to enhance students' academic performance and stimulate higher-order innovative thinking beyond that fostered by traditional educational approaches (Yee-King et al., 2017).

Alongside the rise of STEAM, educational environments have increasingly adopted makerspaces—collaborative learning spaces designed to foster inclusivity and active student engagement. Smith and Light, in their book "*How to Cultivate Sustainable Developments in Makerspaces*" explain that originating from grassroots learning communities centered around shared resources and knowledge exchange, makerspaces serve as community-based learning environments that promote social interaction, innovation, and the collective construction of knowledge. Within the educational context, these spaces align with 21st-century pedagogical imperatives by equipping students with critical thinking, creativity, and collaborative competencies (Kay & Buxton, 2024; Peppler, 2022). Moreover, makerspaces offer entrepreneurial opportunities within socio-technical environments that support the development of self-efficacy, practical skills, and social networks conducive to community-based innovation and business creation (Hui & Gerber, 2017). In educational settings, makerspaces contribute to students' professional development by enhancing technological competencies and career readiness, including within the humanities, which are increasingly incorporating project-based creative methodologies (Medina-Zut, 2023). Thus, makerspaces are not only relevant to technological disciplines but also serve to broaden the scope of learning across academic domains.

Numerous studies have explored the role of makerspaces in promoting creativity, digital empowerment, and inclusivity within STEAM education. However, systematic reviews of the existing literature reveal several gaps and limitations that warrant further investigation. For instance, the significance of inclusivity in makerspaces, examined through a critical theoretical lens, relies on a single theoretical framework and a review of a limited number of studies (Andrew, 2024). Similarly, the relationship between makerspaces and student creativity was found to be positive (Soomro, 2023). However, the study fails to link creativity to STEAM learning outcomes explicitly and does not provide a robust causal analysis; furthermore, the

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operationalization of creativity remains unclear. On the other hand, makerspaces have a role in empowering children and adolescents through digital experiences outside formal educational settings (Smolarczyk, 2023). Despite its broad thematic coverage, the study lacks empirical evidence, particularly from experimental research. The application of makerspaces in early childhood education affirms the relevance of STEAM in that context (Johnston, 2022). However, the study is primarily descriptive and does not provide empirical insights into implementation practices. While makerspaces show promise in enhancing creativity, empowerment, and inclusivity in STEAM education, existing studies are limited by narrow theories, weak empirical evidence, and a lack of focus on practical challenges. Future research should broaden theoretical approaches, strengthen methodological rigor, and address implementation issues more systematically.

Practical issues such as limited funding, infrastructural constraints, insufficient teacher training, and weak curriculum integration are still rarely addressed systematically in the literature. However, these factors represent essential needs that must be fulfilled for the successful implementation of makerspaces in schools. Theoretically, much of the existing research remains grounded in narrow critical frameworks. Alternative pedagogical perspectives, which hold significant potential to enrich understanding and broaden approaches to makerspace implementation in the context of STEAM education, have yet to be thoroughly explored. Therefore, future research should aim to expand theoretical approaches, enhance methodological rigor, and systematically examine practical aspects of makerspace integration across various educational settings, particularly within STEAM education.

Given these gaps, there is a need for a more comprehensive investigation into the contributions of makerspaces to STEAM pedagogy, one that considers not only their potential benefits but also the practical challenges encountered in their implementation. This study seeks to address these shortcomings by examining the primary roles of makerspaces in strengthening STEAM pedagogy, analyzing how makerspaces contribute to student engagement and learning outcomes within STEAM education, and identifying the challenges and barriers faced by educators and students in integrating makerspaces into STEAM pedagogical practices.

LITERATURE REVIEW

STEAM Pedagogy

The evolution of STEAM education can be traced back to its foundation in the STEM framework. Initially, STEM focused on strengthening scientific and technological proficiency. However, the integration of the arts—viewed initially with skepticism—has since been recognized for enhancing creativity and problem-solving. This shift acknowledges the role of aesthetic understanding in promoting design thinking and deeper engagement in learning (Custodio & Rosa, 2024). The expansion from STEM to STEAM reflects a broader educational vision that values interdisciplinary collaboration as essential for addressing complex, real-world problems.

The implementation of STEAM has shown effectiveness across all levels of education. In primary schools, STEAM fosters curiosity and problem-solving through project-based learning (Zakaria & Md Osman, 2024). At the secondary level, students develop analytical and creative skills that prepare them for further education in STEM-related fields (Martín-Cudero, 2024). In higher education, STEAM supports interdisciplinary research and innovation, enabling students to address complex global issues with integrated knowledge and collaborative approaches (Kumar & Deák, 2024). STEAM education also shows promise in promoting inclusivity and equity. When supported by adaptive curricula and inclusive teaching practices, it can provide meaningful learning opportunities for students from diverse backgrounds, including those in underserved communities or with disabilities (Zakaria & Md Osman, 2024). However,

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challenges such as limited resources, inadequate teacher training, and infrastructure constraints continue to hinder its broader implementation (Cevallos, 2024).

Current trends in STEAM education emphasize hands-on learning and the use of emerging technologies. Tools such as 3D printing, robotics, and the Internet of Things (IoT) enhance experiential learning, allowing students to explore abstract concepts in tangible ways (Zakaria & Md Osman, 2024). Visual arts, in particular, are increasingly valued for their role in supporting cognitive development and concept visualization (Zhang, 2023). The growing emphasis on collaborative, project-based work aligns with the demand for real-world application and workplace readiness (Wong & Kwan, 2021).

Despite its demonstrated benefits, STEAM education still faces structural and practical challenges. Among these are insufficient professional development opportunities for teachers, a lack of curricular integration, and limited policy support (Abbas et al., 2024). Addressing these barriers requires strategic investment in teacher training, infrastructure, and inclusive curricular frameworks. Moreover, ongoing research is necessary to assess the long-term effects of STEAM education and its adaptability across diverse educational systems (Cevallos, 2024).

Makerspace

Makerspaces provide experiential learning opportunities, particularly for children, through activities that involve electronics, digital fabrication, and craftsmanship, while simultaneously cultivating 21st-century competencies such as creativity, collaboration, and critical thinking (Buxton et al., 2022). In the context of early childhood education, the Makerspace Learning Assessment Framework has played a crucial role in evaluating learning outcomes, particularly for children aged 3 to 10, by emphasizing the development of constructive habits of mind (Kay & Buxton, 2024). These environments promote the development of self-efficacy and entrepreneurial competence through hands-on experiences that extend beyond formal curricular boundaries. Consequently, makerspaces serve as strategic venues for career development, particularly within the technology and creative industries (Hui & Gerber, 2017).

Outside the classroom and the startup ecosystem, makerspaces also make significant contributions to community development and the preservation of local cultural identities. They play a role in neighborhood revitalization and social innovation by embodying the unique characteristics of the communities they inhabit. The classification of makerspaces into socio-material typologies allows for a more nuanced understanding of their functions and provides a framework for evaluating their social and cultural contributions (Debowski et al., 2024). The integration of makerspaces into policy and institutional frameworks further enhances their transformative potential. Their development is often facilitated by supportive public policies, including entrepreneurial incentives, subsidized usage fees, and employment support programs (Wang & Zeng, 2021).

Makerspaces also support the cultivation of transdisciplinary mindsets by helping learners understand the interconnectedness of diverse fields (Barbara et al., 2024). Through the use of varied materials and technologies, they encourage experimentation, iterative learning, and creative risk-taking practices that are fundamental to the development of critical and innovative thinking (Buxton et al., 2022). Numerous studies have shown that engagement in makerspace activities enhances students' motivation, participation, and conceptual understanding of interdisciplinary content (Boeve-De Pauw et al., 2024; Tan, 2019). These environments enable students to apply constructionist principles by designing and creating tangible artifacts, thereby deepening their understanding through hands-on, practice-based learning (Olabe et al., 2020).

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METHODS

This study employs a systematic literature review to address the questions posed. By using this method, the reporting system used in this systematic literature review is a meta-analysis. This method can provide a systematic display of repeaters and flow diagrams to increase the accuracy of the literature review (Page et al., 2021). This method has two stages, namely (Rincon-Novoa et al., 2022):

1. Search criteria and databases

The search criteria adopted utilize terms related to the role of makerspaces in STEAM education. Recently, a review was conducted to evaluate the search performance of 28 well-known databases for evidence synthesis, concluding that some databases, such as Google Scholar, are helpful for cross-checking but not suitable for systematic reviews (Gusenbauer & Haddaway, 2020). For this reason, the Scopus index database was selected among the primary sources they list.

2. Selection process

The protocol for writing this study was to ensure that the results were transparent and of high quality (Page et al., 2021). In this case, the author sets criteria in the selection process, including:

a. Scientific work related to (makerspaces, STEAM education, makerspaces, STEAM pedagogy, collaborative learning in makerspaces, active Learning in makerspaces, makerspaces in education, or makerspaces STEAM learning);
b. Scientific work that has empirical results and can be accounted for;
c. Scientific work written in an international language and published in 2014 - 2024.

Following a subsequent search, a total of 292 studies were identified. However, six of these studies could not be contacted, and four were limited to English-language abstracts. As a result, the review was conducted based on 209 studies. Upon further screening, 13 studies were deemed relevant for inclusion in the review. The systematic review process is illustrated in **Figure 1**.

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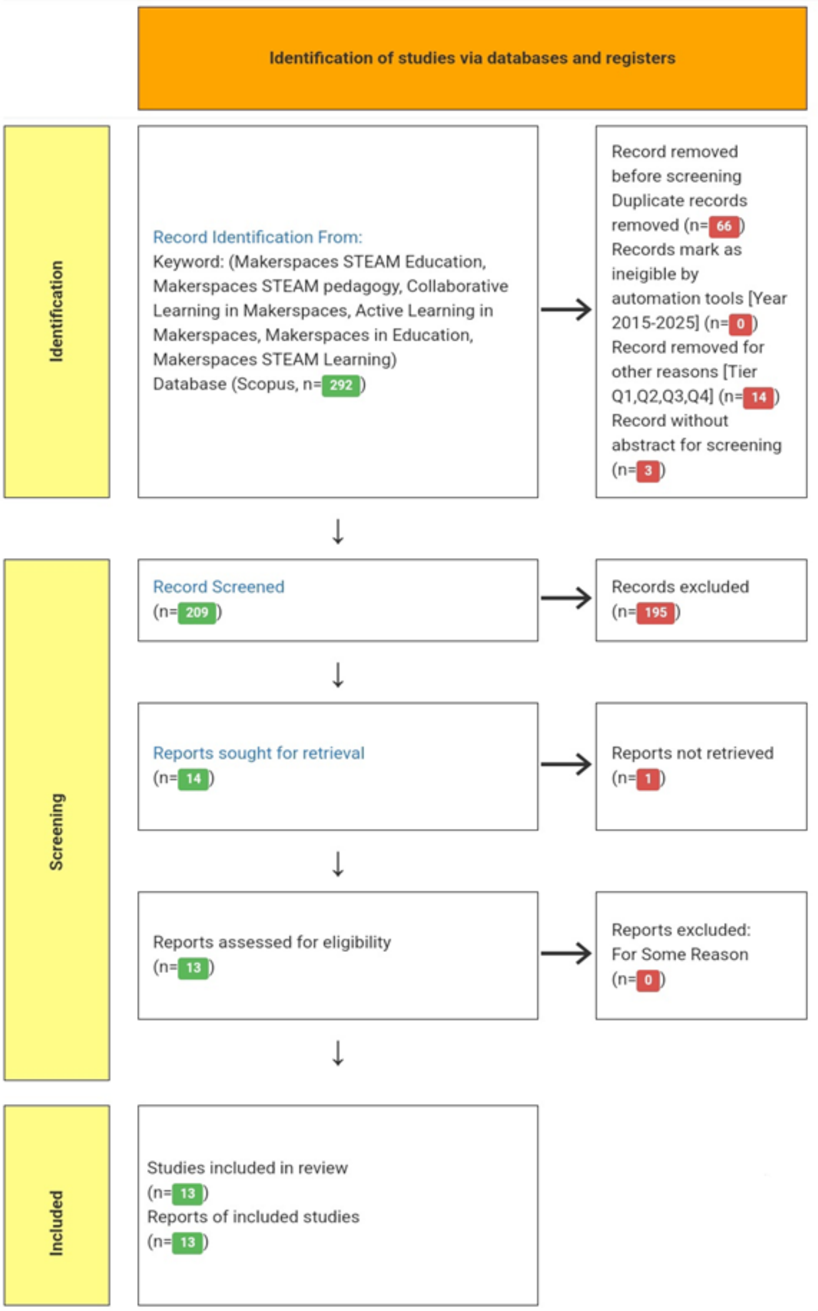

Figure 1. Systematic review process
Sources: Researcher Documentation 2025

During the identification phase, 66 duplicate records were removed. An additional 17 records were excluded due to other criteria: 14 were not from journals classified under Scopus tiers Q1-Q4, and 3 lacked abstracts, leaving 209 records for screening. During the screening phase, 195 records were excluded based on title and abstract relevance, resulting in 14 reports that were sought for full-text retrieval. One report could not be retrieved, leaving 13 reports for complete eligibility assessment. No reports were excluded at this stage, and all 13 were subsequently included in the final synthesis. The resulting dataset, comprising 13 studies, forms the empirical foundation of this review, representing a carefully curated body of literature that adheres to quality standards and relevance criteria. This process underscores the transparency and replicability of the research, ensuring that conclusions drawn are based on a comprehensive and critically evaluated evidence base.

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RESULTS AND DISCUSSION

Result

The 13 reviewed studies, published between 2017 and 2024, explore the role of makerspaces in enhancing STEAM education across various levels. They highlight impacts on student creativity, collaboration, innovation, and equity, as well as their integration into teacher training. Covering themes such as digital making, e-textiles, and leadership, these studies underscore the value of makerspaces as transformative, practice-based learning environments. Following the screening of relevant published research, articles that met the predetermined criteria and aligned with the study's objectives were selected and summarized in **Table 1**.

Table 1. Articles that Meet the Requirement

No	Authors	Title
1	Cheng & Pang (2024)	Making activities for the competency development of school-age children
2	Leskinen et al. (2023)	Learning to innovate: Students and teachers constructing collective innovation practices in a primary school's makerspace
3	Fields & Kafai (2023)	Supporting and sustaining equitable STEAM activities in high school classrooms: Understanding computer science teachers needs and practices when implementing an e-textiles curriculum to forge connections across communities
4	Dúo-Terrón et al., (2022)	Impact of the pandemic on STEAM disciplines in the sixth grade of primary education
5	Kajamaa & Kumpulainen (2020)	Students multimodal knowledge practices in a makerspace learning environment
6	Timotheou & Ioannou (2021)	Learning and innovation skills in making context a comprehensive analytical framework and coding scheme
7	Shively et al. (2021)	Ideation to implementation a 4-year exploration of innovating education through maker pedagogy
8	Leskinen et al. (2021)	The emergence of leadership in students group interaction in a school-based makerspace
9	Jordan et al., (2021)	Making on the move mobility, makerspaces, and art education
10	Shively et al. (2020)	Teaching severe weather examining teacher candidates early field experience in a makerspace environment
11	Woods & Hsu (2020)	Making spaces for STEM in the school library
12	Saorín et al., (2017)	Makerspace teaching-learning environment to enhance creative competence in engineering students
13	Hughes (2017)	Digital making with "At-Risk" youth

Source: The data were processed independently by the researcher in 2024

The primary roles of makerspaces in strengthening STEAM pedagogy

Based on the filtered articles, several findings emerged that address the research question concerning the roles of makerspaces in enhancing STEAM. This is evident in **Table 2**. Makerspaces have evolved into dynamic educational environments that significantly contribute to the enhancement of STEAM (Science, Technology, Engineering, Arts, and Math) pedagogy. Firstly, makerspaces facilitate hands-on and experiential learning, which aligns with constructivist learning theories. By engaging in the process of making, students actively construct knowledge through the manipulation of digital and physical materials,

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often in an informal or semi-structured setting (Cheng & Pang, 2024; J. Hughes, 2018). Scaffolding the constructed knowledge will support deeper conceptual understanding and contextual application of knowledge.

Table 2. The Roles of Makerspace in STEAM Pedagogy

No	Author	Main Roles
1	Cheng & Pang (2024)	Support self-directed, hands-on learning and 21st-century skills
2	Leskinen et al. (2023)	Enable innovation, collaboration, and student ownership
3	Fields & Kafai (2023)	Foster interdisciplinary learning and personal expression
4	Dúo-Terrón et al., (2022)	Develop critical thinking and digital competencies
5	Kajamaa & Kumpulainen (2020)	Encourage multimodal, collaborative, and embodied learning
6	Timotheou & Ioannou (2021)	Promote constructivist and problem-based learning
7	Shively et al. (2021)	Act as design-thinking platforms for creativity and innovation
8	Jordan et al., (2021)	Integrate the arts in digital fabrication and inclusive learning
9	Shively et al. (2020)	Train pre-service teachers, encourage experimentation
10	Woods & Hsu (2020)	Promote inclusive, real-world learning in libraries
11	Saorín et al., (2017)	Provide open-access digital fabrication for creativity and problem-solving
12	Hughes (2017)	Support identity, digital storytelling, and critical making

Source: The data were processed independently by the researcher in 2024

Secondly, makerspaces create an environment conducive to both project-based and problem-based learning. Moreover, the interdisciplinary nature of makerspaces supports the integration of artistic and scientific thinking, thus realizing the full scope of STEAM education. These spaces encourage learners to utilize diverse disciplinary knowledge to engage in creative practices, bridging traditionally siloed domains (Fields & Kafai, 2023; Saorín et al., 2017). Those spaces offer open-ended challenges that encourage learners to identify problems, seek solutions, and iterate on designs, thus fostering inquiry-based learning and critical problem-solving skills (Shively, 2021; Timotheou & Ioannou, 2021). As such, makerspaces play a crucial role in fostering 21st-century competencies, including creativity, collaboration, communication, and digital literacy. The inclusion of technology integration in activities promotes the development of innovation skills and future workforce readiness (Cheng & Pang, 2024; Leskinen et al., 2023).

Makerspaces also serve as innovation ecosystems for both learners and teachers. On the student side, makerspaces provide a space for collective design processes and peer-to-peer learning, thus creating knowledge and practicing democratic participation (Dúo-Terrón et al., 2022; Leskinen et al., 2023). On the other hand, makerspaces also serve as platforms for pedagogical innovation and teacher professional development. Teachers utilize makerspaces to experiment with innovative teaching strategies, integrate design thinking, and develop interdisciplinary curricula that align with real-world challenges (Shively, 2021; Shively et al., 2020). Ultimately, makerspaces foster a growth mindset by legitimizing failure as a learning tool and promoting iterative practice. This emphasis on reflection and resilience supports both cognitive and emotional aspects of learning, which are important for long-term academic and personal development (Shively et al., 2020; Timotheou & Ioannou, 2021).

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How do Makerspaces Contribute to STEAM Education

Several findings emerged that addressed the second research question, specifically how makerspaces contribute to student engagement and learning outcomes in STEAM education. The findings are presented in **Table 3**. Students are more motivated when given the freedom to choose their projects and pursue ideas inspired by real-world experiences (Cheng & Pang, 2024). Autonomy, relevance, and peer interaction contribute significantly to students' sense of ownership and responsibility in learning (Leskinen et al., 2023). Makerspaces also encourage social engagement through collaborative practices. Students construct knowledge through peer tutoring and sharing epistemic challenges (Kajamaa & Kumpulainen, 2020). Improvements in communication, teamwork, and transdisciplinary thinking among students engaged in collaborative STEAM projects (Dúo-Terrón et al., 2022).

Table 3. The Contribution of Makerspace to Engagement and Learning

No	Author	Contribution Highlights
1	Cheng & Pang (2024)	Boost IT skills, motivation, and autonomy through real-life projects
2	Leskinen et al. (2023)	Foster innovation, reflection, and student-led learning
3	Fields & Kafai (2023)	Increase interest and peer collaboration in coding
4	Dúo-Terrón et al., (2022)	Enhance motivation, teamwork, and digital engagement
5	Kajamaa & Kumpulainen (2020)	Support peer learning and knowledge co-construction
6	Timotheou & Ioannou (2021)	Develop creativity, reasoning, and collaboration
7	Shively et al. (2021)	Build empathy and problem-solving for real-world issues
8	Jordan et al., (2021)	Engage students through hands-on, inquiry-based exploration
9	Shively et al. (2020)	Encourage reflective teaching and child collaboration
10	Woods & Hsu (2020)	Increase motivation and inclusivity in STEM
11	Saorín et al., (2017)	Improve creativity and engagement through personalization
12	Hughes (2017)	Build confidence, resilience, and collaboration skills

Source: The data were processed independently by the researcher in 2024

The presence of consistent themes in the literature has the potential to foster higher-order thinking skills. Through an iterative process that embraces failure and reflection, students foster creativity, critical thinking, and innovation (Fields & Kafai, 2023; Timotheou & Ioannou, 2021). These skills are further reinforced by students' increased confidence and sense of ability in complex fields such as computer science and engineering. Makerspaces naturally support interdisciplinary learning by integrating the arts with traditional STEM disciplines. Such an environment enables students to explore the relationship between engineering and artistic design, thereby increasing their awareness and competence in various fields (Jordan et al., 2021). These spaces also unlock the value of open and playful inquiry, allowing students to transfer knowledge across fields (Woods & Hsu, 2020).

Another important contribution of makerspaces is their potential to democratize access to STEAM learning. By providing open access, inclusive spaces, makerspaces support the participation of underrepresented groups, including those from underserved communities (Woods & Hsu, 2020). Such environments empower students to build confidence, resilience, and agency, even among those who have not previously engaged in traditional learning contexts (J. Hughes, 2017). In addition to engagement, makerspaces have shown measurable effects on student learning outcomes. Statistically significant increases in creative competence, while other studies document improvements in digital literacy, problem-solving ability, and transdisciplinary thinking (Cheng & Pang, 2024; Dúo-Terrón et al., 2022).

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Challenges and barriers in integrating makerspaces into STEAM pedagogical practices

While makerspaces offer transformative potential for STEAM education, their integration into formal and informal learning environments presents several ongoing challenges for both educators and students. A synthesis of recent literature also reveals several structural, pedagogical, technological, and social barriers. **Table 4** explicitly illustrates some of the barriers and obstacles to implementing makerspaces.

Table 4. Challenges in the Implementation of Makerspace

No	Author	Main Challenges
1	Cheng & Pang (2024)	Coding difficulty, gender imbalance, and the need for support
2	Leskinen et al. (2023)	Teacher dependence, school constraints, and sustainability
3	Fields & Kafai (2023)	Lack of institutional support and isolation
4	Dúo-Terrón et al. (2022)	Reduced collaboration post-pandemic
5	Kajamaa & Kumpulainen (2020)	Uneven participation, collaborative conflict
6	Timotheou & Ioannou (2021)	Lack of tools to assess complex, spontaneous learning
7	Shively et al. (2021)	Limited access, conflicting curricula, and weak leadership
8	Jordan et al. (2021)	Time limits and difficulty maintaining inquiry focus
9	Shively et al. (2020)	Planning challenges, limited expertise, and classroom management
10	Woods & Hsu (2020)	Equipment gaps, testing pressure, and staff training needs
11	Saorín et al. (2017)	Time and tech limitations; short-term novelty effect
12	Hughes (2017)	Student frustration, teacher scaffolding burden, resource gaps

Source: The data were processed independently by the researcher in 2024

One of the most frequently cited challenges is the pedagogical complexity of implementing makerspace activities. Educators must navigate open, nonlinear learning environments that demand flexible yet deliberate scaffolding. For example, there is a lack of appropriate assessment tools to capture the spontaneous and multimodal nature of learning in makerspaces (Timotheou & Ioannou, 2021). Similarly, there are difficulties with lesson planning in informal project-based settings, especially when balancing student autonomy with curriculum objectives (Shively et al., 2020). Educator expertise and facilitation play a crucial role in the successful integration of makerspaces. However, highlighting the heavy reliance on teacher expertise, which can limit innovation and student ownership if not supported by institutional structures (Leskinen et al., 2023). The need for ongoing professional development and leadership support is also recurrent (Shively, 2021; Woods & Hsu, 2020).

Numerous studies identify practical limitations related to time, space, and equipment. Time constraints impede iterative design processes, which often limit meaningful engagement with digital fabrication tools (Jordan et al., 2021; Saorín et al., 2017). Technical issues, such as low-quality scans or a lack of understanding of digital platforms, also cause frustration among students (Hughes, 2017). In under-resourced schools, the availability of resources remains a significant barrier. Equipment variability, limited access to technology, and inadequate training can hinder equitable participation and long-term sustainability (Hughes, 2017; Woods & Hsu, 2020). Several studies raised concerns about the long-term sustainability of makerspace initiatives. Without consistent support and integration into school policies, these programs risk becoming short-lived or temporary. This is due to threats that suggest a lack of mechanisms to sustain innovation and engagement beyond the initial implementation phase (Fields & Kafai, 2023; Leskinen et al., 2023).

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Discussion

The literature review demonstrates the transformative potential of makerspaces in STEAM education. However, a deeper analysis reveals a complex interplay of pedagogical, cognitive, sociocultural, and institutional factors that can both serve as levers and barriers to makerspace utilization. Makerspaces are not just tools or physical spaces, but represent a paradigm shift in educational practice, from content-based teaching to learner-centered, process-oriented, and interdisciplinary learning.

Knowledge construction through body and context-based learning

Makerspaces play a crucial role in supporting knowledge construction through embodied and context-based learning. These spaces offer hands-on, experiential environments that enable the transformation of abstract ideas into tangible artifacts. In doing so, they foster reflective, collaborative, and situated learning experiences, consistent with constructivist and constructionist learning paradigms (Mersand, 2021). A core feature of makerspaces is the direct interaction between learners and digital fabrication tools, physical materials, and peer discussions. These interactions facilitate embodied learning, in which cognitive processes are tightly integrated with physical activity and contextual engagement. The availability of tools and media in makerspaces serves to concretize abstract concepts, allowing students to construct physical artifacts as a means of internalizing and representing knowledge (Borges & Menezes, 2018).

Learning in makerspaces typically follows an iterative process involving exploration, failure, reflection, and continuous improvement (Shively et al., 2020; Timotheou & Ioannou, 2021). Such learning is meaningful and situated, as it often relates directly to real-world challenges and students' interests. In this way, students not only acquire knowledge but also actively construct it themselves (Cheng & Pang, 2024; Fields & Kafai, 2023). Moreover, makerspaces support multimodal knowledge practices by integrating discourse, digital tools, and physical actions. These modes of engagement mediate learning and facilitate the co-creation of epistemic objects (Kajamaa & Kumpulainen, 2020). Maravilhas and Martins, in their book “Tacit Knowledge in Maker Spaces and Fab Labs,” further highlight that makerspaces promote collaborative learning through joint projects in which learners exchange knowledge and experiences, thereby enhancing creativity and innovation.

The design of learning experiences within makerspaces is informed by Piagetian epistemology and related educational theories, which emphasize learner autonomy and structured guidance (Borges & Menezes, 2018). Such frameworks help educators implement didactic structures that effectively support learners in achieving their intended learning outcomes through makerspace-based activities (Kaar & Stary, 2019).

Negotiating identity, equality, and agency

Makerspaces serve not only as environments for skill development but also as spaces for identity negotiation and social empowerment. When students engage in personally meaningful projects—especially those that reflect cultural, aesthetic, or community elements—they do more than acquire technical knowledge; they begin to see themselves as creators, designers, programmers, and collaborators (J. Hughes, 2017; Jordan et al., 2021). Through creative expression and collaborative engagement, learners can explore and construct identities that may not be afforded to them in traditional academic settings. Research shows how girls navigating STEM-rich environments—despite initial reluctance—participate through craft-based technologies, revealing the complexity of identity work and the social pressures embedded in gendered expectations (Parekh, 2024). Tzuriel, in his book “*The Socio-Cultural Theory of Vygotsky*” said that this process aligns with sociocultural learning theory, which emphasizes the importance of meaningful participation in authentic cultural practices.

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Makerspaces also hold critical potential to challenge systemic patterns of exclusion that persist in conventional STEM education. Their open, interest-driven nature offers inclusive pathways for participation, particularly for underrepresented groups such as women, racial minorities, and students from socioeconomically disadvantaged backgrounds (Woods & Hsu, 2020). When intentionally designed, makerspaces can embed principles of social justice by involving diverse learners in co-designing assistive technologies, particularly alongside students with disabilities, emphasizing both accessibility and shared ownership (Higgins et al., 2023).

To ensure meaningful and equitable engagement, deliberate design strategies must be employed to reduce barriers and foster inclusive participation. These include creating spaces where all learners feel heard, respected, and empowered (Fasso & Knight, 2020). However, studies also caution that without conscious and intentional facilitation, existing participation inequalities—such as the dominance of certain groups—can be reproduced, even within spaces intended to be inclusive (Cheng & Pang, 2024; Leskinen et al., 2021).

From engagement to deep learning

Makerspaces promote active student participation by allowing learners to engage directly with materials and technologies, thereby increasing motivation and interest in learning (Falloon et al., 2022). As dynamic learning environments, makerspaces facilitate the transition from surface engagement to deep learning by fostering creativity, problem-solving, and collaboration. These spaces are intentionally designed to support diverse educational outcomes, particularly in STEM and computational thinking, by providing experiential opportunities that encourage exploration and innovation.

The importance of structured guidance from educators to fully realize the potential of makerspaces in building conceptual understanding, especially in STEM domains (Falloon, 2022). Similarly, observations in kindergarten makerspaces indicate that environments supported by intentional facilitation can significantly enhance children’s Positive Technological Development (PTD), leading to higher engagement and improved learning outcomes (Strawhacker & Bers, 2018).

The engagement generated in makerspaces should not be viewed solely as increased enthusiasm, but rather as an integral part of the learning process that promotes higher-order thinking. With appropriate scaffolding, makerspaces can cultivate cognitive skills such as analysis, synthesis, abstraction, and reflection. This is evident in students' ability to integrate cross-disciplinary knowledge and view failure as a constructive component of the innovation process (Fields & Kafai, 2023; Saorín et al., 2017).

Moreover, affective dimensions—such as self-confidence, perseverance, and curiosity—play a vital role in holistic STEAM learning. These attributes enable learners to navigate uncertainty, tolerate ambiguity, and persist through complexity, all of which are essential dispositions in preparing students for 21st-century challenges (Bobic, 2023).

Makerspace as a space for pedagogical and professional transformation

Makerspaces function as transformative learning environments that support both pedagogical innovation and professional growth. These spaces encourage educators to critically re-evaluate traditional curriculum frameworks and embrace hands-on, constructionist approaches to teaching and learning. Several studies have demonstrated that teacher engagement in makerspaces can stimulate pedagogical experimentation, curriculum innovation, and interdisciplinary teaching practices that are more closely aligned with real-world contexts (Shively, 2021; Shively et al., 2020).

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Through participation in design-based research and hands-on practice, educators are prompted to reconsider their teaching methods and curricular goals, leading to the adoption of more inquiry-driven and learner-centered approaches (Becker & Jacobsen, 2020). Otieno, in his book "*Teaching in a Makerspace: The Pedagogical Practices of Makerspace Instructors*" explains that, in makerspace settings, instructors often shift to facilitative roles that empower students to explore, experiment, and iterate on their ideas—thereby cultivating a growth mindset and deeper engagement with content.

Collaboration plays a central role in the success of makerspaces. Productive partnerships between educators, industry stakeholders, and school leadership help build teachers' confidence and capacity to implement new pedagogical strategies (Stevenson et al., 2019). Professional learning programs that emphasize practical exposure to design thinking and emerging technologies have also been shown to enhance teachers' pedagogical enthusiasm and competence significantly.

However, such transformations are highly dependent on institutional support. Without systemic backing from schools and educational leadership, the pedagogical shifts inspired by makerspaces are often unsustainable. For this reason, integrating makerspaces into education policy, teacher training frameworks, and school ecosystem design is essential. Educators must navigate these systemic challenges in order to fully realize the transformative potential of makerspaces in reshaping teaching practices (Yusuf et al., 2019).

Tensions and future directions

The implementation of makerspaces is often marked by a range of inherent tensions that may impact their effectiveness and inclusivity. These tensions stem from the differing needs, expectations, and institutional frameworks of users, educators, and stakeholders. Understanding these dynamics is crucial to creating an environment that fosters creativity and collaboration while addressing barriers that may hinder meaningful participation.

A key area of tension lies in the balance between playful learning and functional utility. While users often seek an enjoyable, exploratory atmosphere, they also expect a space that is structured and efficient. This tension directly influences how makerspaces are designed and utilized (Smit et al., 2024). Similarly, there is a duality between encouraging collaboration and supporting individual project work. Makerspaces must navigate the need for social learning opportunities alongside students' desire for focused, independent exploration, often leading to conflicting spatial or instructional arrangements (Smit et al., 2024).

In educational settings, students frequently experience a push-and-pull between autonomy and the need for faculty guidance. This dynamic can significantly shape their level of engagement and their evolving identities within the makerspace (Tomko et al., 2017). Moreover, linguistic and interactional practices between educators and students can introduce additional tensions, influencing the overall culture and inclusivity of the school-based makerspace environment (Campos et al., 2019).

Beyond interpersonal and pedagogical dynamics, makerspaces are also situated within broader structural tensions that challenge their long-term sustainability. Traditional education systems still emphasize standardization, high-stakes testing, and strict disciplinary boundaries. This mismatch can result in fragmented or unsustained implementation of makerspaces within formal schooling (Fields & Kafai, 2023; Leskinen et al., 2023). To address these challenges, an adaptive and transformative pedagogical framework is necessary—one that supports nonlinear, process-oriented learning. Such a framework should include the development of contextually relevant assessment tools, teacher training grounded in design thinking, and the integration of inclusive design principles to ensure accessibility and relevance for all learners.

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CONCLUSION

This review demonstrates that makerspaces play a vital role in enhancing STEAM pedagogy by shifting the focus of instruction from teacher-centered approaches to learner-centered, process-oriented, and interdisciplinary methods. Makerspaces function not only as physical environments but also as pedagogical frameworks that encourage hands-on and inquiry-based learning. They support the construction of knowledge through real, contextual, and iterative experiences, which align with constructivist and constructionist learning theories. Furthermore, makerspaces enable the integration of various disciplines through project-based exploration, fostering creativity, collaboration, and innovation — all essential characteristics of effective STEAM learning environments.

In terms of student engagement and learning outcomes, the literature suggests that makerspaces promote deep and meaningful involvement by allowing students to explore real-world problems, take ownership of their learning, and express themselves through multimodal artifacts. Makerspaces help develop higher-order thinking skills, such as analysis, synthesis, and reflection, while also supporting affective outcomes, including self-confidence, perseverance, and curiosity. Additionally, makerspaces contribute to inclusive participation by providing opportunities for students from diverse backgrounds, including girls, underrepresented minorities, and students with disabilities, to access and succeed in STEAM learning experiences.

However, implementing makerspaces in formal education is not without challenges. Educators and students face several obstacles, such as limited institutional support, rigid curricular structures, insufficient professional development, and unequal access to resources. Moreover, unresolved tensions, such as finding the balance between autonomy and structure or between collaboration and individualization, can hinder the effectiveness and sustainability of makerspace initiatives. Addressing these challenges requires a systemic approach that includes the development of adaptive pedagogical frameworks, contextually relevant assessment tools, inclusive design strategies, and ongoing teacher training grounded in design thinking. Through such comprehensive and purposeful integration, makerspaces can realize their full potential as transformative tools in STEAM education.

AUTHOR'S NOTE

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