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Shaping Learning in 3D: Approaching STEM in Science Education

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ABSTRACT

This study examines the integration of 3D printing in science education through a qualitative review of ten studies published between 2015 and 2025. The analysis identifies key educational, pedagogical, and technological components supporting curricular integration in basic education. Findings reveal three convergent patterns: strong grounding in constructivist and maker-centered pedagogies; consistent short-term gains in conceptual understanding, spatial reasoning, modeling, and transversal competencies; and limited evidence regarding long-term transferability, scalability, and equity impact. Across cases, 3D printing *functions as a cognitive mediator that enables students to embody abstract concepts through iterative design and physical artifacts. Effective implementation depends on structured instructional sequences, teacher mediation, curricular alignment, and sustainable institutional support. Overall, 3D printing emerges as a powerful pedagogical resource that enhances knowledge construction, student motivation, and the acquisition of twenty-first-century competencies.*

Keywords: 3D printing, active learning, learning inquiry-based, science education, STEM education

RESUMEN

Este estudio examina la integración de la impresión en 3D en la educación científica a través de una revisión cualitativa de diez casos de estudio publicados entre 2015 y 2025. El análisis identifica componentes educativos, pedagógicos y tecnológicos clave que respaldan la integración curricular en la educación básica. Los hallazgos revelan tres patrones convergentes: una sólida base en pedagogías constructivistas y centradas en la fabricación; beneficios consistentes a corto plazo en comprensión conceptual, razonamiento espacial, modelado y competencias transversales; y evidencia limitada con respecto a la transferibilidad, escalabilidad e impacto en la equidad a largo plazo. En todos los casos, la impresión 3D funciona como un mediador cognitivo que permite a los estudiantes dar forma a conceptos abstractos a través del diseño iterativo y artefactos físicos. La implementación efectiva depende de secuencias de instrucción estructuradas, mediación docente, alineación curricular y apoyo institucional sostenible. En general, la impresión 3D emerge como un poderoso recurso pedagógico que mejora la construcción del conocimiento, la motivación de los estudiantes y la adquisición de competencias del siglo XXI.

Keywords: Impresión 3D, aprendizaje activo, aprendizaje basado en la indagación, enseñanza de las ciencias, educación STEM.

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INTRODUCTION

STEM education has gained increasing relevance as a strategic approach to strengthening science education worldwide. International assessments such as PISA reveal persistent gaps in mathematics and science achievement in Mexico, where performance remains below the OECD average (OECD, 2023). Science literacy frameworks emphasize students' capacity to identify problems, explain phenomena, and reason about natural processes using scientific knowledge and models (OECD, 2019). These findings highlight the need for pedagogical approaches that promote deeper conceptual understanding and active engagement in scientific inquiry.

In response to these challenges, the Mexican public education system has introduced the New Mexican School (Nueva Escuela Mexicana), which focuses on critical thinking, reflection, environmental awareness, and scientific literacy beginning in early education (SEP, 2024a; SEP, 2024b; SEP, 2024c). Within this reform, curiosity and inquiry-based learning are positioned as central mechanisms for knowledge construction (Domínguez-Saldívar & Vázquez-Castelán, 2025). STEM education, characterized by its interdisciplinary and transdisciplinary orientation, aligns with these objectives by fostering problem-solving and learning-by-doing environments (Rahman-Bidita, 2024; Zolotareva et al., 2021).

Among the emerging technologies integrated into STEM contexts, 3D printing has attracted growing scholarly attention (Castro-Romero & Kang, 2022). Research highlights its potential to enhance student motivation, creativity, conceptual visualization, and scientific reasoning (Aslan, 2024; Qurraie et al., 2025; Üçgül & Altiok, 2023). However, existing studies have largely concentrated on short-term classroom interventions or isolated technological implementations. Limited attention has been given to how 3D printing can be systematically aligned with curricular design principles, competency development frameworks, and pedagogical decision-making processes in basic education—particularly within the context of national reforms such as those underway in Mexico.

To address this gap, the present study aims to identify key educational components for curricular design and pedagogical strategies that support the meaningful integration of 3D printing into science education. A qualitative case study review of ten educational experiences at the primary and secondary levels was conducted using the integrative model proposed by Al-Kamzari and Alias (2025).

The guiding research question is: How can 3D printing be effectively integrated into science education in basic education in Mexico to support curricular alignment, pedagogical strategies, and the development of scientific and transversal competencies? By employing an integrative conceptual and methodological framework, this study seeks to provide evidence-informed guidance for teachers, curriculum designers, and policymakers. Ultimately, it contributes to a more comprehensive understanding of the mechanisms and design components through which 3D printing can function as a tool for promoting active learning and strengthening science education outcomes.

THEORETICAL BACKGROUND

3D Printing Technologies in Science Education

The integration of 3D printing technologies has been driven by STEM education, which emphasizes the broader implications of three-dimensional modeling and printing for teaching and learning. These technologies have emerged as innovative tools that allow students to embody their ideas through rapid prototyping and physical models (Arango-Caro et al., 2025; Monroy et al., 2025). In primary science classrooms, 3D printing facilitates connections across disciplinary fields and provides hands-on experiences that reinforce conceptual understanding, particularly of complex scientific principles (Aslan et al., 2024; Edelsztein & Galagovsky, 2021).

Empirical studies suggest that 3D-printing models, such as representations of molecular structures, planetary systems, or cellular components, can support students' comprehension across physics, chemistry, and biology (Anđić et al., 2024; Scalfani & Vaid, 2014). Similarly, they support the teaching of spatial concepts, including atomic orbitals and molecular structures (Smith et al., 2020). By enabling learners to visualize events they cannot observe, such as cell division, gene expression, heat transfer, or extinct species, 3D models contribute to deeper cognitive processing, thereby reducing cognitive load and mitigating misconceptions (Teplá et al., 2022). These affordances suggest that 3D printing operates not merely as a visualization aid but as a mediating artifact.

However, the implementation of 3D printing technologies presents structural barriers. Xin et al. (2017) emphasize the need for adequate infrastructure, materials, teacher training in 3D modeling, clear curricular standards, inclusive learning environments, and scaffolded interdisciplinary projects. Effective integration requires shifting from traditional and teacher-centered instruction toward active, participatory, and project-based methodologies (Kefalis et al., 2024; Munir et al., 2025). Such approaches enable students not only to develop technical competencies but also to cultivate curiosity, critical thinking, creativity, problem-solving, and other skills like collaboration, communication, motivation, and autonomy (Ammar et al., 2024; Novak & Wisdom, 2018).

The use of 3D printing in primary and secondary education often remains dependent on teachers' individual initiative rather than institutional policy, resulting in inconsistent adoption and limited recognition of its impact on science learning (Khurma et al., 2023). The effective design of learning activities involving 3D printing technologies is grounded in engineering design principles, allowing students to progress from theoretical understanding to practical activities for making, testing, and evaluating (Xin et al., 2017; Zabalawi, 2018). Iterative design cycles are central to this approach, guiding learners through problem identification, experimentation, and refinement within a progressive, spiral workflow that reflects authentic engineering practice (Barbosa et al., 2024; Güleryüz, 2023). Thus, the educational potential of 3D printing depends less on the technology itself and more on the pedagogical ecosystems within which it is embedded.

Science Education in the New Mexican School

The New Mexican School (NEM) represents a significant curricular transformation in science education at the basic education level. Conceived as a comprehensive and humanistic governmental initiative, the NEM is grounded in a community-oriented perspective that seeks to contextualize learning within students' social realities (SEP, 2022a). Its curricular framework reorganizes knowledge into four formative fields, among which Knowledge and Scientific Thinking aims to cultivate students' curiosity, their capacity to explore their local environment, explain natural phenomena, and make informed decisions when addressing real-world problems (Hernández-Moreno, 2024; SEP, 2024a).

This orientation emphasizes exploration, observation, experimentation, and socially situated problem-solving. It represents a change from the previous secondary curriculum, in which biology, physics, and chemistry were taught in isolation with a strong emphasis on disciplinary content. In contrast, the NEM promotes interdisciplinarity and aligns with core STEM principles, including inquiry-based learning, project-based approaches, critical thinking, and real-world engagement. However, it reframes these principles through a humanistic lens, distancing itself from the predominantly technical-industrial orientation often associated with traditional STEM models. The overarching goal is to develop students' problem-solving capacities while fostering social responsibility and contextual transformation (López et al., 2020). Accordingly, the model prioritizes learning environments that encourage autonomy, reflective engagement with error, and the development of self-confidence (Vázquez-Carrillo, 2012).

Within this framework, the Ministry of Education recommends the implementation of active methodologies such as Community Project-Based

Learning, Problem-Based Learning, Service Learning, and Inquiry-Based Learning (SEP, 2022b). Inquiry-based approaches, in particular, connect directly with STEAM education, understood as an interdisciplinary and transdisciplinary perspective that integrates scientific reasoning with community knowledge and contextual problem-solving.

In this pedagogical landscape, 3D printing may function as a mediating technological tool that operationalizes STEAM principles. Through hands-on modeling, experimentation, and iterative problem-solving, it supports the integration of scientific concepts with engineering design and creative production. By facilitating the transition from abstract theory to tangible practice, 3D printing can enhance innovation-oriented learning environments while reinforcing conceptual understanding and applied reasoning (Ammar et al., 2024; Novak & Wisdom, 2018; Rahman-Bidita, 2024; Zolotareva et al., 2021).

RESEARCH METHOD

This study employed a qualitative multiple-case research design to examine how 3D printing is integrated into STEM/STEAM education and to identify convergent patterns across implementations. A multiple-case approach was selected to enable analytical generalization rather than statistical generalization, allowing theoretical propositions to emerge through systematic cross-case comparison (Snyder, 2019).

Cases were collected through a systematic literature search conducted from July to December 2025 through Scopus, Web of Science, and ERIC. The search combined descriptors and keywords, including "3D printing," "STEM education," "STEAM education," "science education," and "primary/secondary education." Publications from 2015 to 2025 were considered in order to collect recent developments in technology-enhanced science education. Only peer-reviewed articles published in English or Spanish were included. Studies were screened using the following inclusion criteria: 1) explicit focus on STEM or STEAM educational contexts, 2) empirical evidence documenting the implementation of 3D printing through active or inquiry-based pedagogical approaches, and 3) reported learning outcomes, competency development, or documented best practices in science education.

Ten studies met all inclusion criteria and were selected as cases for in-depth analysis. The selection process followed a structured screening procedure from the integrative model proposed by Al-Kamzari and Alias (2025), which conceptualizes technology-enhanced education as the dynamic articulation of theoretical foundations, pedagogical design, and learning outcomes. Drawn on this model, three analytical dimensions were defined: (1) theoretical and conceptual framework, (2) articulation of pedagogical and technological components, and (3) outcomes and best practices in science education. These dimensions were operationalized into a structured coding matrix comprising nine indicators (see the following Table 1), which guided systematic data extraction and cross-case comparison.

Indicators were deductively derived from the theoretical framework and iteratively refined through collaborative review among the four authors to ensure conceptual coherence and alignment with the study's objectives.

Table 1
Analytical Framework

Category	Indicator	Description
1. Theoretical and conceptual framework	1. Learning theories linked to STEAM	It identifies the learning theories related to STEAM and the teaching models used in science education.
	2. Science teaching model	
2. Articulation of pedagogical and technological components	3. Teaching–learning methodologies	It identifies the teaching-learning methodologies that incorporate technologies, digital tools, and/or educational resources, such as 3D printing, within science education. It also includes understanding the role of the teacher and other actors involved in the educational process.
	4. Technological integration of digital tools and educational resources	
	5. Teacher role and mediation of other specified actors	
3. Outcomes and best practices in science education	6. Acquisition of competencies and transversal skills	It examines the impact on learning based on the acquisition of competencies and skills related to science education and its connection to STEAM. It also provides insights for further practices.
	7. Deliverables	
	8. Evaluation instruments for science education	
	9. Replicability and sustainability	

To strengthen methodological rigor, coding and scoring were conducted independently by the research team. Discrepancies were resolved through iterative analytical discussion until consensus was achieved, establishing an explicit audit trail and enhancing dependability and confirmability.

Finally, a cross-case synthesis was performed to identify recurring patterns, conceptual alignments, divergences, and emerging best practices. The analysis emphasized coherence and depth of articulation across dimensions rather than frequency counts alone, supporting analytical generalization and theory-informed interpretation.

RESULTS

The findings highlight three main patterns:

(1) a grounding in constructivist and maker-centered pedagogies,
(2) evidence of short-term outcomes, particularly gains in conceptual understanding and competencies development, and
(3) a lack of long-term transferability, scalability, and equity impact.

Table 2 summarizes the demographic characteristics of the selected articles, including the authors, year of publication, journal of publication, country of implementation, educational level, and a brief description of each study. The data provide a comprehensive overview of how 3D printing integrated with STEAM practices is implemented in basic education settings and how these interventions influence learning outcomes, student engagement, and competency development.

Table 2
Articles Demographics

No.	Author	Year	Journal	Country	Educational level	Description
1	Karatrantou & Christodoulou	2025	International Journal of Teaching and Learning Sciences	Greece	Elementary school	The use of 3D printing tools and 3D design software to teach geometric concepts.
2	Khurma, O. et al.	2023	Contemporary Educational Technology	United Arab Emirates	Elementary school	The use of 3D printing technologies and its impact on students' attitudes toward STEM careers.

3	Jarillo-Aguilar	2023	Educación y Ciencia	Mexico	Elementary school	The experience of digital fabrication activities fosters creativity, teamwork, and equity.
4	Nadal O. & Dominguez, X.	2023	Revista UTE Teaching & Technology	Spain	Elementary school	A project that introduces the maker culture through STEAM in primary education
5	Sormunen et al.	2023	Disciplinary and interdisciplinary science education research	Finland	Elementary school	Students designed and constructed a prototype to solve a challenge they face in daily life through a collaborative invention project.
6	Haas et al.	2022	Frontiers in Education	Luxembourg	Elementary school	Parent-assisted remote teaching using CAD software and 3D printing over three weeks during COVID-19.
7	Tanabashi	2021	Journal of Microbiology and Biology Education	Japan	Elementary school High school University	Collaborative project on learning cell microstructures through 3D modeling and visualiza-tion.
8	Leinonen et al.	2020	International Journal of Art & Design Education	Finland	Elementary school	The experience of integrating 3D design and printing into projects run "in the wild" by non-expert school teachers.

9	Xin et al.	2017	Journal of Schooling Studies	China	Elementary school High school	The experience in the design and teaching of 3D printing integrated STEM education projects.
10	Brown	2015	TechTrends	USA	Elementary school High school K-12	The experience of the author engaging in 3D printing activity in K-12.

Findings are organized according to the analytical framework described in the methodology, which comprises three main dimensions: theoretical and conceptual foundations, articulation of pedagogical and technological components, and outcomes and best practices in science education.

Theoretical and Conceptual Foundations

The theoretical and conceptual foundations of the reviewed studies are grounded in constructivist, experiential, and active learning approaches, with an emphasis on student-centered and competency-based frameworks. Several studies highlight how STEAM education, learning through the creation of devices or prototypes, and project-based pedagogies foster meaningful knowledge construction, creativity, and problem-solving (Jarrillo-Aguilar, 2023; Nadal & Domínguez, 2023). These approaches also incorporate perspectives on equity, inclusion, and the development of 21st-century skills.

In the context of 3D printing and digital fabrication, studies such as Leinonen et al. (2020) and Tanabashi (2021) emphasize the use of digital tools and fabrication to facilitate interdisciplinary learning and the tangible exploration of scientific concepts, including 3D modeling software (such as Tinkercad, Fusion 360, SketchUp), simulation platforms, 3D scanning tools, and parametric design environments. Students are positioned as active agents in constructing their own learning, thereby fostering autonomy, engagement, and self-efficacy. Haas et al. (2022) extend this perspective to remote STEAM environments, recognizing the role of teacher mediation, as well as the support of parents and other adults, in facilitating learning outcomes. Karatrantou and Christodoulou (2025) demonstrate similar principles in mathematics education, using 3D models to improve spatial visualization, strengthen conceptual understanding, and enable realistic and tangible learning experiences.

Collaborative projects (Sormunen et al., 2023) reinforce the value of integrating disciplinary content with transversal competencies such as creativity, critical thinking, collaboration, and resilience. Across all studies, the theoretical frameworks position digital fabrication and maker-centered activities not merely as technical tools but as means for pedagogical support to support meaningful, student-centered learning.

Articulated Pedagogical and Technological Components

The studies describe how pedagogical and technological components are structured within the curriculum to support effective learning. These include clearly defined learning tasks, sequenced activities, and specified roles for teachers and students, often incorporating collaborative and hands-on methodologies. Technological tools, such as 3D modeling software (such as CAD, Tinker, Blender, etc.), 3D printers, robotics, and digital fabrication materials, are integrated into the instructional design to achieve the intended learning outcomes.

Leinonen et al. (2020) implemented 3D printing modules in primary school classrooms, combining accessible design software and basic-level 3D printers with guided hands-on exploration and interactive problem-solving. Maker-centered interventions (Nadal & Domínguez, 2023) use project-based learning and STEAM methodologies, in which teachers facilitate autonomy and active participation while technology provides practical support for experimentation. Remote STEAM implementations (Haas et al., 2022) combined digital tools during the pandemic with structured pedagogical strategies and parental mediation to ensure meaningful and contextually relevant learning experiences.

Mathematics-focused interventions (Karatrantou & Christodoulou, 2025) integrated 3D printing into instructional sequences on geometric shapes. In this approach, abstract concepts, such as properties of solids, spatial relationships, measurement, symmetry, or geometric transformations, were explored through concrete manipulations of 3D-printed physical models that students could observe, rotate, measure, disassemble, or reconstruct. This process enabled students to move from theoretical understanding to practical exploration, facilitating the analysis of complex mathematical structures and their application to real-world problems in fields such as engineering, physics, or architecture. Collaborative invention projects (Sormunen et al., 2023) combined interactive prototyping, interdisciplinary STEAM approaches, and team-based problem-solving, with teacher facilitation and reflection using documentation as a guiding tool.

Overall, these studies demonstrate that the effective integration of digital tools depends on carefully planned instructional sequences that are systematically structured by teachers or support staff (instructors, engineers, external collaborators). It also requires explicit teacher guidance, including continuous pedagogical support through the explanation of procedures, modeling of strategies, timely feedback, and decision-making guidance throughout the creation process.

Likewise, the studies underscore the importance of aligning activities with curricular objectives, which requires intentionally articulating the official subject curriculum with the aims and competencies of the STEM curriculum. This alignment not only ensures coherence among content, skills, and assessment but also allows digital fabrication experiences to directly contribute to achieving expected learning outcomes and integrating transversal competencies across multiple disciplinary areas.

Outcomes and Best Practices

The evidence collected indicates positive impacts on conceptual understanding, the development of STEAM competencies, and transversal skills. Improvements in spatial reasoning and 3D visualization are consistently reported, particularly in contexts involving geometry and scientific modeling (Karatrantou & Christodoulou, 2025).

The studies document progress in: conceptual understanding and correction of persistent misconceptions; critical thinking, autonomy, and creativity in design processes (Brown, 2015; Leinonen et al., 2020); collaborative problem-solving and scientific communication (Nadal & Domínguez, 2023; Sormunen et al., 2023); and STEAM competencies, particularly modeling, experimentation, and prototyping (Haas, 2022; Tanabashi, 2021).

The artifacts produced, such as 3D-printed prototypes, geometric models, robots, structures, and design portfolios, serve as tangible evidence of learning, and many studies employ them as authentic assessment instruments (Brown, 2015). These assessment instruments include pre- and post-tests, rubrics, observations, prototype analyses, interviews, and questionnaires, supporting the validity of the findings (Karatrantou & Christodoulou, 2025).

Despite the positive results, the literature points out limitations such as small sample sizes, time constraints, limited availability of technological resources, and the need to strengthen teacher training (Haas, 2022; Leinonen et al., 2020; Tanabashi, 2021). Additionally, the best practices identified include: (a) aligning technology and curriculum through clear instructional sequences, (b) promoting continuous iteration and experimentation, (c) documenting design processes in addition to final products, (d) designing rigorous assessment strategies for STEAM competencies, and (e) developing scalable and replicable learning experiences.

Table 3

Comparative Synthesis of Selected Studies

Study	Educational Context	Pedagogical Approach	Technological Integration	Learning Outcomes	Reported Limitations
Karatrantzou and Christodoulou (2025)	Elementary	Maker-based STEAM; exploration & prototyping	CAD software; 3D printing of geometric figures	Improved spatial reasoning & geometric understanding	Small sample; context-specific implementation
Khusuma et al. (2023)	Elementary	Inquiry-based; model-centered learning	Research-designed models; manipulatives	Increased engagement; conceptual understanding	Need for instructional alignment
Jarillo-Aguilar (2023)	Elementary	Digital fabrication in STEAM	3D printers; FabLab tools	Creativity, collaboration & leadership	Limited curricular integration
Nadal et al. (2023)	Elementary	Maker STEAM; experimentation	3D printing; robotics; prototyping	Critical thinking; transversal skills	Resource and planning demands
Sormunen et al. (2023)	Elementary	Collaborative project-based	Robotics; digital documentation	Scientific design & creativity	Teacher preparation required
Haas et al. (2022)	Elementary	Design-based STEAM	CAD; 3D printing; parental mediation	Motivation & meaningful learning	Small sample
Tanisah (2021)	Elementary/High School	Interdisciplinary STEAM	3D modeling; printers	Interdisciplinary understanding	Infrastructure demands
Leinonen et al. (2020)	Elementary	Maker-centered learning	Design & print process	Technical skills & collaboration	Focus on technical aspects
Xin et al. (2017)	Elementary/High School	Structured 3D integration	CAD; iterative prototyping	Critical & interdisciplinary thinking	Implementation-dependent
Brown (2015)	High school	Progressive 3D curriculum	Engineering design; CAD	Autonomy & STEAM competencies	Lack of experimental validation

Note. CAD = computer-aided design; STEAM = science, technology, engineering, arts, and mathematics; FabLab = fabrication laboratory.

These categories align with core theoretical constructs such as cognitive mediation, embodied modeling, and iterative learning. Each construct is represented across the cases, illustrating how 3D printing facilitates conceptual understanding, hands-on experimentation, and active engagement in science education.

DISCUSSION

The analyzed studies show that 3D modeling and 3D printing function as cognitive and epistemological mediators that deepen scientific understanding. Karatrantou and Christodoulou (2025) argue that students learn more deeply when they externalize abstract concepts through manipulable models that promote reflection and revision. Haas et al. (2022) highlight that iterative design compels students to apply and test scientific principles, strengthening conceptual clarity. Likewise, Leinonen et al. (2020) demonstrate that creating physical models makes spatial and causal relationships visible, enabling students to refine their ideas through comparison and redesign. This mediating function aligns directly with the theoretical foundations identified in the review (constructivism, situated learning, iterative design, scientific inquiry, and maker pedagogy), all of which provide a solid conceptual basis for the STEAM experiences (Brown, 2015; Xin et al., 2017).

The most effective experiences are those that follow iterative cycles of design, testing, and reflection and that incorporate active learning methodologies such as project-based learning (PBL), inquiry-based learning, or engineering design (Brown, 2015; Castro-Romero & Kang, 2022; Haas et al., 2022; Sormunen et al., 2023). These approaches are consistently supported in the literature as catalysts for deeper conceptual learning because they require students to articulate, test, and revise their scientific explanations through cycles of problem analysis, design, and evidence-based iteration. Tanabashi (2021) demonstrates that engineering design tasks promote conceptual depth, requiring students to justify each design decision using scientific principles, thereby confronting misconceptions during prototype testing. Similarly, Haas et al. (2022) show that PBL and inquiry-driven fabrication activities strengthen understanding by engaging learners in reasoning processes that connect theory to functional models, encourage reflection on errors, and promote refinement based on observed performance.

The studies also highlight the importance of teacher mediation: successful interventions ensure that teachers have prior training in STEM and possess the pedagogical skills needed to guide students' learning processes. Some cases also involve broader learning communities, FabLabs, external experts, or the participation of families as complementary support (Karatrantou & Christodoulou, 2025; Leinonen et al., 2020). It reinforces the idea that technology alone does not guarantee meaningful learning; rather, its value depends on curricular coherence, methodological organization, and the active participation of educational stakeholders.

Regarding learning outcomes, the studies report improvements in three dimensions: (1) conceptual understanding, particularly in areas such as geometry, space sciences, and physical phenomena; (2) the development of STEAM competencies, including modeling, spatial reasoning, experimentation, decision-making, and iterative design; and (3) transversal skills such as collaboration, creativity, communication, and autonomy (Khurma et al., 2023; Sormunen et al., 2023). The analysis of final products, together with instruments such as pre- and post-tests, rubrics, and interviews, suggests that educational environments combining design, prototyping, and reflection tend to generate meaningful learning and, in some cases, sustained learning outcomes (Brown, 2015; Xin et al., 2017). However, evidence regarding long-term transferability and scalability remains limited, indicating the need for further longitudinal and large-scale research.

The literature also acknowledges several important limitations: unequal access to technological resources depending on context, limited time to complete projects, challenges in aligning curricula effectively with STEM education, the technical learning curve for teachers and students, and the need for specialized teacher training in design methodologies and engineering thinking (Haas et al., 2022; Nadal & Domínguez, 2023; Tanabashi, 2021). These constraints suggest that although STEAM experiences involving 3D printing are promising, their sustainable implementation requires concrete educational policies, institutional planning, teacher training, and ongoing professional development, and scalable models that do not depend on fashionable or expensive infrastructure.

Overall, the review of case studies indicates that integrating STEM through tools such as digital fabrication and 3D printing in primary education can have a positive and consistent effect on scientific learning, when combined with well-grounded pedagogical models, strategically integrated technological tools, and competency-based assessment practices (Haas et al., 2022; Karatrantou & Christodoulou, 2025; Sormunen et al., 2023). This evidence may inform Mexican primary education under the NEM framework by supporting the integration of STEAM practices aligned with national curricular goals. In this manner, the reviewed literature offers not only empirical results but also a set of guiding principles that can guide the design of innovative, coherent, and sustainable STEAM curricular proposals in diverse educational contexts.

CONCLUSIONS

This study aimed to identify the educational, pedagogical, and technological components that support the use of 3D printing in science education, as well as to establish a conceptual and methodological framework to guide its curricular integration in basic education contexts. Based on the review of ten case study analyses and practices associated with the use of digital fabrication technologies in STEAM environments, it was found that 3D printing functions as a cognitive mediator that facilitates the understanding of abstract concepts through processes of modeling, iterative design, and manipulation of physical objects. These types of experiences promote active learning, strengthen scientific skills such as spatial reasoning, experimentation, and problem solving, as well as, stimulate the development of transversal competences such as creativity, collaboration, autonomy, and communication. Moreover, the use of previously planned and structured instructional sequences grounded in active methodologies, such as problem-based learning (PBL), inquiry-based learning, or engineering design, emerges as one of the most effective strategies, with explicit alignment between curricular objectives and STEAM education identified as essential for successful implementation.

Taken together, the results suggest that 3D printing constitutes a valuable pedagogical resource for science education, as it supports meaningful knowledge construction, enhances student motivation, and contributes to the development of twenty-first-century competencies. However, its effectiveness depends on factors such as adequate teacher training for appropriate mediation and guidance, curricular alignment, currently framed as co-design in the Mexican educational context, the availability of technological resources, the strategic use of alternative materials when resources are limited, and the institutional capacity to sustain practices based on design, exploration, and experimentation.

Despite its relevance, the studies analyzed present important limitations: small sample sizes, short intervention periods, limited longitudinal evaluation, dependence on technological resources that vary across contexts, and heterogeneous levels of teacher preparation in 3D design and active methodologies. These limitations indicate the need for caution when generalizing the results and highlight the inequities that affect the adoption of emerging technologies in schools, as well as the need for co-design processes to be conducted thoroughly, consciously, and collaboratively among teachers.

Consequently, future research should deepen comparative and longitudinal research that evaluate the impact of 3D printing on scientific learning over time; analyze in greater detail the role of teacher mediation and professional development; explore sustainable and feasible implementation models in contexts with limited infrastructure; and examine the effects of the technology on diverse populations, including students with special educational needs or those from rural areas.

The value of this study lies in providing a comprehensive perspective that synthesizes existing evidence and offers an analytical framework to understand how and under what conditions 3D printing can become an effective tool for enriching science education. These findings provide conceptual and practical guidance for integrating 3D printing and digital fabrication. It could include interdisciplinary STEAM projects, competency-based assessment practices, and teacher training to support the effective use of these technologies in the classroom. At the same time, the general principles are applicable to diverse educational settings, emphasizing the alignment of technological tools with sound pedagogical models and learning objectives. The systematic incorporation of digital fabrication technologies constitutes an expanding educational strategy with the potential to transform pedagogical practices, broaden opportunities for scientific participation, and contribute to reducing gaps associated with access, representation, and the development of STEAM competencies. In this sense, the study not only synthesizes current evidence but also highlights the emerging role of these technologies as drivers of educational innovation, equity, and context-relevant implementation.

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