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THE UTILIZATION OF 3D PRINTERS BY ELEMENTARY-AGED LEARNERS: A SCOPING REVIEW

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ABSTRACT

Aim/Purpose	This review's main objective was to examine the existing literature on the use of 3D printers in primary education, covering students aged six to twelve across general, special, and inclusive educational environments.
Background	A review of the literature indicated a significant oversight – prior reviews insufficiently distinguish the application of 3D printing in primary education from its utilization at higher educational tiers or focused on particular subject areas and learning domains. Considering the distinct nature and critical role of primary education in developing young students' cognitive abilities and skills, it is essential to concentrate on this specific educational stage.
Methodology	The scoping review was selected as the preferred research method. The methodological robustness was augmented through the utilization of the backward snowballing technique. Consequently, a total of 50 papers were identified and subjected to thorough analysis.
Contribution	This review has methodically compiled and analyzed the literature on 3D printing use among elementary students, offering a substantial addition to academic conversations. It consolidated and organized research on 3D printers' educational uses, applying robust and credible criteria.
Findings	Many studies featured small sample sizes and limited research on inclusive and special education. The analysis revealed 82 distinct research goals and 13 educational fields, with STEM being the predominant focus. Scholars showed considerable interest in how 3D printers influence skills like creativity and problem-solving, as well as emotions such as engagement and motivation. The majority

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of studies indicated positive outcomes, enhancing academic achievement, engagement, collaboration, creativity, interest, and motivation. Nonetheless, challenges were noted, highlighting the necessity for teacher training, the expense of equipment, technical difficulties, and the complexities of blending new methods with traditional curricula.

Recommendations for Practitioners
To capitalize on the benefits that 3D printers bring, curriculum planners are urged to weave them into their programs, ensuring alignment with educational standards and skill development. The critical role educators play in the effective implementation of this technology necessitates targeted professional development programs to equip them with the expertise for successful integration. Moreover, 3D printing presents a unique opportunity to advance inclusive education for students with disabilities, offering tailored learning experiences and aiding in creating assistive technologies. In recognizing the disparities in access to 3D printing, educational leaders must address the financial and logistical barriers highlighted in the literature. Strategic initiatives are essential to democratize 3D printing access, ensuring all students benefit from this educational tool.

Recommendations for Researchers
Comparative studies are critical to elucidate the specific advantages and limitations of 3D printing technology due to the scarcity of research contrasting it with other tools. The variability in reporting durations of interventions and research environments underscores the necessity for uniform methodologies and benchmarks. Because research has predominantly focused on STEM/STEAM education, expanding into different educational areas could provide a comprehensive understanding of 3D printing's capabilities. The existence of neutral and negative findings signals an opportunity for further investigation. Exploring the factors that impede the successful integration of 3D printing will inform the creation of superior pedagogical approaches and technological refinements.

Future Research
As the review confirmed the significant promise of 3D printing technology in enriching education, especially in the context of primary education, the imperative for continued research to refine its application in primary education settings is highlighted.

Keywords
3D printers, additive manufacturing, educational technology, primary education, scoping review

INTRODUCTION

Production is a complex process that begins with the conception of an idea and ends in its transformation into a tangible product. Throughout the history of industrial production, professionals and technicians have collaborated, merging their scientific knowledge and technical expertise to materialize an idea. Historically, the tools and machinery employed in the production process have been fundamental. However, technological advancements have revolutionized these tools, leading to the development of more automated systems, many of which are based on robotic technologies. One such technology that has gained increasing prominence in recent years is 3D printing. 3D printing, also known as additive manufacturing, enables the fabrication of 3D objects by successively adding material layer by layer (Diegel, 2014). This method of additive manufacturing is performed using specialized equipment called 3D printers. These printers facilitate the production of physical items that can be unique creations, replicas, or individual components of more complex assemblies.

The decline in the cost of 3D printers has advanced its integration across various educational settings (Buehler et al., 2016). The pedagogic applications of 3D printing are manifold, encompassing active and passive forms of engagement that cater to a broad spectrum of educational objectives (Ford &

Minshall, 2019). The versatility of 3D printing is further exemplified by its application across diverse subjects, including Mathematics, Physics, and STEM, where it has been shown to positively impact learning outcomes (e.g., Arvanitidi et al., 2019; Aslan & Çelik, 2022). Furthermore, studies reported that engagement with 3D printers fosters the development of design thinking, enhances visualization skills, augments cognitive abilities such as spatial reasoning, and encourages a higher degree of creativity (e.g., Katsioloudis & Jones, 2015; Trust & Maloy, 2017). This technology also facilitates collaborative learning environments, fosters autonomy, and serves as a potent motivational tool, thereby promoting an engaging educational experience (e.g., Kostakis et al., 2015; Schelly et al., 2015).

Past literature reviews highlighted the implementation of 3D printers across health sciences, engineering, and other specialized disciplines (de Souza et al., 2021; Javaid & Haleem, 2018). These reviews have collectively underscored the potential of 3D printing to positively influence educational methodologies, advocating for its broader adoption and the development of robust pedagogical frameworks that harness its full capabilities (e.g., Leung et al., 2022; Pernaa & Wiedmer, 2020). Yet, as will be further elaborated in a later section, the literature reviews that have been conducted in the past have insufficiently distinguished the application of 3D printing within specific educational levels or focused on particular academic fields and domains of learning.

Primary education, catering to children between the ages of six and twelve, stands as a distinct and pivotal stage within the educational spectrum. This critical period is marked by the implementation of pedagogical methodologies specifically fashioned for young learners, which are fundamentally different from those employed at secondary and tertiary levels. From a curricular perspective, primary education places a pronounced focus on the acquisition of essential literacy and numeracy skills. Developmentally, primary education coincides with a crucial growth phase in a child’s life. Thus, primary education is not only foundational in terms of academic content but is also essential in preparing young learners for the multifaceted challenges of future educational stages and life itself. As such, it warrants attention to pedagogical approaches, curricular design, and developmental imperatives to cultivate the potential inherent in every child.

In light of these considerations, it becomes evident that the unique attributes of primary education justify a focused examination of 3D printer applications, as this technology could potentially align with and enhance the distinctive pedagogical and developmental objectives at this critical stage of education. As a result, it was deemed important to conduct a review of the literature focusing on the use of 3D printers by elementary-aged students. The primary goal was to clarify the extent of the use of 3D printers in diverse educational settings (i.e., general, special, and inclusive education) by students of the above-mentioned age group. As it was important to shaping a comprehensive view, it was considered crucial to investigate the influence of 3D printers on the acquisition of knowledge, skills, and other learning-related aspects (e.g., emotional and affective ones), as well as to clarify the nature of these effects. To address the above, a scoping review methodology was utilized. Scoping reviews are particularly adept at charting the extent of the research landscape on a given topic. They provide an overview of the volume of available studies and the robustness of their evidence, which is especially beneficial in emerging research domains (Munn et al., 2018). The forthcoming sections delineate the methodology employed and the results obtained, followed by a discussion of the findings.

BACKGROUND

3D PRINTING

The advancement of 3D printing technology has led to the development of diverse additive manufacturing processes. According to the American Society for Testing and Materials, these processes are classified into seven categories: binder jetting, directed energy deposition, material extrusion, material jetting, powder bed fusion, sheet lamination, and vat photopolymerization (Lee et al., 2017). The spectrum of materials compatible with 3D printing is extensive, encompassing polymer plastics, wood, various metals and metal alloys, ceramics, concrete, and even edible substances. These materials are not only available in a multitude of colors but also exhibit a range of mechanical and aesthetic properties, including variations in durability, elasticity, and appearance. The fabrication of a 3D-printed object is typically delineated into three essential stages (Diegel, 2014). Initially, the design phase involves the creation of a 3D model utilizing computer-aided design (CAD) software. Subsequently, the actual printing process commences; specialized slicing software deconstructs the CAD model into discrete layers, subsequently translating these into executable instructions for the 3D printer on how to construct each layer using the provided raw material. The final stage, post-processing, entails the refinement of the printed object; superficial flaws are rectified, and additional treatments may be applied to augment both the aesthetic and functional attributes of the final product.

The convergence of these technological capabilities with their increasing cost-effectiveness has made 3D printers a compelling asset across a plethora of sectors. Their application is rapidly expanding within critical industries, including aerospace, automotive, healthcare, fashion, and construction. This proliferation is fundamentally transforming the paradigms of product design, prototyping, and manufacturing, signaling a revolutionary shift in the way tangible goods are conceptualized and realized.

3D PRINTERS IN EDUCATION

The reduction in the cost of 3D printers over time has facilitated their integration into educational settings, enabling the application of this innovative technology within pedagogical contexts (Buehler et al., 2016). The utilization of 3D printing spans across all educational levels, as indicated by Ford and Minshall (2019), underscoring its versatility and widespread applicability. Most data for the implementation of 3D printing in educational institutions is predominantly derived from lesson plans at the middle and high school levels (Pearson & Dubé, 2022).

Educational activities designed around 3D printing are predicated on fostering both active and passive engagement with the technology (Ford & Minshall, 2019). Active engagement in this context is characterized by lesson plans that incorporate the use of 3D printing as a central element, with the explicit intent of imparting 3D printing-related competencies to students. Conversely, passive engagement denotes the utilization of 3D printing as a supplementary tool to enhance the instruction of other academic subjects. While this approach does result in the development of 3D printing skills, it is not the primary educational focus.

3D printers were used for teaching diverse subjects including, but not limited to, ones related to mathematics and physics (Aslan & Çelik, 2022), cultural heritage (Turner et al., 2017), interior design (Greenhalgh, 2016), chemistry (Pernaa & Wiedmer, 2020), biology (Hansen et al., 2020), and STEM education (Arvanitidi et al., 2019), having a positive impact on learning. The inclusion of 3D printing technology in various learning domains not only enriches the learning experience but also equips students with valuable skills pertinent to the evolving technological landscape, as will be further elaborated in the next section.

The integration of 3D printing technology at the tertiary level has been noted to surpass the other levels of education (Ford & Minshall, 2019). This innovative tool is not only utilized as a standalone subject but also serves as a pivotal resource in the acquisition of scholarly knowledge and the fabrication of prototypes for testing purposes. Bagley and Galpin (2015) highlighted the application of 3D-printed models in laboratory settings, which facilitated a more tangible grasp of theoretical concepts. These models also served as instrumental components in experimental procedures, allowing students to investigate and analyze the mechanical properties of various materials utilized in 3D printing. Furthermore, the role of 3D printing in robotics education cannot be overstated. As a cost-effective means for producing robotic components, it has gained considerable traction as an instructional tool (Ford & Minshall, 2019). The use of open-source software empowers students to conceive and construct robotic systems, fostering a culture of innovation and collaboration through the modification and dissemination of their designs within the educational ecosystem. These interdisciplinary applications of 3D printing not only cultivate technical skills in machinery but also establish meaningful connections with other academic fields, including Mathematics. The strategic incorporation of 3D printing into university curricula offers a multidimensional educational experience, equipping students with the competencies required to meet the demands of the 21st-century job market.

In the realm of special education, the advent of 3D printing technology has emerged as a transformative tool, facilitating the design of tailored activities that cater to the unique needs of individuals with visual, motor, and cognitive disabilities. These activities aim to cultivate essential knowledge and skills, thereby promoting inclusive learning environments (Ford & Minshall, 2019). Notably, 3D printing has played a pivotal role in formulating systems that augment the participation of students with disabilities in STEM education, enriching their academic experience and potential for future employment in these fields (Buehler et al., 2016). The paramount contribution of 3D printing within special education lies in its capacity to generate customized artifacts. These artifacts function as assistive technologies, granting students with disabilities the opportunity to engage in authentic, hands-on learning experiences that are instrumental in surmounting the educational barriers imposed by their disabilities (Horowitz & Schultz, 2014). By harnessing this technology, educators are empowered to provide students with a more equitable learning journey, reflective of a commitment to inclusivity and accessibility. However, the integration of 3D printing into educational strategies for students with disabilities is not devoid of challenges. The complexity of CAD software necessitates extensive training, a process that can be time-intensive and potentially lead to diminished interest among students. As such, the implementation of 3D printing requires thoughtful consideration of the students' engagement and the development of pedagogical approaches that are both effective and captivating (Buehler et al., 2016).

THE BENEFITS OF USING 3D PRINTERS IN EDUCATION

Several studies have demonstrated that incorporating 3D printing activities into educational curricula fosters the development of design thinking (Trust & Maloy, 2017; Trust et al., 2018). Additionally, it was argued that learners can develop visualization skills and improve their ability to predict how they should design an object for it to be functional (Huang & Lin, 2017; Smith, 2018). When designing objects, students are often required to undertake complex calculations. Consequently, these activities facilitate the advancement of a range of cognitive skills, including visualization, mental rotation, and spatial skills (Katsioloudis & Jones, 2015). The intricacy of the 3D printing process naturally lends itself to cultivating more sophisticated thought processes. This complexity is reflected in the designs produced by students using 3D printing technology, which have been observed to possess a higher degree of intricacy compared to those crafted manually (Chien & Chu, 2018; Greenhalgh, 2016).

While CAD software streamlines the creation of 3D models, students occasionally need to think creatively to overcome certain software limitations (Trust & Maloy, 2017). In fact, empirical evidence supported the correlation between creativity and 3D printing, as the latter necessitates students to assume the role of creators (Trust et al., 2018; Wright et al., 2018). The iterative process of designing and refining a 3D object is a fundamental aspect of 3D printing, one that significantly enhances students' capacity for critical thinking (Martin et al., 2014; Trust & Maloy, 2017). This reflective practice, whereby students evaluate the efficacy of their design outcomes, is instrumental in developing higher-order cognitive skills, as reported by Kostakis et al. (2015). While it is acknowledged that engaging in critical reflection and problem-solving within the context of 3D printing presents challenges for learners, the attainment of a successful prototype provides a substantial sense of satisfaction (Pearson & Dubé, 2022).

In both formal and informal settings, 3D printing can be used to engage students in collaborative activities (Schelly et al., 2015). The inherent collaborative nature of this technology is an essential component during the design phase, fostering a community of practice (Novak & Wisdom, 2018). Within such a cooperative milieu, students engage in a reciprocal exchange of ideas and queries and collectively subject their concepts to practical tests, thus fostering innovation and cultivating more sophisticated designs (Stone et al., 2020). Collaboration develops both among peers and with lab coordinators responsible for carrying out 3D printing activities (Pantazis & Priavolou, 2017; Trust et al., 2018). Consequently, through such synergistic endeavors, students not only enhance their communicative competencies but also learn to value and integrate diverse perspectives (Liu et al., 2020).

The autonomy afforded by students' selection of specific objects for 3D printing significantly bolsters their motivation and engagement in the learning process. This self-directed aspect of 3D printing activities not only spurs enthusiasm but also allows students to confront any emergent challenges (Kostakis et al., 2015). Pantazis and Priavolou (2017) further contended that the motivational impact of 3D printing was augmented by its capacity to facilitate enriched communicative exchanges among peers. The inherently creative and decision-driven nature of 3D printing endows students with a sense of agency over their educational journey and develops motivation to persevere to overcome difficulties (Cook et al., 2015).

The role of the printed object itself is of importance due to its capacity to provide tactile feedback that enhances comprehension of scientific concepts (Hsiao et al., 2019). The printed object can function as a catalyst for further investigative endeavors and critical reflections. These activities may encompass the exploration of various designs or material choices for reproducing a given object (Martin et al., 2014). Moreover, students must engage with the dimensions and properties of printed objects to ensure their conceptualizations are realistic. This approach is exceptionally beneficial within the domain of special education, offering a tactile dimension that can facilitate the learning process (Pearson & Dubé, 2022). Stone et al. (2020) supported that 3D-printed objects were instrumental in yielding superior educational outcomes for visually impaired students. The assertion was based on the premise that such objects furnish a more nuanced and lifelike tactile experience, which is particularly advantageous when dealing with intricate designs.

RELEVANT LITERATURE REVIEWS

Literature reviews on the educational uses of 3D printers do indeed exist, with a substantive corpus focusing on its utilization within particular educational sectors, predominantly those related to the health sciences, engineering, and construction disciplines. A notable study by de Souza et al. (2021), which encompassed a systematic review of 39 articles disseminated over the period 2012 to 2021, concluded that 3D printing is well-established in otolaryngological education and the development of simulation models. The researchers underscored the imperative for innovation in technologies related to 3D printing to mitigate the constraints in sourcing suitable animal and cadaveric specimens for educational purposes.

In an analysis of 426 scholarly manuscripts spanning the years 2004 to 2016, Javaid and Haleem (2018) outlined 40 prominent applications of 3D printing within the medical sphere, including but not limited to the customized fabrication of bones and implants, the creation of scaffolds for tissue engineering, and the production of prosthetic and orthotic devices. The significance of 3D printing in medical contexts was highlighted in terms of heightened precision, expeditious production, enhanced visualization and personalization of products, and substantial augmentation of clinical decision-making processes. The authors posited that, because of these attributes, 3D printing harbors the potential to address complex medical challenges and confer extensive benefits upon society.

Furthermore, an intriguing finding was presented by Ávila et al. (2016), who, upon reviewing 33 articles, ascertained that the entirety of the contributions originated from medical professionals rather than computer science researchers. The authors contended that the merits of 3D printing are inextricably linked to patient wellbeing and the bolstering of medical pedagogy. They advocated for the integration of advanced features into 3D-printed models that replicate not only the visual but also the functional characteristics of their real-life counterparts. Despite acknowledging certain obstacles, such as the significant investment required for the procurement of sophisticated equipment, the considerable expenditure of time and labor in object fabrication, technical limitations, and the specialized expertise needed to customize virtual models, the authors concluded that 3D printing possesses a formidable capacity for integration into medical practice and education.

In another review from the health sciences domain, a total of 46 articles published up to the year 2021 were scrutinized (Leung et al., 2022). The authors discovered that 3D printing interventions within the field of otolaryngology offered considerable surgical, anatomical, and pedagogical benefits. Furthermore, there has been an observable positive trajectory in the approval ratings of 3D-printed models over time. Derived from these findings, the authors advocated for the integration of 3D printing technologies into future educational curricula on a broader scale. Similarly, Li et al. (2017) posited that 3D printing could serve as an adjunct to established methods of instruction in anatomy education and surgical preparation.

Within the realm of architecture, Žujović et al. (2022) conducted a review encompassing 65 publications spanning from 2013 to 2022. A noteworthy trend in this body of literature was the concentration on design projects, which typically delineated particular cases and individual educational experiences where 3D printers were employed, such as landscape architecture. A subset of the literature predominantly addressed the impact of 3D printing on architectural design curricula, revealing that the incorporation of this innovation into the design process can stimulate creative thinking and culminate in more intricate design solutions when contrasted with conventional instructional methodologies. The authors concluded with a call for additional research to forge novel pedagogical strategies and approaches.

In the context of science and manufacturing technology education, Wibawa et al. (2021) executed a systematic literature review related to the application of 3D printing. They concluded that this technology not only promoted “learning by doing” but also bolstered active learning and augmented knowledge creation and assimilation. The authors suggested that 3D printing is versatile, serving not only as an educational tool about the technology itself but also as supportive equipment during instruction, a means to fabricate educational aids, and a conduit for the development of beneficial technologies.

Pernaa and Wiedmer (2020) conducted a review to ascertain the scope of research conducted on the application of 3D printing within the domain of chemistry education in all levels of education. Their investigation involved an analysis of 47 papers, focusing on three primary objectives: to identify the nature of the work executed in this field, to discern the design strategies employed, and to understand the extent to which 3D printing has been incorporated into chemistry education research. Their findings revealed that 3D printing primarily served the purpose of creating research instruments to study students’ perceptions of physical models. However, there was a notable lack of studies delving into the impact of 3D printing on learning outcomes or students’ attitudes toward this technology. The authors concluded with a call for the development of robust, student-centered pedagogical frameworks that would fully leverage the potential of 3D printing in chemistry education.

Hansen et al. (2020) executed a review of two decades’ worth of literature, spanning up to the early months of 2020, to evaluate the incorporation of 3D printing in biological education. Despite the extensive temporal range, their search yielded only 13 articles that aimed to assess the educational benefits of 3D printing for students. The authors reported difficulties in formulating overarching conclusions about the enhancement of student learning through the use or creation of 3D-printed models in biological settings. Given these challenges, they called for further empirical research to methodically explore the influence of student-initiated production, particularly in the fields of biology, engineering, and computer science education.

Regarding the incorporation of 3D printers in education in general, Pearson and Dubé (2022) conducted a review focusing on the learning theories employed and the consequent educational outcomes of 3D printing. Their analysis encompassed a corpus of 41 studies dating from 2013 to 2022. Yet, the review did not differentiate among educational settings, such as formal versus informal, nor did it segregate by type (general, special, or inclusive education) or educational levels. The authors found that five learning theories, namely situated learning, experiential learning, critical making, constructionism, and self-directed learning, were consistently referenced across the studies. The pedagogical benefits ascribed to 3D printing were multifaceted, ranging from an understanding of the design process to an appreciation of the tangible object created. Furthermore, learners encountered curricular concepts concretely through the act of creation, which in turn fostered critical thinking, creativity, design thinking, and collaboration. The authors supported that proficiency in 3D printing transcended mere operational knowledge, extending into broader, domain-general competencies. Moreover, the authors suggested that 3D printing activities hold the potential to cultivate both specialized and transferrable skills, although they acknowledged that certain outcomes are more attainable and synergistic with educational theories within a classroom setting than others.

In another review, Ford and Minshall (2016) examined where and how 3D printers were used in education. Notably, the number of studies reviewed was not specified, and the analysis did not stratify educational levels. Nonetheless, the authors discerned that 3D printing technology is utilized across a spectrum that includes K-12 education, higher education institutions, libraries, maker spaces, and special education environments. In addition, they found that despite its broad application, the integration of 3D printing technology is sporadic, confined to isolated instances of exemplary practice, and not without challenges to widespread adoption. The authors also noted that 3D printers serve a dual pedagogical role: as a subject of direct instruction for students and educators to develop 3D printing competencies and as a tool for fostering design skills and creative methodologies. Additionally, they highlighted the utility of 3D printing in the creation of artifacts that not only serve as educational aids but also as assistive technologies in specialized learning contexts. This dual application underscores the technology's versatility and contribution to both the instructional process and the advancement of inclusive educational practices.

Aslan and Çelik (2022) analyzed 101 studies to evaluate the application of 3D printing technology within educational settings from 2009 to 2022. The synthesis of these studies revealed a predominant focus on the K-12 sector, encompassing core subjects such as physics, chemistry, biology, and mathematics. It was identified that the sample populations most frequently studied were undergraduate and secondary school students. A preferential inclination towards qualitative research methodologies was observed, though quantitative approaches were also notably employed. Common instruments for data collection included in-class assessments, direct observations, and the administration of questionnaires. The review concluded that 3D printing technology offers a versatile tool that can be integrated across various age groups and disciplines, significantly benefiting interdisciplinary educational approaches. The authors posited that enhancing the pedagogical strategies associated with 3D printing technology could yield more effective educational outcomes.

Finally, Novak et al. (2021) conducted an extensive analysis of both published and unpublished studies up to the year 2019, encompassing 78 works in total. Their conclusions underscored the positive impact of 3D printing on learning processes, its pivotal role in fostering innovative curricular frameworks, and its capacity to facilitate cross-disciplinary scholarly endeavors. This review also delineated five emergent trends in 3D printing education: the preparation of a new generation of engineers, the democratization of additive manufacturing, the utilization of low-cost 3D printed educational aids, the production of assistive technologies, and the enhancement of creativity and innovation. Novak et al.'s study stands out as it provided details of several parameters of interest. In detail, the authors found that 72% of the studies were situated within formal education systems. The research sample demographics indicated that approximately 40% of the studies involved K-12 students, distributed fairly evenly across elementary, middle, and high school levels, while the remaining 60% pertained to post-secondary learners. The majority of the studies focused on the domains of engineering, technology, and science, which accounted for 58% of the research, with medical and pharmacy education representing the second-largest category. Content knowledge emerged as the primary research focus in 77% of the studies, with additional investigations delving into student affective responses, motivation, attitudes, spatial skills, creativity, and problem-solving capabilities. However, as in all the previously presented reviews, there was no differentiation between educational levels in the presentation of results.

WHY FOCUS ON ELEMENTARY-AGED LEARNERS?

It could be argued that restricting a literature review to the exploration of 3D printer applications solely within the realm of primary education (i.e., students aged between six and 12) may not be entirely justified. Yet, primary education is distinct from other levels of education in several fundamental ways (GGI Insights, 2023; Kumari, 2022). Pedagogically, it employs teaching methods that are designed to introduce basic concepts and foster foundational skills in a way that is accessible and engaging for young learners. For that matter, educators typically employ interactive and play-based techniques that are conducive to the cognitive and attentional capacities of young children. This contrasts with the methods employed at higher levels of education, where teaching is often more formal and abstract. In terms of curriculum, primary education emphasizes the acquisition of basic literacy and numeracy skills as the focus is on core subjects such as reading, writing, and mathematics. This fundamental curriculum is designed to ensure that students develop the essential skills required for all future academic endeavors. Secondary education builds on these skills with more specialized and in-depth study, while tertiary education is characterized by a high degree of specialization and requires advanced critical thinking.

Developmentally, primary education coincides with a critical period in a child’s growth. During this stage, children are developing their cognitive, emotional, social, and physical capabilities at a rapid pace. Educators are, therefore, trained to recognize and support the holistic development of their students, often integrating lessons that promote social skills, emotional well-being, and physical coordination alongside academic content. This is in contrast to higher levels of education, where the focus progressively shifts towards intellectual development and subject-specific expertise. Importantly, it is during this initial stage that children learn how to learn; they develop curiosity, a sense of confidence in their abilities, and the foundational knowledge that will support all subsequent educational experiences. Moreover, it is often within the primary school setting that children establish their initial attitudes towards school and learning, which can have a long-lasting impact on their motivation and academic success. Furthermore, the role of primary education extends beyond individual learning to include socialization and the inculcation of civic values. Primary schools are typically the first place where children engage with the wider society beyond their immediate families, learning to interact with peers and authority figures in a structured environment.

METHOD

Reflecting upon what was presented in the preceding sections, certain conclusions can be drawn. First, 3D printing emerges as a technology holding considerable potential for educational applications. Second, primary education is distinctly different from secondary and tertiary levels of education in terms of pedagogical approaches, students’ intellectual stage, and learning objectives, necessitating tailored pedagogical approaches and resources. Finally, a survey of existing literature reveals a notable gap: previous reviews have not adequately differentiated between the use of 3D printing in primary education and its use in other educational levels or put an emphasis on specific disciplines and learning domains. In light of these observations, it can be asserted that the endeavor to conduct a literature review on the use of 3D printers by young students is not only justified but essential. This is because it can fill the gap in current reviews and also help to forge an understanding of the impact of this technology, thereby advancing its integration into early education curricula.

As delineated in the Introduction section, among the array of review methodologies, the scoping review was chosen due to its widespread acceptance as an efficacious approach for the synthesis of research data (Daudt et al., 2013). The principal objective of a scoping review is to comprehensively map the existing body of literature, rendering it particularly beneficial in instances where the subject matter remains insufficiently explored or is characterized by its heterogeneity and intrinsic complexity (Arksey & O'Malley, 2005; Mays et al., 2001).

OBJECTIVES OF THE REVIEW AND RESEARCH QUESTIONS

The primary aim of this review was to map the corpus of literature related to the deployment of 3D printers within the domain of primary education (students six to 12 years old), encompassing general, special, and inclusive education settings. Subsidiary to this overarching aim, the review sought to collate and present general data, including publication year, type, and country of publication. Furthermore, an examination of the research methodologies employed across the studies was also an objective. This involved an analysis of various dimensions such as the research settings, learning/teaching subjects, target groups, sample sizes, duration, equipment utilized in conjunction with 3D printers, the array of data collection instruments, the identified issues and challenges associated with integrating 3D printers into educational environments, along with the proposed recommendations to overcome these obstacles. Arguably, the most imperative objectives centered on the critical evaluation, synthesis, and categorization of the empirical findings reported in the studies. As a result, the research questions that guided this review were the following:

RQ1. To what extent does the current body of literature address the educational applications of 3D printing technology in primary school settings?

RQ2. Within which domains of learning have 3D printers been most frequently integrated? Which additional aspects related to the utilization of 3D printing technology have been investigated?

RQ3. What were the research settings in studies concerning the educational uses of 3D printers in primary schools?

RQ4. What impact do 3D printers have on the learning and skill development of primary school students?

RQ5. What are the other significant factors influenced by the use of 3D printers in primary school settings, and in what ways were they affected?

RQ6. What issues and challenges have been identified associated with integrating 3D printers into educational environments, and what suggestions have been made to overcome these obstacles?

PROCEDURE

The systematic search for scholarly articles was executed across multiple academic databases, including ERIC, LearnTechLib, Google Scholar, and Scopus. This search was delimited to the timeframe of 2013 to 2023, a period marked by significant technological advancements related to 3D printing and the more systematic application of this technology in education. The search criteria were all the possible combinations of keywords grouped into two distinct categories: (i) those related to 3D printing technology (encompassing terms such as "3D printing," "3D printers," "additive manufacturing," and "additive technology") and (ii) those related to primary education (including variations like "primary education," "primary school," "elementary education," and "elementary school").

Only empirical studies that had undergone the scrutiny of publication in journals, conference proceedings, and edited volumes were included. Moreover, the review also encompassed research that, besides primary school students, incorporated participants from additional educational stages, such as kindergarten and high school or any other age group. It is important to note the deliberate inclusion of studies focused on special education, provided they targeted the primary school cohort, consisting of students approximately aged between six and 12 years. This inclusion acknowledges the importance of educational inclusivity and the relevance of 3D printing technology across diverse learner populations. All studies had to be written in English.

The gray literature, technical reports, papers that solely examined or presented specific facets of 3D printing technology without empirical grounding, theoretical papers, incomplete submissions (such as posters and abstracts), non-empirical narratives, and any studies inaccessible for review were omitted. In addition, articles with educators as their only target group and articles in which 3D printers were not used by the children (e.g., cases in which parts of a robot were printed by educators or researchers) were also excluded. This exception did not apply to papers related to special education, given the nature of this type of education. Finally, studies in which 3D pens (also known as handheld 3D printers or hot-glue guns) were used as the prime tool were also excluded due to their substantial divergence in functionality and application from conventional 3D printers.

Furthermore, the methodological rigor was enhanced by employing the backward snowballing technique, a supplemental approach to keyword searches. This method involves a thorough analysis of the reference lists from the collected papers, thereby uncovering additional studies that may have eluded initial search efforts (Wohlin, 2014). Through this multifaceted search strategy, the review aimed to construct a comprehensive and authoritative corpus of literature on the intersection of 3D printing technology and primary education.

To present this process with greater clarity, the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flowchart was chosen (Moher et al., 2009) (Figure 1). The PRISMA framework delineates a structured progression through four distinct phases: identification, screening, eligibility, and inclusion. This flowchart graphically represents the trajectory of the review process, commencing with the initial compilation of articles retrieved through database searches and snowballing (*n* = 1584) and culminating in the selection of the corpus of studies that satisfied the inclusion criteria (*n* = 50).

As Figure 1 illustrates, a large number of papers were deemed ineligible for inclusion on the grounds of irrelevance. This determination arose during both the Screening and Eligibility stages, at which point it was determined that although the search terms were present within the texts, they were confined to the theoretical framework of the studies (e.g., the introduction or literature review sections), rather than in the method or empirical findings. Consequently, these papers were excluded to maintain the focus of the review. In addition, several other papers were deemed irrelevant as the 3D printers were not used by the participating students.

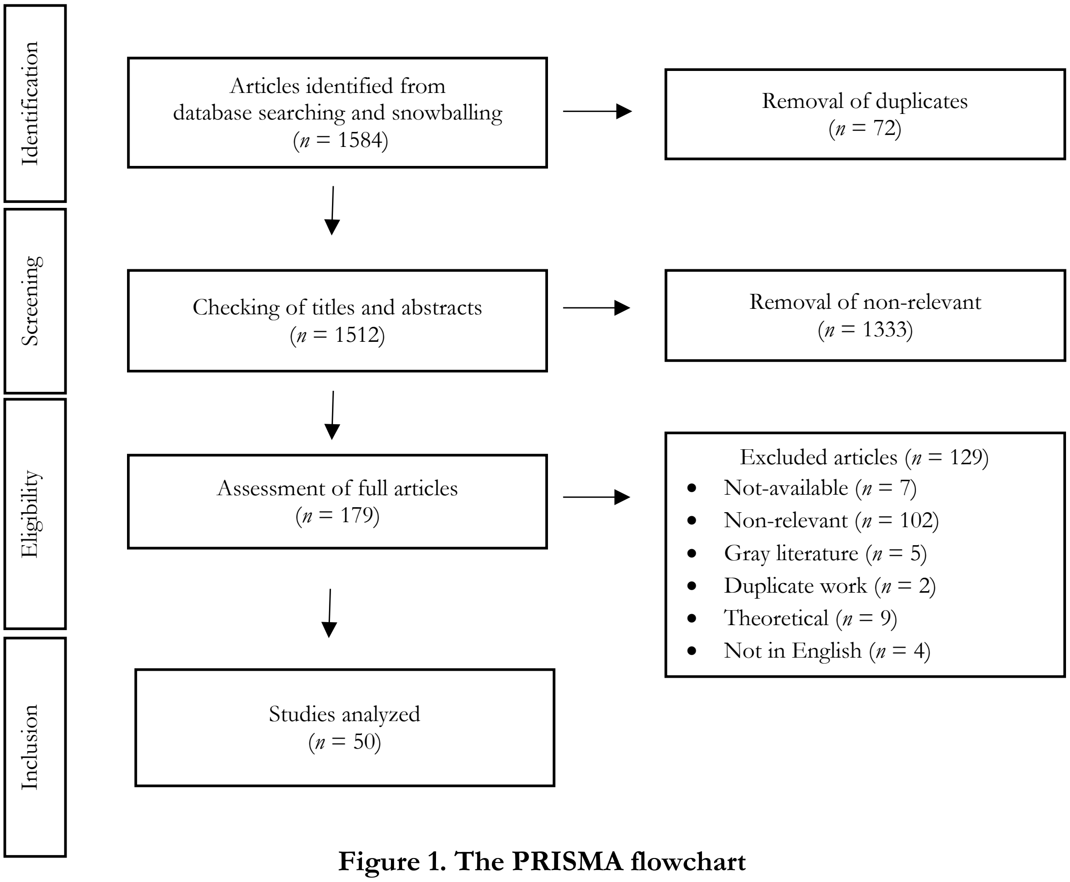

Figure 1. The PRISMA flowchart

RESULTS

GENERAL DATA

The list of the 50 analyzed studies is presented in Table 1, with their full citations enumerated in the Appendix. The trajectory of scholarly investigation into the integration of 3D printing technology within educational settings for young learners exhibits an upward trend. Early research in this field was sparse, with a mere four studies recorded from 2013 until the end of 2017, and notably, no contributions to the literature were made in either 2013 or 2015. However, a marked shift in academic focus is apparent, as six studies were published on the subject in the year 2021, while both 2019 and 2022 saw a modest increase, each yielding seven contributions. This growing interest among researchers was further underscored by the publication of eight studies in each of the years 2018 and 2020, while in 2023, the academic output was nine studies.

It is noteworthy that an overwhelming majority of the studies under analysis (*n* = 34) were published in journals, two in edited volumes, 13 were disseminated through conference proceedings, and one was an extensive report on a multi-year project. Geographically, the distribution of study origins indicates a predominant research focus in the United States and China (including Taiwan), hosting nine and seven studies, respectively. Spain, Australia, and the United Kingdom are followed by six, five, and four studies. Montenegro and Ireland each contributed to the corpus with three studies. Additionally, a diverse array of other countries (13 in total) was represented by one or two studies, with examples including but not limited to Türkiye, Saudi Arabia, Finland, Australia, Germany, Greece, Canada, and Thailand.

Table 1. List of the articles included in the review

Authors and year of publication	Title
Akyol et al. (2022)	3D printers as an educational tool in gifted education: effective use, problems, and suggestions.
Anđić et al. (2022)	3D printers as an educational tool in gifted education: effective use, problems, and suggestions.
Anđić et al. (2022)	Contribution of 3D modeling and printing to learning in primary schools: a case study with visually impaired students from an inclusive Biology classroom.
Anđić et al. (2023)	The effects of 3D printing on social interactions in inclusive classrooms.
Avinal and Aydin (2022)	The effects of activities designed with three-dimensional printing technology on science education.
Berman et al. (2018)	Exploring the 3D printing process for young children in the curriculum-aligned making in the classroom.
Bower et al. (2018a)	Makerspaces in primary school settings; advancing 21st century and STEM capabilities using 3D design and 3D printing.
Bower et al. (2018b)	Investigating the implications of 3D printing in special education.
Castro-Calviño et al. (2020)	Patrimonializarte: a heritage education program based on new technologies and local heritage.
Chen et al. (2014)	Effects of a 3D printing course on mental rotation ability among 10-year-old primary students.
Chen and Chang (2018)	3D printing assisted in art education: a study on the effectiveness of visually impaired students in space learning.
Chu et al. (2019)	An investigation of relevance from curriculum-aligned making in the elementary school science classroom.
Cueva (2018)	Advanced education through innovation via remote access to digital fabrication technologies.
Dilling and Witzke (2020)	Comparing digital and classical approaches: the case of tessellation in primary school.
Dooly et al. (2021)	Launching a solidarity campaign: technology-enhanced project-based language learning to promote entrepreneurial education and social awareness.
Fanny et al. (2020)	Developing a critical robot literacy for young people from conceptual metaphors analysis.
Fell et al. (2017)	Additive manufacturing and collaborative learning for pre-hospital care environment.
Forbes et al. (2021)	An analysis of the nature of young students' STEM learning in 3D technology-enhanced makerspaces.
Fowler et al. (2022)	Technology-enhanced learning environments and the potential for enhancing spatial reasoning: a mixed methods study.
Gratani et al. (2023)	Learning in the post-digital era: transforming education through the Maker approach.

Authors and year of publication	Title
Haas et al. (2021)	Case study on augmented reality, digital and physical modeling with mathematical learning disabilities students in an elementary school in Luxemburg.
Hatzigianni et al. (2020)	Children's views on making and designing.
Hu et al. (2023)	Scaffolding young children's computational thinking with teacher talk in a technology-mediated classroom.
Huang and Wang (2022)	Effectiveness of a three-dimensional-printing curriculum: developing and evaluating an elementary school design-oriented model course.
Junthong et al. (2020)	The designation of geometry teaching tools for visually-impaired students using plastic geoboards created by 3D printing.
Khasawneh and Darawsheh (2023)	Analyzing the effects of maker spaces and 3D printing technology on student innovation and design thinking.
Leinonen et al. (2020)	3D printing in the wild: Adopting digital fabrication in elementary school education.
Lozano (2022)	PRINT3D, a service-learning project for improving visually impaired accessibility through educational 3D printing.
Madani (2019)	Achieving teacher-free child-led design and additive manufacturing using the sense.
Maričić et al. (2023)	Contribution of STEAM activities to the development of 21st-century skills of primary school students.
Martínez Moreno et al. (2021)	Maker education in primary education: changes in students' maker-mindset and gender differences.
Matere et al. (2021)	Effect of design-based learning on elementary students computational thinking skills in visual programming maker course.
Maxwell et al. (2019)	Applying design fiction in primary schools to explore environmental challenges.
McLean et al. (2020)	The importance of collaborative design for narrowing the gender gap in engineering: an analysis of engineering identity development in elementary students.
Nikou (2024)	Student motivation and engagement in maker activities under the lens of the Activity Theory: a case study in a primary school.
Nikou et al. (2021)	Investigating elementary school students' attitudes in makerspace activities through design-based learning.
O'Reilly and Barry (2021)	The effect of the use of computer-aided design (CAD) and a 3D printer on the child's competence in mathematics.
Pantazis et al. (2021)	The effect of 3D printing technology on primary school students' content knowledge, anxiety, and interest in science.
Pijls et al. (2022)	Activities and experiences of children and makerspace coaches during after-school and school programs in a public library makerspace.
Schlegel et al. (2019)	Making in the classroom: Longitudinal evidence of increases in self-efficacy and STEM possible selves over time.
Smith (2018)	Children's negotiations of visualization skills during a design-based learning experience using nondigital and digital techniques.

Authors and year of publication	Title
Stapleton et al. (2019)	Girls' tech camp: librarians inspire adolescents to consider STEM careers.
Togou et al. (2018)	Raising students' interest in STEM education via remote digital fabrication: an Irish primary school case study.
Togou et al. (2019)	Newton Fab Lab initiative: attracting K-12 European students to STEM education through curriculum-based Fab Labs.
Turner et al. (2017)	Using 3D printing to enhance understanding and engagement with young audiences: lessons from workshops in a museum.
Vones et al. (2018)	3D printing "Ocean plastic" - fostering children's engagement with sustainability.
Vuopala et al. (2020)	Implementing a maker culture in elementary school students' perspectives.
Zhang et al. (2022)	An outreach/learning activity for STEAM education via the design and 3D printing of an accessible periodic table.
Zhaochen (2017)	Alternative 3D education for children: course design of 3D printing interactivity for Beijing's primary schools.
Zhou et al. (2019)	Experience in co-creation with 3D printing: Design model and feasibility test.

EDUCATIONAL SETTINGS AND RESEARCH OBJECTIVES

A segment of the studies (*n* = 5) delved into the realm of special education in formal educational settings. A slightly smaller collection of four studies involved inclusive education and was also situated in formal educational environments. Dominating the scholarly landscape, however, was research that involved students from the general population (*n* = 40), encompassing formal, informal, and extracurricular settings (Table 2). One study presented the results of a project that included students with special needs and students belonging to the general population.

Table 2. Type of education and educational settings

Type of education/settings	*n*	Type of education/settings	*n*
General/formal	35	Inclusive/formal	3
General/informal	4	Inclusive/formal-visually impaired	1
General/extracurricular	1	Special/formal	2
General and Special/formal	1	Special/formal-gifted students	1
		Special/formal-mathematics disabilities	1
		Special/formal-visually impaired	1

To examine the research focus of the respective studies, a thorough examination of their research questions and hypotheses was undertaken. This scrutiny revealed that, in numerous instances, the exploration of broader constructs necessitated their deconstruction into a multitude of sub-constructs or factors at both the data collection and result analysis sections. For example, when assessing the impact of 3D printing within a specific educational context, data related to various factors (e.g., enjoyment, motivation, and the effect on an array of competencies) were gathered. Given the multifaceted nature of such research endeavors, it was decided that each factor under investigation merited recognition as an individual research objective. This methodological decision led to the identification of 82 unique research objectives and 13 learning subjects/domains across the studies in question, as presented in Table 3, together with the number of times each was examined.

Table 3. Research focus and objectives

Learning subjects/domains	*n*
STEM	18
Mathematics	9
STEAM	7
Art education	6
Science education	5
Environmental science	5
Cultural history/heritage	5
English	2
Biology	1
Chemistry	1
Social sciences	1
Life sciences	1
History	1

Emotions/ feelings	*n*
Engagement	17
Motivation	7
Interest	7
Enjoyment	4
Satisfaction	4
Autonomy	3
Self-efficacy	3
Confidence	2
Empathy	2
Enthusiasm	1
Boredom	1
Anxiety	1
Empowerment	1

Impact on learning	*n*
Learning outcomes	5
Digital literacy	2
Scientific concepts understanding	2
Effectiveness of training programs	1
Misconceptions	1
Impact of 3D modeling and printing	1
Impact of hands-on experiences	1
Technical proficiency	1

Related to teachers	*n*
The effect of teacher involvement	2
Teacher professional development	2
The effect of teacher involvement	2

Table 3. Research focus and objectives (continued)

Skills and thinking	*n*
Creativity	12
Problem-solving skills	6
Spatial skills	4
Computational thinking	4
Communication skills	3
Design thinking	3
Critical thinking	3
Thinking kills	2
21st-century skills	2
Innovative thinking	2
Engineering skills	1
Entrepreneurial skills	1
Process skills	1
Mental rotation skills	1
Technical skills	1
Visualization skills	1
Debugging strategies	1
Decision-making	1
Visual-spatial memory	1

Maker education specific	*n*
Maker interest	3
Maker mindset	2
Maker efficacy	1
Maker identity	1
Maker self-efficacy	1
Attitudes towards Maker	1
Aspirations for making activities	1

Integration strategies	*n*
Integration of 3D printing into the classroom	7
Pedagogical strategies	4
ICT tools in education	3
Education using 3D printers	2
Learning behavior in the classroom	1

Identity development	*n*
Identity development	1
Engineering identity	1
Science identity	1

Types of learning	*n*
Project-based learning	2
Self-directed learning	1
Game-based learning	1
Design-oriented learning	1

Challenges/managerial	*n*
Ease of use/usability/accessibility	5
Challenges encountered in utilizing 3D printers	4
Material availability	2
Usefulness	2
Administrative support	1
The practicality of deploying 3D media in museums	1

Other issues	*n*
Design processes	11
Collaboration	10
Gender issues and differences	6
Social and civic competencies	1
Digital competence	1

Special education specific	*n*
Accessibility for individuals with disabilities	1
Assistive technology development for individuals with disabilities	1
The use of 3D printing technology to assist visually impaired students in art education	1
Social awareness towards individuals with visual impairments	1
The feasibility and implications of using 3D modeling software for occupational therapy	1
The use of 3D printers to assist visually impaired students	1
Social responsibility	1

RESEARCH SETTINGS

Regarding the methodological design of the studies, it was observed that 30 employed a mixed methods framework, incorporating both quantitative and qualitative research techniques. Thirteen studies utilized qualitative methodologies, and seven studies were quantitative. Students were the exclusive subjects in a substantial majority of the cases (*n* = 40); a further eight studies incorporated both students and teachers as their focal groups; one included students and coachers, while another involved students, teachers, families, and local authorities. It should be noted that in just five studies, the outcomes of employing 3D printers were contrasted with those derived from alternative tools or media. In the vast majority of cases, however, 3D printers were either utilized in conjunction with an array of other tools or stood as the sole apparatus, as will be presented in a coming paragraph.

The sample sizes across the studies were generally modest, with the majority (*n* = 27) comprising no more than 50 individuals. Nine studies featured a slightly larger sample size, ranging from 51 to 100 participants. A minimal number of studies explored populations of 101 to 150 individuals (*n* = 6) and 151 to 200 individuals (*n* = 1), and one study investigated a cohort of 201 to 250 participants. At the higher end of the spectrum, one study encompassed 301 to 350 individuals, while the sample size in three studies was 451 to 500 individuals. Two studies failed to report their sample sizes. It is important to clarify that the reported sample sizes pertain exclusively to the student participants; teachers and any other individuals were not encompassed within these figures.

Regarding the demographic characteristics of participants, particularly their age and educational level, the majority of the research concentrated on students within the 9- to 12-year-old cohort (grades 4 to 6), with 18 studies in total. Furthermore, as presented in Table 4, a subset of the research focused on students aged 7 to 11 (*n* = 7); students aged 10 to 13 were the target group in five studies, and students aged 4 to 8 were targeted in four.

Table 4. The age groups of the participants

Grades (ages)	*n*	Grades (ages)	*n*
K-2 (4-8)	4	5-7 (10-13)	5
1-3 (6-9)	2	1-12 (6-17)	2
4-6 (9-12)	18	Unspecified primary and high school	4
3-5 (7-11)	7	K-12 (4-17)	2
1-6 (6-12)	1	Ages 8-18	1
Unspecified primary school	3	Ages 3-21	1

Regarding the quantification and duration of the interventions of projects, the presentation of results must be approached with caution. A notable limitation of the studies included in this review was the lack of explicit detail concerning these parameters. Not only that, but eight studies exhibited a complete absence of such information. Furthermore, others are ambiguous, as the authors failed to mention the number of interventions, explain whether they referred to the duration of all the interventions or the individual span of each, and, in general, provide figures that would have made the process of determining the duration of their projects easier. Having said that, a synthesis of the available data reveals that 15 studies can be characterized as short-term, with durations ranging from a few hours to two weeks. Sixteen studies qualify as medium-term, lasting from one month to several months, while 11 studies reported intervention durations of over one year. Regrettably, eight studies failed to report any relevant duration data.

In the context of the hardware and software deployed in the studies, 16 utilized 3D printers as the sole piece of equipment. Contrastingly, the remainder of the studies employed 3D printers in conjunction with an array of devices and materials presented in Table 5. Concerning the software aspect, Tinkercad emerged as the predominant choice across the studies (*n* = 23). This preference can be attributed to its status as an accessible, web-based 3D modeling application. Please note that in several cases, the specific software was not mentioned.

Table 5. Hardware and software used

Hardware	***n***
3D printer only	16
3D scanner	8
Electronics kits and parts	7
Conventional materials (e.g., paper, pencils, crayons, colored pencils, markers, hot glue, modeling clay	7
Various robots	6
iPads	6
Computers and laptops	5
Arduino	4
Laser cutters	4
Textbooks	4
Braille typewriters	2
Tablets	2
3D pens	2
CNC machines	2
Arts and craft materials	1
Clay	1
Everyday classroom objects and materials	1
GPS trackers	1
Industrial granulator	1
Makey Makey	1
Mobile devices	1
Pottery tools	1
Recycled or everyday materials	1
Sewing machines, saws, scissors	1
Various art materials and media	1
Various construction materials	1
Vinyl cutters	1

Software	***n***
TinkerCad	23
Ultimaker Cura	4
FreeCAD	3
Scratch	3
SketchUp	3
Adobe Spark	2
Inkscape	2
Makers Empire 3D design	2
PowerDirector	2
Adobe Premiere	1
Arduino scripts	1
Aurasma/HP Reveal	1
AutoCAD	1
Autodesk 123D Catch	1
Blockly	1
BlocksCAD	1
Canva	1
FlashPrint	1
GeoGebra	1
MakeCode	1
Maker Empire	1
MakerBot PrintShop	1
mBlock visual programming software	1
PrintLab	1
Qr code generator website	1
Simplify3D	1
Thinglink web app	1
Unity	1
VEnvI (programming environment)	1

Finally, regarding the data collection instruments employed, questionnaires/scales emerged as the predominant tool, with 33 instances (Table 6). Interviews were also notably prevalent, being utilized in 28 cases, and observations were recorded in 20 instances. Additionally, audio and video recordings were adopted in 13 occurrences. Furthermore, evaluation tests were implemented in seven instances, and the analysis of focus group interactions in six.

Table 6. Instruments used for data collection

Instrument	*n*	Instrument	*n*
Questionnaires/Scales	33	Feedback forms	2
Interviews	26	Analysis of final group presentations	1
Observations	20	Evaluation of students' devices	1
Audio and video recordings	13	Checklists for basic modeling exercises	1
Knowledge tests	7	Coding of interactions	1
Focus group discussions	6	Computational Thinking test	1
Notes	5	Daily reflective exit tickets	1
Teacher's diary/logs/checklists	5	Descriptions of the user interaction with the 3D design applications	1
Pre-post knowledge tests	4	Think-aloud protocols	1
Photos	3	Evaluation of the written programs	1
Reflective texts/journals/feedback	3	Group reviews	1
Evaluation of the 3D-printed objects	3	Logbooks	1
Evaluation of drawings	2	Product design rubric evaluation	1
Screen recordings	2	Test data from schools	1
Self-assessments	2	Student self-evaluation charts	1
Evaluation of student work	2	Students' reflection sheets	1

ANALYSIS OF THE STUDIES' FINDINGS

A critical focal point in the analysis of the articles was related to their reported findings. To enhance the clarity of the analysis but also to reinforce the reliability and validity of the conclusions drawn from the compiled data, the findings of the studies, as delineated in the data analysis and discussion sections, were systematically categorized according to their respective domains and classified based on the nature of their outcomes (positive, neutral, or negative). Tables 7, 8, and 9 present the results of this procedure in detail, while Table 10 summarizes the results. Cases were designated as positive when they featured instances where the group employing 3D printing technology demonstrated superior performance compared to those utilizing other tools/media. In scenarios where 3D printers were employed as the only tool or were used in conjunction with other tools, the outcome was deemed positive if a beneficial impact on the users was reported. A similar approach was followed for the neutral and negative outcomes. The analysis demonstrated that, in the overwhelming majority of instances, the findings were skewed in favor of 3D printers ($n = 187$); the negative results were significantly fewer ($n = 44$), while the neutral outcomes were even fewer ($n = 24$).

Table 7. Positive results (there was a positive impact on …)

Related to learning	*n*	Related to feelings/emotions/attitudes	*n*
Academic achievement	12	Engagement	18
Concretization of learning and abstract subjects	2	Interest	11
Mental rotation ability	2	Motivation	8
Application of knowledge	1	Confidence	5
Conceptual understanding	1	Self-efficacy	5

Focused learning	1
Language	1
Learning of new technologies	1
Mathematical competence	1
Mental imagery and understanding	1
Misconceptions	1
Understanding complex scientific concepts	1
Understanding of 2-D and 3-D forms	1
Understanding of 3D printing and modeling concepts	1
Understanding of scientific concepts	1
Use of analogies	1

Related to skills	***n***
Collaboration	4
Problem-solving skills	4
Communication skills	3
Technical skils	3
21st-century skills	2
Organizational skills	1
3D modeling skills	1
Development of entrepreneurial skills	1
Digital skills	1
Interpersonal skills	1
Interpersonal skills	1
Maker skills	1
Social skills	1
Visualization skills	1

Related to 3D printers	***n***
Ease of use	3
Usefulness	2

Satisfaction	5
Enjoyment	4
Boredom decrease	2
Enthusiasm	2
Positive learning experiences	2
Attitudes toward Mathematics	1
Attitudes toward school subjects	1
Attitudes towards STEM	1
Desire to continue integrating maker spaces	1
Empowerment	1
Girls' confidence in STEM	1
Innovation	1
Positive emotions	1
Pride	1
Resilience	1
Science self-efficacy	1
Science-related anxiety reduction	1
Self-esteem	1
Sense of responsibility	1

Related to mental abilities	***n***
Creativity	8
Design thinking	3
Critical thinking	2
Logical organization	2
Spatial skills	2
Analytical reasoning	1
Cause-and-effect thinking	1
Conceptualization of the design model	1
Maker mindset	1
Process Skills	1

Familiarity with 3D printing and modeling concepts	1
Identifying 3D printing principles and mistakes	1

Related to special education	***n***
Aid visually impaired students	1
Promoted empathy	1
Potential benefits of 3D printing in special education	1
Social awareness	1
Social consciousness	1

Other classified as positive	***n***
Uncategorized	17

Related to teachers and teaching	***n***
Facilitated the integration of multiple competencies and knowledge across various disciplines	1
Pedagogical shift towards more dynamic teaching	1
The potential of Making to bridge school science and everyday science	1
Professional growth	1
Recognition of the importance of pedagogical practices in facilitating meaningful integration of activities	1
Teacher confidence	1

Table 8. Neutral results (there was no impact on/no change of…)

Related to learning	***n***
Children's perspective on the repurposed materials	1
Language use	1
No difference between conventional and digital approaches	1

Skills	***n***
Collaboration	1
Study skills	1
Technical skills	1

Related to mental abilities	***n***
Computational thinking skills	1
Design thinking	1

Related to feelings/emotions/attitudes	***n***
Interest in science	2
Acceptance and usage of technology	1
Engagement	1
Enjoyment	1
Making interest	1
No difference in genders regarding interest in Maker activities	1
No difference in genders regarding motivation in Maker activities	1
Satisfaction	1
STEM career interest	1
Interest in different camp activities and learning experiences	1

Related to special education	***n***

Girls' spatial ability developed faster than boys	1
No significant improvement among girls in mental rotation ability	1
Specific spatial sub-skills	1

Levels of positive verbal and nonverbal interactions among SWD and SWOD remained the same	1

Other, classified as neutral	***n***
Maker identity	1

Table 9. Negative results (there was a negative impact on/there were issues in …)

Related to learning	***n***
Problem understanding	2
Distraction by gamification aspects of the app	1
Focus on visual attributes over semantic relevance	1
Understanding certain concepts	1
Understanding the relevance of STEM knowledge in tasks	1

Related to mental abilities	***n***
Creativity	2
Design thinking	1

Technical issues related to printers	***n***
Technical problems	6
Long printing times	1
Material limitations	1
The printing process	1

Related to managerial issues	***n***
Resource/logistical management	4
Budget limitations	1
The schools' curriculum has to change	1

Students' challenges/difficulties/problems	***n***
Preference for conventional materials	2
Steep learning curves	2
Students encountered problems in 3D modeling and printing	1
Students encountered problems in creating 3D printable models	1
Some students needed additional guidance	1
Problems with the use of digital tools	1
Usability issues	1

Related to teachers and teaching	***n***
Limitations in the pedagogical approach	1
Need for explicit linkages between activities and the curriculum	1
Need for explicit STEM concept instruction	1
Need for structured, responsive professional learning programs	1

Related to feelings/emotions/attitudes	***n***
Negative attitudes towards interventions	2
Difficulty and frustration with learning Fab Lab technologies	1
Frustration with certain activities	1
Mismatched expectations between digital representations and actual prints	1
Relative lower sense of self-efficacy in math and science	1

Related to special education	***n***
New misconceptions among visually impaired students	1

Table 10. Summary of the results

Category	Positive (*n*)	Neutral (*n*)	Negative (*n*)
Learning-related	29	3	6
Feelings/Emotions/Attitudes related	76	11	6
Skills related	25	3	0
Mental abilities related	22	5	3
Related to 3D printers	7	0	9
Related to special education	5	1	1
Related to teachers and teaching	6	0	4
Students' challenges/difficulties/problems	0	0	9
Managerial issues	0	0	6
Uncategorized	17	1	0

ISSUES, CHALLENGES, AND SUGGESTIONS

As demonstrated in Tables 8 and 9, a considerable proportion of both the neutral and negative outcomes can be attributed to the challenges encountered by students and educators in the utilization of 3D printers. It was, therefore, considered important to examine the full range of issues and obstacles documented by the authors during the execution of their projects. Moreover, an analysis of the suggestions made to circumvent these difficulties was equally critical. The pertinent information, as reported in the discussion, implications for research and practice, and limitations and future work sections, was systematically classified according to the nature of the identified challenges and suggestions, as presented in Table 11. It has to be noted that this compilation exclusively encompasses challenges and recommendations that are directly related to 3D printing; any other issues not directly associated with 3D printing (e.g., because of the use of other devices) have been omitted from this synthesis.

Table 11. Challenges identified and suggestions to overcome them

Challenges general education	*n*
Pedagogical challenges	21
Instructional challenges	20
Technological challenges/problems	19
Design and creativity barriers	14
Materials and resources issues	12
Educational context and curricular integration issues	12
Challenges special education	***n***
Teacher and student proficiency issues	7
Educational methodology and curriculum development issues	5
Technological and accessibility issues	5
Social and emotional challenges	2

Suggestions general education	*n*
Adoption of innovative teaching methods/strategies	28
Curriculum and instructional design revisions	28
Professional development programs	27
Technology integration in the curriculum	17
Collaborative and community involvement	17
Infrastructure and resources/materials management/investments	15
Suggestions special education	***n***
Adoption of innovative teaching methods/strategies	5
Curriculum and instructional design revisions	5
Infrastructure and resources/materials management/investments	4
Professional development programs	4

		Collaboration and interdisciplinary efforts	4
		Focus on inclusion and community engagement	4

MAIN FINDINGS AND ANSWERS TO THE RESEARCH QUESTION

On the basis of the outcomes of the review and for addressing the research questions, the following observations can be made:

- **RQ1:** The corpus of existing literature that explores the educational applications of 3D printers within primary school environments appears to be relatively scarce. This assertion is substantiated by the fact that, of the 179 papers that entered the Eligibility stage (which, by itself, is a small number), 50 were deemed directly relevant to the research scope. Furthermore, when examining the subsets of special and inclusive education, the scarcity of literature becomes even more pronounced. On the positive side, there has been a noticeable growth in the publication of related studies during the past four years.

- **RQ2:** The utilization of 3D printing technology has been significantly prevalent in the domain of STEM/STEAM education, with its application extending to an additional 11 academic disciplines. The review revealed that researchers have examined a substantial number of other factors, totaling 82, in association with 3D printer usage in educational settings. Just eight factors were related to the impact of 3D printers on learning. Among the remaining ones, student engagement, motivation, interest, enjoyment, and satisfaction garnered the most interest related to emotional and affective responses. Concurrently, the enhancement of creativity, the cultivation of problem-solving capabilities, the development of spatial abilities, and the advancement of computational thinking skills emerged as the foremost areas of investigation relating to cognitive and skill-based outcomes. Furthermore, scholarly inquiry has encompassed an array of other pertinent aspects. These include the examination of design processes, collaboration, and gender-related issues. Additionally, the integration of 3D printers into classroom environments, the obstacles faced during their implementation, effective pedagogical approaches for their use, and concerns surrounding usability have also been focal points of research interest.

- **RQ3:** In terms of research methodologies, the majority of studies (30 out of 50) related to the educational use of 3D printing in primary schools have favored mixed methods approaches. Just five studies have undertaken a comparative analysis of the results achieved through the use of 3D printers against those obtained from other tools or media. It was observed that 3D printers were employed alongside various other instruments, or they were used exclusively as the primary equipment in the majority of instances. The sample sizes were often relatively small, and there was a notable lack of comparative analysis between the outcomes of 3D printing and other educational tools or media. Additionally, inconsistencies and inadequacies have been identified in the reporting of intervention durations, which may affect the robustness of the research findings. In addition to 3D printers, a diverse array of hardware tools was employed. Among the prevalent tools were 3D scanners, electronic components and kits, conventional/everyday materials, iPads, a multitude of robotic devices, and computers. Regarding software tools, TinkerCad emerged as the predominantly favored application. As for the data collection instruments, questionnaires, interviews, observations, and audio and video recordings were the most common ones.

- **RQ4:** The evidence indicated that the integration of 3D printers within primary education positively influenced students’ knowledge acquisition and skill development. That is because there were 29 cases with positive outcomes, three with neutral, and seven with negative results regarding learning, while there were 25 positive, three neutral, and no negative results regarding skills.

- **RQ5:** Beyond academic performance and skills acquisition, the utilization of 3D printers in the classroom has been shown to have a positive impact on primary school students' mental abilities (22 positive, five neutral, and three negative cases) and feelings, emotions, and attitudes (76 positive, 11 neutral, and six negative cases). Moreover, the introduction of 3D printers in special education seems to have a positive impact as well (five positive, one neutral, and one negative case). As for their impact on teachers and teaching, the results were mixed, as there were six positive and four negative cases.
- **RQ6:** In both general and special educational realms, a multitude of challenges have been identified. Issues extending from technological hindrances to problems in materials and resources, coupled with the inadequate training received by educators and students alike, were among the anticipated difficulties. Beyond these issues, researchers have pinpointed significant obstacles within the domains of pedagogy and instructional methods, specifically concerning the integration of 3D printing technology into educational contexts. Moreover, within special education settings, accessibility emerged as a concern. To address these challenges, the authors proposed a suite of reforms. These included a transformative approach to teaching methodologies, the embracement of innovative educational strategies, and adjustments to the curriculum to promote the seamless incorporation of technology. Investments in educational infrastructure were deemed essential to facilitate these advancements. Furthermore, the implementation of robust professional development programs was advocated to enhance the skill set of educators. In parallel, the authors underlined the necessity for a heightened focus on inclusion and the adoption of community engagement strategies within the sphere of special education, asserting that these measures are critical for fostering an inclusive educational environment. The above will be further elaborated in the coming section.

DISCUSSION

Several interesting conclusions emerge from the review's findings. Notably, the integration of 3D printing into educational settings, especially at the elementary level, presents a promising avenue for impacting a crucial developmental stage where the groundwork for lifelong learning and skill acquisition is laid. Despite the nascent interest and increased empirical scrutiny reflected in the literature, the use of 3D printers as an instructional resource for primary school-aged students remains a largely untapped area of research. This assertion is substantiated by two key observations.

Firstly, the existing body of research is notably sparse. This observation is consistent with the outcomes presented by Novak et al. (2021), who reported that 60% of the studies focused on post-secondary learners, with the remaining 40% encompassing K-12 students with a relatively equitable distribution across elementary, middle, and high school levels. Likewise, Aslan and Çelik (2022) observed that the majority of studies in their review were addressed to undergraduate and secondary school students. Secondly, the annual output of scholarly articles on this subject remains modest, with fewer than ten papers published per year. Both indicators suggest that within the domain of elementary education, 3D printing is still an emergent niche in educational technology research, far from being established as an integral component of contemporary pedagogical strategies.

A limited number of research projects have been carried out within the realm of special and inclusive education, highlighting a significant gap in our understanding of the potential benefits of 3D printing for students with disabilities. Although there is a body of evidence suggesting that students with visual, motor, and cognitive disabilities may experience positive outcomes from the integration of 3D printing into their learning environments (e.g., Buehler et al., 2016); Ford & Minshall, 2019; Horowitz & Schultz, 2014), and further corroborated by this review, the scarcity of such studies is a call for a more rigorous and focused exploration of how 3D printing can be effectively incorporated into special and inclusive education settings.

In addressing RQ2, it became evident that a majority of the research concerning 3D printing in primary education has been situated within STEM/STEAM education. This trend is reflective of the technology's congruence with educational curricula that prioritize hands-on, experiential learning and the cultivation of critical thinking competencies. Pearson and Dubé (2022) have observed that pedagogical approaches such as situated learning, experiential learning, critical making, constructionism, and self-directed learning are prevalent themes throughout the studies considered in their review. However, it is important to note, and as will be further elaborated in the subsequent section, that this emphasis on STEM/STEAM may have inadvertently narrowed the scope of inquiry, leaving other subject areas relatively unexplored.

During the review process, it was determined that the objectives of the studies should be deconstructed into several sub-constructs based on what the authors examined, treating each as a distinct research objective. This methodical approach not only clarified the aims of the studies but also highlighted the depth and intricacy of these inquiries. Such a strategy significantly contributed to a more sophisticated comprehension of the field. A total of 82 unique research objectives were identified, with 74 of them associated with factors including emotional and affective responses, cognitive and skill-based outcomes, encountered challenges, effective pedagogical strategies, and usability concerns. These findings collectively emphasize the strong and diverse interest in the educational implications of 3D printing technology.

It has to be noted that, according to the review's findings, learning outcomes were not the central focus of the majority of the studies. In fact, they were directly examined in only five instances, while the impact on other learning-related factors was considered in nine cases, as delineated in Table 3. In contrast to these observations, Novak et al. (2021) concluded in their review that content knowledge was the predominant research focus in 77% of the studies evaluated. The discrepancy between these findings can be attributed to differences in the scope of the two reviews, as Novak et al. included studies spanning all educational levels. There might also be variations in how research objectives were categorized. Nonetheless, it is highly plausible that within the context of primary education, given its critical role in student development, learning intersects with numerous other vital factors that shape students' personalities and are thus deserving of exploration.

Regarding RQ3, the review indicated a discernible preference for mixed-methods research approaches, highlighting the complex nature of evaluating the educational impact of 3D printing. A considerably smaller number of studies adopted a qualitative approach (*n* = 13), and an even more limited subset utilized quantitative methods (*n* = 7). These findings appear to be at odds with the conclusions drawn in the review by Aslan and Çelik (2022), which posited favoritism towards qualitative methodologies. However, it is critical to note that their analysis spanned the entire range of K-12 education without a specific focus on elementary-aged students, which may account for this discrepancy.

Comparative research was found to be sparse, with the majority of studies implementing 3D printers either as standalone tools or in conjunction with other tools and materials. On the one hand, this methodological stance serves to underscore the importance of exploring the combined effects of multiple tools and media when used synergistically, which is particularly vital in creating a multifaceted and enriching educational experience. Conversely, such approaches fail to isolate and clarify the distinct educational value attributed to 3D printers alone since the observed outcomes represent the aggregate effect of all tools utilized in the research.

The prevalence of studies with small sample sizes was also observed, suggesting that the high costs associated with procuring 3D printers may constrain the feasibility of conducting studies with more extensive participant numbers. Although the synthesis of study durations revealed a relatively even distribution across short-, medium-, and long-term investigations, the frequent inconsistencies in reporting durations and the number of interventions (or the complete omission of such data) cast doubt on the reliability of this finding. This inconsistency underscores the critical need for enhanced precision and standardization in reporting intervention durations to enable more rigorous and comparable research in the future.

Consistent with Aslan and Çelik's (2022) findings, questionnaires/scales, interviews, and observations were identified as the most prevalent instruments for data collection. Nevertheless, the discovery of 32 distinct instruments used across studies indicates a commitment by researchers to a diverse array of tools for data collection, aiming to comprehensively capture the multifaceted impact of 3D printers in educational settings.

The findings related to RQ4 and RQ5 do not come as a surprise. The analysis of the relevant studies reveals a consistently positive impact of 3D printing on the acquisition of knowledge and skills. This uniformity in findings lends substantial credence to the technology's utility and efficacy across a diverse array of research settings, thereby highlighting its considerable promise as an instructional medium. In fact, it can be supported with confidence that 3D printers play a vital role in enhancing students' understanding and in cultivating advanced cognitive abilities, including but not limited to creativity, problem-solving, and critical thinking. These educational outcomes are not only in harmony with the instructional goals of primary education, which is fundamentally concerned with the nurturing of core competencies in young learners, but also resonate with the educational imperative of fostering intellectual growth during pivotal stages of cognitive development. Furthermore, these cognitive skills are essential across a wide range of academic disciplines. The augmentation of such skills through engagement with 3D printing activities offers tangible benefits, particularly for students in primary education who are undergoing critical phases of cognitive maturation. In addition, the findings underscore the positive influence of 3D printing on students' emotional and affective responses, with engagement, interest, and motivation being the most frequently examined factors. The evidence suggests that 3D printing can stimulate curiosity and significantly bolster students' enthusiasm for learning. These aspects are pivotal in maintaining sustained interest and involvement in educational activities, thus contributing to a more fulfilling learning experience.

As previous research has noted (e.g., Buehler et al., 2016; Ford & Minshall, 2019; Horowitz & Schultz, 2014), the current review verifies the notion that the integration of 3D printing within special education environments, despite its limited scope, yields positive outcomes. This is particularly evident in its capacity to assist visually impaired learners, to cultivate empathy, and to enhance social awareness. The capacity of 3D printing to create customized, tactile learning aids can bridge the gap for students with visual impairments and other disabilities, reinforcing the technology's value as a tool for inclusivity.

While the impact on teachers and teaching was not extensively examined, the evidence suggests that 3D printers are instrumental in steering instructional methods toward more dynamic, learner-centric paradigms. Positive impacts on teacher professional development and confidence in technology integration were observed in six instances. However, four cases highlighted a critical need for structured professional learning initiatives, clear connections between 3D printing activities and educational curricula, and the establishment of innovative pedagogical frameworks. These findings echo the imperative for sustained support in the integration of cutting-edge educational technologies, as also articulated in subsequent reviews (Aslan & Çelik, 2022; Pernaa & Wiedmer, 2020).

Notwithstanding these favorable outcomes, it has to be acknowledged that in a number of cases, there were negative (*n* = 44) or neutral (*n* = 24) effects, which brings to light the various obstacles associated with the deployment of 3D printers in educational settings.

Indeed, pedagogical and instructional challenges were prominent; educators grappled to balance structured activities with the autonomy necessary for students to engage in meaningful activities with

3D printers, while students encountered challenges in design precision, feasibility, and spatial awareness. This tension underscored the need for pedagogical adjustments to cater to diverse learning styles and encourage autonomy while maintaining curriculum standards. Technical and practical limitations together with notable logistical challenges, were equally significant, with issues like slow Internet connectivity, limited access to necessary devices, and the complexity of software operations like Tinkercad hindering effective integration of 3D printing in educational settings. These technical challenges were compounded by the steep learning curves associated with operating 3D modeling software and hardware, pointing to a critical need for technical skill development among both students and teachers. Resource and infrastructure constraints were prevalent, with inadequate support for the necessary infrastructure, such as modern computer labs, limiting the potential for widespread adoption of 3D printing. The high cost of 3D printers and the lack of trained personnel further exacerbated these constraints, presenting barriers to access and integration of this technology in education. Fostering creativity and conceptual understanding was a challenge, indicative of a need for curricula that promote critical thinking and problem-solving. While 3D printing has the potential to enhance creativity, there is a risk of its use becoming overly focused on the technology itself, potentially detracting from deeper conceptual learning. Moreover, in the context of special education, accessibility challenges emerged, as the authors noted a pressing need to establish accessible spaces and resources for students with disabilities, such as the visually impaired, including making complex scientific concepts accessible. In addition, the cultivation of empathy toward individuals with disabilities and teaching the broader implications of civic responsibility emerged as a need.

To address the challenges associated with 3D printing in education, substantial emphasis has been placed on professional development programs to build teacher confidence and expertise. This includes not just technical training but also pedagogical competencies to integrate 3D printing within the curriculum effectively. Curricula need to be carefully designed with practical elements and integrated learning approaches that cater to diverse learning styles. These can be supported by establishing collaborative learning environments and community-building initiatives, allowing students to engage effectively in 3D printing and beyond. Pedagogical strategies require adaptation to include various teaching methods and to ensure they are responsive to student needs. A variety of instructional methods, such as scaffolded learning, project-based learning, and differentiated instruction to address different learning needs and styles, has been suggested. Also, age-appropriate challenges and materials were advised to better suit the developmental stages of different student groups. A thoughtful integration of technology is crucial, ensuring that it is meaningful, engaging, and supportive of the learning objectives. Recognizing the importance of peer-to-peer interaction and cultivating a supportive and collaborative learning environment, the implementation of peer mentoring systems and the development of a shared coaching philosophy were recommended. Engaging the wider community and encouraging collaborations beyond the classroom were also highlighted. Managing infrastructure and resources effectively, including the use of reliable technological tools, was considered vital for the successful implementation of 3D printing in educational settings. Ensuring the accessibility of technology and the inclusion of all students was also deemed crucial for equitable education. For the successful inclusion of 3D printing technology in special education settings, in addition to the above suggestions, the development of tailored teaching and learning materials, focusing on individualized assessment and learning plans, and employing motivational strategies that build confidence and facilitate engagement were considered of paramount importance.

All in all, it can be supported that while the existing literature on the educational use of 3D printers by elementary-aged students is limited, the available evidence robustly supports the positive impact of this technology on various aspects of student learning and development. On the other hand, the challenges related to the integration of 3D printers in education cannot be overlooked, and several steps have to be taken to successfully mitigate them.

IMPLICATIONS FOR RESEARCH AND EDUCATION

The reviewed body of literature emphasized the potential of 3D printing technology in primary education. In this respect, significant implications for research and education can be discerned. Few studies compared 3D printers with other tools or technologies; therefore, comparative analyses are essential to contextualize the unique benefits and challenges associated with this technology. The inconsistencies in reporting intervention durations and the scope of research settings highlight the need for standardized methodologies and metrics in studying 3D printing in education. Clear and consistent reporting will facilitate cross-study comparisons and contribute to a more cohesive body of literature. With a concentration of research efforts on STEM/STEAM education, there is an opportunity to diversify into other learning domains, offering a holistic view of the potential of 3D printing across the broader educational spectrum. Studies should also aim to consider diverse learner populations with a wide range of abilities and learning styles to ensure the technology's adaptability and accessibility. The presence of neutral and negative results, though not so prominent, invites researchers to delve deeper into the reasons behind these outcomes. Understanding the barriers to effective 3D printing integration can lead to the development of more effective instructional strategies and technological enhancements.

As for education, the demonstrated impact of 3D printing on student engagement, creativity, and problem-solving abilities advocates for the inclusion of 3D printing in curriculum design. Educators and curriculum developers should consider incorporating 3D printing projects that align with academic standards while fostering these valuable skills. The role of educators is pivotal in the successful deployment of 3D printing technology. Professional development programs should focus on equipping teachers with the necessary skills and knowledge to integrate 3D printing into their teaching practices effectively. The positive implications of 3D printing for students with disabilities indicate a promising avenue for creating more inclusive and customized learning experiences. Tailored 3D printing activities can support individualized learning plans and assistive technology development. Beyond cognitive gains, the review revealed that 3D printing enriches the development of interpersonal and intrapersonal competencies. Educational stakeholders should emphasize the cultivation of these soft skills, which are increasingly important in the 21st-century job market. To ensure equitable access to 3D printing technology, educational institutions must consider the budgetary and resource management challenges identified in the review. Efforts should be directed towards making 3D printers an accessible tool for all students.

LIMITATIONS

Several limitations inherent to this work must be acknowledged, many of which stem from the nature of the review and the selection process employed. First, the literature search was confined to specific databases to identify studies concerning the use of 3D printers by elementary-aged students. It is almost certain that a number of relevant papers were not captured due to lack of access or because they were not indexed in the databases consulted. Second, the temporal scope of the search was restricted to publications from 2013 to 2023. Despite the scant volume of work published between 2013 and 2017, it remains a possibility (albeit an unlikely one) that some early adoptions of the technology may have evaded detection. Among the works included in this review, thirteen papers were derived from conference proceedings. It is often the case that such papers present preliminary results or work in progress, which may not provide a comprehensive view of the research findings, potentially influencing the outcomes of this review. The phenomenon of publication bias, whereby the decision to publish is influenced by the nature of experimental outcomes, is also a factor to consider. Subtle variations in experimental design can skew results in favor of a particular tool or approach. Both publication bias and uncertainties inherent in the design of the studies reviewed could have an effect on the findings of this analysis.

CONCLUSION

This review has methodically synthesized the existing body of literature related to the use of 3D printing technology by elementary-aged students. In this regard, the work provides a significant contribution to the scholarly discourse by systematically summarizing and categorizing research related to the educational applications of 3D printers, utilizing robust and well-founded criteria. Addressing the relevant research questions, the findings confirm that while the volume of studies is limited, researchers have delved into a wide array of factors related to 3D printer usage in educational environments. The findings from the reviewed studies overwhelmingly demonstrated positive outcomes. Specifically, they suggest that 3D printers can significantly improve students' knowledge acquisition and skill development. Moreover, 3D printing has elicited favorable responses in terms of students' mental abilities and emotional/affective domains. The deployment of 3D printers in special education also yielded positive results, though mixed outcomes were noted in relation to teacher and teaching impacts. Usability and managerial concerns were the main negative findings. In conclusion, the review affirms the substantial potential of 3D printing technology as a tool for educational enhancement and underscores the necessity for further research to optimize its integration within the primary educational sphere.

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APPENDIX

SOURCES OF THE STUDIES ANALYZED IN THE REVIEW

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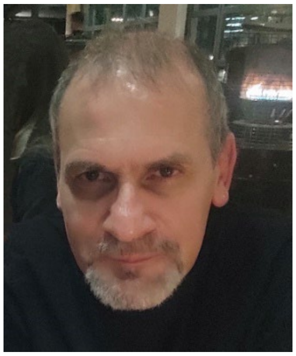
AUTHORS



Dr. Emmanuel Fokides is an Associate Professor at the Department of Primary Education, University of the Aegean, Greece. His courses focus on the educational uses of emerging technologies, virtual reality, digital storytelling, augmented reality, and serious games. Since 1994, he has been involved in a number of research projects regarding distance and lifelong learning and the educational uses of virtual and augmented reality. He is also the founder of the Emerging Technologies in Education initiative (ETiE). His work has been published in several conference proceedings, chapters in edited books, and journals. He is also the co-author of three books.

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