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RESEARCH REVIEW

3D Modelling and Printing in Teacher Education: A Systematic Literature Review

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Abstract

This systematic literature review investigates the integration of 3D modelling and printing (3DMP) into teacher education to understand current practices and propose future directions. Following PRISMA guidelines, a search was conducted across four databases (ERIC, Web of Science, Scopus, IEEE Xplore) for studies published up to 2023. Studies involving preservice teachers were included based on predefined inclusion and exclusion criteria. Content analysis was employed to examine study characteristics, and open-coded thematic analysis was conducted to identify themes related to technological, pedagogical, and content knowledge (TPACK) and to categorise the benefits, challenges, and needs described in the studies. Results from 20 selected papers indicated that 3DMP integration could enhance skill development, hands-on experience, and participant engagement but may encounter challenges associated with resource availability, time constraints, and school integration. Our findings emphasise the need for teacher education programs integrating 3DMP with a practical approach, incorporating content, pedagogical, and technological components to prepare future educators to utilise this emerging but increasingly relevant technology. Building on this study, we highlight the importance of future research to extend theoretical and practical approaches, particularly in underrepresented regions. This review offers insights for developing training programs and informs policies supporting 3DMP integration in teacher education.

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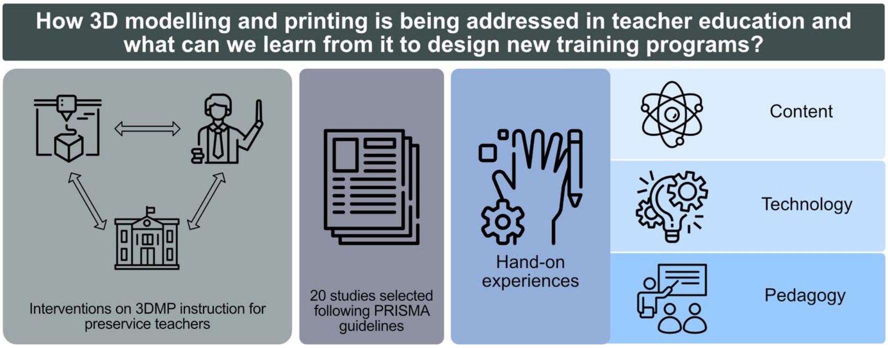
Graphical abstract



Keywords 3D modelling and printing · Teacher education · Teacher knowledge · TPACK · Educational technology · Preservice teacher

Introduction

Integrating 3D modelling and printing (3DMP) technology into education offers substantial promises but faces significant challenges. 3DMP has gathered considerable attention in recent years, leading to a growing body of research on its potential to enhance teaching and learning (Ng et al., 2022). This interest is particularly pronounced in STEM education, where 3DMP, among other things, can make abstract concepts more tangible, thereby improving student comprehension and engagement (e.g., Chien & Chu, 2018; Turgut & Uygan, 2015). Furthermore, 3DMP has shown significant potential in STEM education by fostering critical thinking, problem-solving skills, and creativity (Anđić et al., 2023; Cheng et al., 2021; Fokides & Lagopati, 2024; Levin and Verner, 2021), while also improving learning outcomes and increasing student interest in STEM careers (Cheng et al., 2021; Fokides & Lagopati, 2024). It serves as a valuable tool in STEM education by connecting engineering, technology and science, and engaging students in hands-on, iterative design processes that enhance these essential skills (Novak & Wisdom, 2018).

Nevertheless, integrating 3DMP into classroom practices presents significant obstacles, including resource limitations, teacher training, and curriculum adaptation (e.g., Anđić et al., 2023; Arslan & Erdogan, 2021). As noted by Roberts (2014), technology integration in the classroom heavily depends on teachers' abilities to include it meaningfully in instruction. Thus, teacher preparation becomes crucial in introducing technological and pedagogical changes to impact educational practices (Graham et al., 2021). Moreover, research on novice and preservice teachers' integration of technology (e.g., Stein et al., 2020; Tondeur et al., 2012) suggests that teacher education is crucial in scaffolding technology integration in preservice teachers' future practices. Therefore, research efforts on technology integration, especially 3DMP, in teacher education are increasingly significant (Novak et al., 2021). This is particularly important in STEM education, where the effective integration of 3DMP can significantly enhance learning experiences and prepare students for future STEM careers (Abu Khurma et al., 2023).

Systematic research is essential to guide the development of teacher education programs that address the barriers to integrating technology into teaching. Studies, such as that by Graham et al. (2021), suggest that these programs should facilitate the fundamental pedagogical shifts necessary for technology integration. For instance, Urbina and Polly (2017) advocate for hands-on experiences with technology through content-specific examples in teacher education, while Ruthven and Lavicza (2011) emphasise providing educators with challenging tasks to better understand and apply technological tools in teaching, improving educational practices and student learning. Nevertheless, despite our existing knowledge of technology in teacher education and the increasing volume of studies on 3DMP in education (Fig. 1), including some recent systematic literature reviews (e.g., Aslan & Celik, 2022; Pearson and Dube 2022), there is no systematic review on teacher education specifically focused on 3DMP. Moreover, there is a lack of comprehensive research on how 3DMP integration in teacher education programs can specifically address STEM education and contribute to existing knowledge in this field (Lin et al., 2018). Therefore, it is our aim with this review to investigate current initiatives and systematise the knowledge and strategies to support teacher education programs in integrating 3D modelling and printing.

As mentioned, integrating 3D modelling and printing into educational settings presents considerable challenges. As Pearson and Dube (2022) discuss, educators often find it challenging to align 3DMP projects with curriculum requirements and high-stakes assessments, leading to uncertainty about how to incorporate these technologies into their teaching practices. Additionally, Song (2021) highlights the substantial time investment required for teachers to learn new technologies,

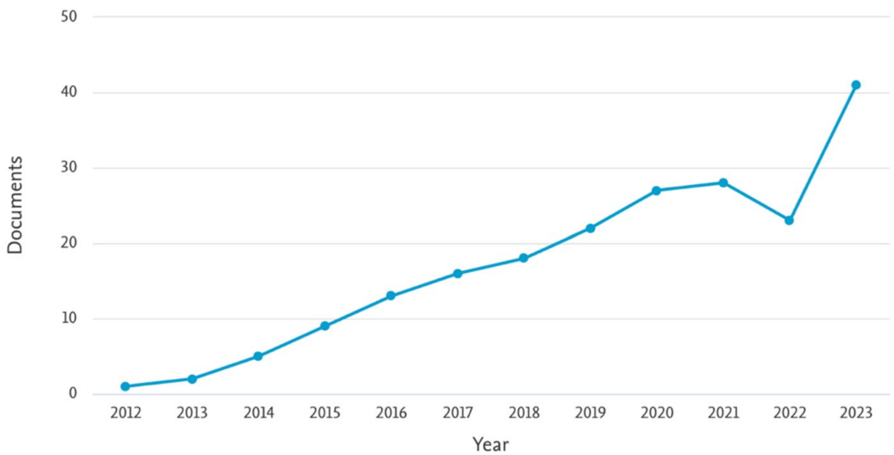


Fig. 1 The trend of publications on 3DMP and education (Scopus data). Source: Scopus search TITLE-ABS-KEY ((“3D modelling and printing “ OR “3D modeling and printing “ OR “3DMP “ OR (“3D modelling” AND “3d printing “) OR (“3d modeling “ AND “3d printing “)) AND education)

develop relevant curricula, and manage digital fabrication processes, areas that current teacher education programs frequently overlook. Regardless of the growing interest in 3DMP in education, there is a lack of systematic examinations on how teacher education programs prepare teachers to integrate 3D modelling and printing into education. To explore this, we employ the Technological Pedagogical Content Knowledge (TPACK) framework, providing a structured lens to analyse and interpret the approaches in teacher education concerning 3DMP. The following section will present and justify our decision to utilise the TPACK framework in more detail.

Theoretical Framework: TPACK for Analysing 3DMP in Teacher Education

The Technological Pedagogical Content Knowledge (TPACK) framework (Mishra & Koehler, 2006) extends Shulman's (1986) concept of pedagogical content knowledge (PCK) by incorporating technological knowledge (TK) as a key component for effective teaching with technology. TPACK is built around three primary knowledge domains: technological knowledge (TK), pedagogical knowledge (PK), and content knowledge (CK), and their intersections: technological pedagogical knowledge (TPK), technological content knowledge (TCK), and pedagogical content knowledge (PCK). At its core, TPACK represents the integration of all three domains, providing a comprehensive understanding of teachers' knowledge of integrating technology to support effective teaching (Koehler et al., 2007, 2013).

Furthermore, TPACK's widespread adoption in educational research (Schmid et al., 2024; Ortiz Colón et al., 2023; Irwanto, 2021; Willermark, 2018) makes it a suitable framework for this review. Its approach allows an analysis of how teacher education prepares educators to integrate emerging technologies such as 3D modelling and printing into their practices. By examining the interplay of TK, PK, and CK, the framework enables a holistic understanding of the strategies and challenges involved in integrating 3DMP into teacher education (Lee et al., 2022).

While other frameworks like SAMR (Substitution, Augmentation, Modification, and Redefinition) (Puentedura, 2006) and TIM (Technology Integration Matrix) (Harmes et al., 2016) offer valuable perspectives on technology integration, TPACK provides a more comprehensive approach to analysing teacher knowledge and skills. For example, while SAMR focuses on levels of technology integration, it may not fully capture the interplay between technological, pedagogical, and content knowledge required for 3DMP implementation (Hamilton et al., 2016). Similarly, TIM emphasises the learning environment but may not adequately address the specific knowledge teachers need for integrating 3DMP in various subjects.

In 3DMP, TK includes knowledge of operating and troubleshooting 3D printers, using modelling software, and managing digital fabrication processes. PK involves designing instructional strategies incorporating 3DMP, such as project-based learning or inquiry-based approaches. CK aligns 3DMP with subject-specific curricula, such as teaching spatial geometry principles in mathematics or structure stability in engineering education. Integrating these domains is necessary for addressing the challenges presented earlier, including resource limitations, teacher training, and curriculum adaptation (Ulbrich et al., 2024; Araújo Filho & Gitirana, 2022).

Furthermore, TPACK is particularly valuable for this review because it provides a common theoretical language for comparing and synthesising diverse studies on 3DMP in teacher education. Its focus on the intersections of technology, pedagogy, and content aligns well with 3DMP's multifaceted nature (Ulbrich et al., 2024; Yi et al., 2016). It supports identifying gaps and opportunities in current teacher preparation programs. Using TPACK, this review will conduct a comprehensive and theoretically grounded analysis of teacher education programs to integrate 3DMP into teachers' practices.

The application of TPACK to 3DMP in teacher education extends the framework's use by highlighting the challenges and opportunities presented by this emerging technology. For instance, the rapid evolution of 3D printing technology requires teachers to continually update their technological knowledge while considering how these advancements can improve content delivery and pedagogical approaches (Trust & Maloy, 2017). The confluence between a fast-evolving technology and established educational practices offers an interesting context for examining the specialised knowledge teachers need to implement 3DMP.

In conclusion, TPACK provides a strong and flexible framework that aligns well with the complex nature of 3DMP integration in education. Its broad approach, proven usefulness in analysing technology integration (Ortiz Colón et al., 2023; Araújo Filho and Gitirana, 2022), and widespread adoption in educational research make it a good choice for this systematic literature review. By applying TPACK to the specific context of 3DMP in teacher education, this study contributes to the broader understanding of teacher preparation for technology integration in education.

Rationale for the Review and Research Questions

Our systematic review examines the integration of 3D modelling and printing in teacher education, starting from the growing body of studies on implementing 3DMP (e.g., Pearson & Dube 2022; Ford & Minshall, 2019). Teacher education refers to the types of degrees held, including advanced degrees, and is a comprehensive process that equips future teachers with the necessary knowledge and skills to implement that knowledge efficiently in practice (Darling-Hammond, 2006). Although researchers frequently discuss the educational benefits of 3DMP, their focus is predominantly on students rather than on how teachers prepare to integrate this technology into their classrooms. For example, Aslan & Celik̆ (2022) found that only 11 out of 111 reviewed studies centred on educators. This focus overlooks the pedagogical and content knowledge teachers require to manage 3DMP effectively (Trust & Maloy, 2017). Successful implementation needs to address this gap by embedding sound pedagogical practices and robust content knowledge into teacher education programs (Sullivan & McCartney, 2017). While some studies introduce preservice teachers to 3DMP (e.g., Carmona-Medeiro et al., 2021; Novak & Wisdom, 2018), empirical research on systematically incorporating 3D modelling and printing into teacher preparation programs remains insufficient (Verner & Merksamer, 2015).

Expanding on and complementing existing studies, we investigate how teacher education programs address the technological, pedagogical, and content dimensions when preparing educators to use 3DMP. While researchers widely adopt the TPACK framework to understand teachers' knowledge for technology integration in education (e.g., Schmid et al., 2024; Ortiz-Colon et al. 2023), limited explorations of its application in the context of 3DMP within teacher education programs have been conducted. Therefore, we examine how teacher education programs align with the dimensions of the TPACK framework, identifying where their primary focus lies and how they equip teachers to incorporate 3DMP into their professional practices.

Alongside characterising the field and examining the focus of these programmes, we find it essential to understand the practical outcomes of the training initiatives documented in the literature. Implementing 3DMP in teacher education presents unique opportunities and challenges; nevertheless, researchers still need to systematically analyse the reported benefits, difficulties, and needs. This review aims for a comprehensive understanding of these factors, providing insights to guide the development of future teacher education programmes centred on 3D modelling and printing. We summarise the purpose of this review with three research questions:

RQ1: What are the characteristics of the study conducted on 3DMP in teacher education (including publication countries, years, types, study designs, educational levels, sample sizes, and theoretical frameworks)?
RQ2: How are the technological, pedagogical, and content knowledge addressed in the studies conducted on 3DMP in teacher education?
RQ3: What are the benefits, challenges, and needs associated with the design and implementation of teacher education programs with 3DMP?

By answering these research questions, we address the presented issues by analysing current practices and trends in integrating 3DMP into preservice teacher training. We examine the technological, pedagogical, and content knowledge required for effective implementation, identify associated benefits and challenges, and offer actionable insights to support the integration of 3DMP into teacher preparation programs.

Materials and Methods

In order to answer the research questions, we follow the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework (Page et al., 2021), ensuring rigour and transparency. A systematic review is a rigorous method that involves addressing clearly formulated questions by systematically identifying, selecting, and critically appraising relevant research and analysing data from the included studies (Moher et al., 2009). It seeks to comprehensively search for, appraise, and synthesise research guided by explicit inclusion and exclusion criteria (Grant & Booth, 2009). This approach enhances the reliability and reproducibility of the findings, providing a thorough synthesis of evidence (Cohen et al., 2013). This study offers a comprehensive approach to understanding 3DMP in teacher education

Table 1 Inclusion and exclusion criteria

Inclusion criterion	Exclusion criterion
IC1: Studies published in peer-reviewed journals or conference proceedings	EC1.1: Studies published as conference abstracts, opinion pieces and non-peer-reviewed literature EC1.2: Review articles
IC2: Studies published between 2008 and 2023	EC2: Studies published before 2007 or in 2024
IC3: Studies published in English	EC3: Studies not published in English
IC4: Studies analysing an implementation of teacher training in 3D modelling or 3D printing	EC4.1: Studies not focused on teacher education EC4.2: Studies not focused on 3D modelling or 3D printing EC4.3 Studies without an implementation

Table 2 Search string used in searching for papers from the database

Databases	Search string
ERIC	abstract: ("3D modeling" OR "3D modelling" OR "3D printing" OR "additive manufacturing") AND abstract: ("teacher education" OR "teacher training" OR "pre-service teacher" OR "preservice teacher" OR "pre service teacher" OR "prospective teacher")
WoS	("3D modeling" OR "3D modelling" OR "3D printing" OR "additive manufacturing") AND ("teacher training" OR "pre-service teacher" OR "teacher education" OR "preservice teacher" OR "pre service teacher" OR "prospective teacher")
Scopus	TITLE-ABS-KEY (("3D modeling" OR "3D modelling" OR "3D printing" OR "additive manufacturing") AND ("teacher education" OR "teacher training" OR "pre-service teacher" OR "preservice teacher" OR "pre service teacher" OR "prospective teacher"))
IEEE Xplore	abstract: ("3D modeling" OR "3D modelling" OR "3D printing" OR "additive manufacturing") AND abstract: ("teacher education" OR "teacher training" OR "pre-service teacher" OR "preservice teacher" OR "pre service teacher" OR "prospective teacher")

by performing a systematic literature review guided by PRISMA. In the following subsections, we describe the eligibility criteria, information sources, search strategy, selection process, data collection, data items, and synthesis process.

Data Identification and Screening

The criteria were established to ensure a comprehensive literature screening, encompassing factors such as publication year and research aim. Based on these criteria and the proposed research questions, we adopted the inclusion criteria (IC) and exclusion criteria (EC) detailed in Table 1.

In March 2024, we conducted the search in four online databases: Education Resources Information Center (ERIC), Web of Science (WoS), Scopus, and IEEE Xplore. These databases were selected for their high-quality indexing standards and high international reputation. Following the definition of the research problem and questions, a unique search string was defined for each database, utilising the same keywords (Table 2). The search strings were refined in several iterations to maximise the reach within the scope of the review and contain a combination of keywords and phrases, including “3D modelling”, “3D printing”, and “teacher education”.

Following the completion of the search for pertinent literature in the databases, the filter option was employed to restrict the publication year, publication type, and language. Documents were selected based on the predefined eligibility criteria (Table 1). The documents were selected following the procedures outlined by PRISMA (Page et al., 2021). We detected 288 possible articles from the specified databases in the identification process. Following the removal of 13 duplicated articles, the screening procedure commenced (Fig. 2) utilising the Rayyan app (Ouzzani et al., 2016). Upon retrieving the documents from the databases, two authors conducted a preliminary screening of all papers’ titles, abstracts, and keywords. This process involved classifying each article as included or excluded based on the eligibility criteria established for the screening process. The authors

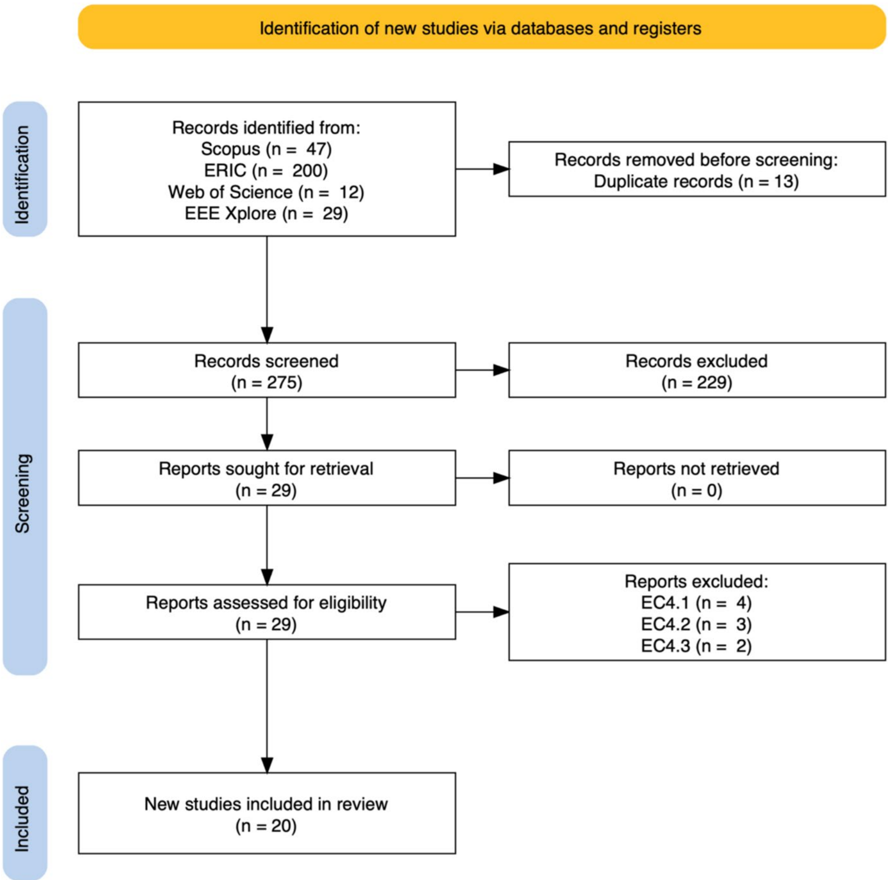


Fig. 2 The process of selecting articles follows the PRISMA framework (Page et al., 2021)

compared their respective findings and discussed until a consensus was reached. This resulted in the identification of 29 articles.

Data Monitoring

Subsequently, the full text of the selected documents was monitored throughout the identification and screening process. Twenty articles (see Appendix 1) were selected for inclusion in the systematic review.

During data monitoring, all authors prepared a coding sheet to collect data from articles. This included the name of the authors, the title of the article, the publication year, the document type, the study context, the methodology of the study, educational level, the theoretical approaches used in the study, the implementation process, the barriers and enablers, the key findings, recommendations for future studies and syllabi (if available). Two authors randomly selected two articles and reviewed them according to the coding sheet. They compared their results and resolved any disagreements through in-depth discussion. Finally, they revised the review protocol. This process was repeated three times until a consensus was reached. The revised review protocol was implemented, and no issues were identified during the review process. Finally, arriving at the 20 included documents, as illustrated in Fig. 2.

Although this study focuses on teacher education, it is important to note that some reviewed studies include preservice teachers alongside other participant groups (e.g., educators and in-service teachers). However, the review primarily centres on studies involving preservice teachers. The authors included all studies with preservice teacher participants to ensure a comprehensive perspective, even when they also involved other groups. In some cases, studies focusing primarily on related participant groups provided insights that were relevant to preservice teacher education and were therefore included. The authors carefully considered including these studies through several discussion sessions. During these sessions, all authors thoroughly examined each study and critically discussed its contributions to preservice teacher education. This rigorous evaluation ensured that every included study offers valuable insights into preservice teacher education, justifying its inclusion in the review.

Data Synthesis

This review involved the analysis of 20 studies, and the process primarily consisted of a screening and coding procedure. Initially, the relevant studies were screened twice by the authors and examined in-depth. A coding scheme was subsequently developed, and the codes were organised around three main categories based on our research questions:

- Study characteristics and research methodologies (Research Question 1)
- Identification of the technological, pedagogical, and content knowledge addressed in the reviewed studies (Research Question 2)

- Identification of the benefits, challenges, and needs related to the design and implementation of the reviewed interventions (Research Question 3)

The data were systematically analysed according to the research questions. For Research Question 1, content analysis was employed to define the studies' general characteristics across seven categories: publication year, type, country, study design, educational level, sample size, and theoretical or conceptual frameworks. This process was facilitated by a coding sheet developed during the data monitoring phase. For Research Questions 2 and 3, all 20 studies were reviewed by three researchers, focusing on the findings, discussion, and conclusion sections as primary data. Open-coded thematic analysis (Braun & Clarke, 2006) was conducted to identify themes and link them to the proposed framework. Given the qualitative nature of most studies, open coding provided the flexibility to categorise the broad range of results and conclusions.

The reviewed studies were collaboratively analysed using a shared Atlas.ti project. Two authors independently coded the data, selecting relevant sentences and identifying commonalities designated as representative data. Discrepancies were discussed, irrelevant data was excluded, and overlapping codes were merged into a refined coding scheme. A joint analysis of 25% of the studies established initial codes. As new codes emerged, they were discussed and added to the scheme. For Research Question 2, codes were linked to the TPACK framework (Mishra and Koehler, 2006) to address its dimensions. Co-occurrence analysis was conducted to identify patterns and relationships between themes, mapping their frequency and interconnections.

For Research Question 3, the authors individually categorised the identified benefits, challenges, and needs, followed by collaborative review and discussion to reach a consensus. This iterative process allowed us to classify various results, identify representative data, and link findings to relevant theoretical frameworks and literature (Bingham & Witkowsky, 2022), ensuring a comprehensive analysis.

Results

This section presents the findings of our systematic literature review on 3D modelling and printing in teacher education, addressing the study's research questions. We begin by providing an overview of the trends and characteristics of the reviewed studies, including the distribution of publications by country, the methodologies employed, and the focus on different educational levels. The analysis further explores the integration of 3DMP within teacher education, examining the extent to which various studies incorporate theoretical or conceptual frameworks. Through this exploration, we aim to uncover prevailing patterns and identify critical areas for future research and practice. The following subsections will detail these aspects, offering insights into the global landscape of 3DMP in teacher education and its implications for developing new training programs.

Overview of Review Studies on 3D Modelling and Printing in Teacher Education (RQ1)

To present the characteristics of the reviewed studies on 3D modelling and printing in teacher education, we conducted a content analysis of the 20 included studies. In this section, we have addressed the initial research question of the study, namely the characterisation of the field's landscape, through the distribution of the number of publications by year, publication type, country, study design, educational level, sample size, and the use of theoretical or conceptual frameworks.

The integration of 3DMP in teacher education has been a topic of growing interest on a global scale. As illustrated in Fig. 3, the USA assumed leadership in the number of publications, with 40% of the studies, followed by Turkey (25%). China (15%), Israel (10%), Spain (5%), and Greece (5%) have collectively contributed a relatively small number of papers to the field of 3D modelling and printing in teacher education. No publications were identified from Africa or South America.

Figure 4 illustrates the number of publications related to 3DMP in teacher education, which fluctuated upward from 2015 to 2023. A search of relevant publications published in the last 15 years revealed no publications before 2015. The year 2021 saw the highest number of studies ($n = 5$) conducted in this field.

In this review, we analysed the sample characteristics of the included studies (Table 3), categorising participants based on the authors' descriptions. While our primary focus is on preservice teachers, we also included studies involving in-service teachers (e.g., Song, 2018; Wan & Ivy, 2021), as teacher education can encompass both groups due to curriculum and policy contexts. Table 3 details the sample sizes, with most studies (35%, $n = 7$) involving 21–50 participants. Additionally 20% ($n = 4$) included 11–20 participants, 15% ($n = 3$) had fewer than 10 participants, and 15% ($n = 3$) included more than 51 participants. Notably, Carmona-Medeiro et al. (2021) conducted a more extensive study with 203 preservice teachers, using a SWOT analysis to assess the effectiveness of Sketchup software in teacher training.

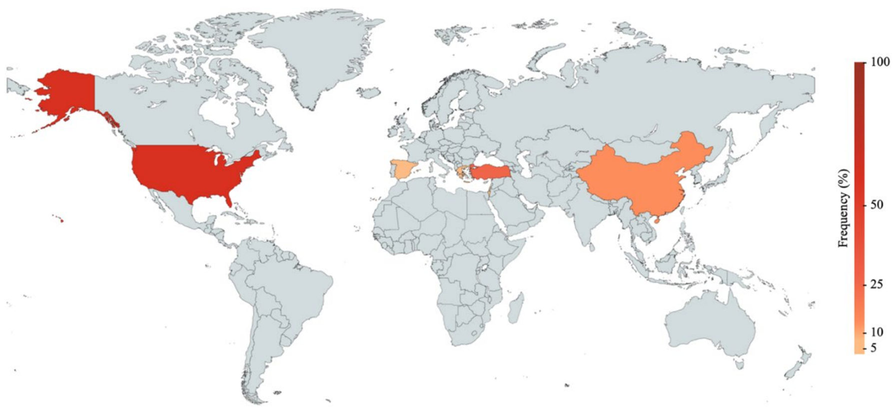


Fig. 3 Frequency of publications by countries (in percentage)

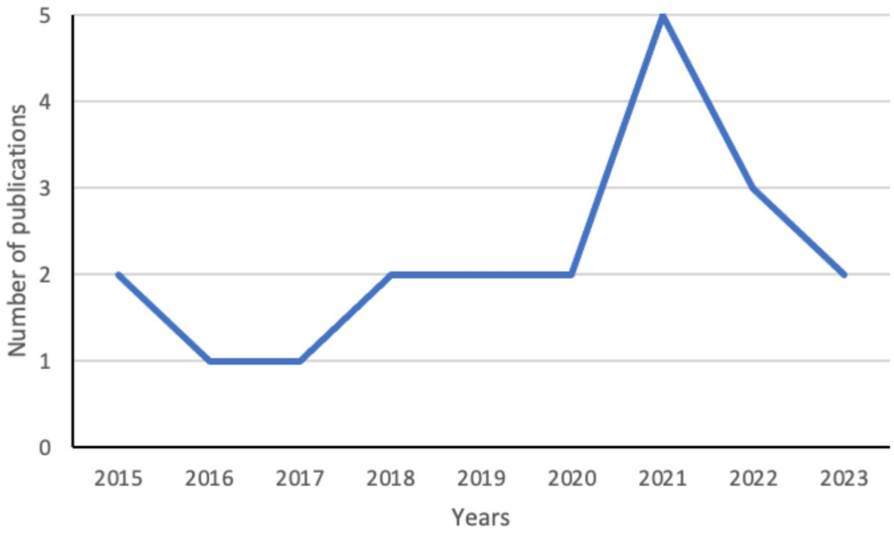


Fig. 4 Publication years

Table 3 Educational level and sample size

Sample size*	Frequency (n)	Percentage (%)
1–10	3	15
11–20	4	20
21–50	7	35
51–100	2	10
101 +	1	5

*Three papers did not mention the sample size

To understand the methodologies researchers employed in conducting the studies, we also examined the methodologies employed in the reviewed studies, including research design and data analysis (Table 4). The results indicated that the qualitative design was the most frequently used (65%), reflecting the dominance of case studies and exploratory qualitative studies in this field. This alignment emphasises the exploratory nature of research on 3DMP in teacher education, where researchers

Table 4 Research design

Research design	Frequency (n)	Percentage (%)	Examples studies
Qualitative	13	65%	Ucgul and Altiok (2023), Sullivan and McCartney (2017)
Quantitative	1	5%	Benzer and Yildiz (2019)
Mixed	6	30%	Novak and Wisdom (2018), Song (2020)

choose qualitative methods to capture insights into the implementation, challenges, and opportunities associated with integrating emerging technologies.

The reviewed studies employed diverse data collection methods, including interviews (e.g., Arslan & Erdogan, 2021; Wargo et al., 2022), field notes (e.g., Schelly et al., 2015; Wargo et al., 2022), questionnaires (e.g., Alimisi et al., 2020; Levin & Verner, 2021), and observations (e.g., Alimisi et al., 2020; Sullivan & McCartney, 2017). Many studies combined these methods to better understand 3DMP in teacher education, such as Wargo et al. (2022), which used interviews and field notes. Some studies employed mixed methods, while only one study relied solely on quantitative data (Benzer & Yildiz, 2019). The methods employed can be grouped into two categories: self-reported methods, such as interviews, questionnaires, and reflections, which capture participants' perceptions and experiences, and observational methods, such as field notes and classroom observations, documenting interactions and program implementation. This mix of methods highlights the exploratory nature of the research, prioritising teachers' experiences and practical challenges over quantifiable outcomes. The methodological choices emphasise understanding how preservice teachers engage with 3DMP and its integration into teaching. While these approaches provide valuable insights, they also underscore the need for future studies to develop structured interventions systematically and evaluate broader impacts.

To gain insight into the prevailing discipline focus on 3D modelling and printing in teacher education, we examined the included studies, looking for specific mentions of a discipline. In the case of the studies we classified as "Others", the focus was unclear, as they worked with preservice teachers at primary and early childhood education levels. As illustrated in Fig. 5, science (24%) represents the most prevalent discipline in utilising 3DMP. The next most prevalent disciplines are technology (22%) and mathematics (22%), followed by arts (8%).

Finally, we performed a content analysis to examine the theoretical and conceptual frameworks. The findings revealed that out of 20 review studies, only 11 explicitly incorporated any theoretical or conceptual framework. Of the studies that included a framework, Technological Pedagogical Content Knowledge (TPACK) was used most frequently ($n = 6$). In a limited subset of the studies, design framework ($n = 1$), Fred Rogers Centre Framework ($n = 1$), constructionism ($n = 2$), mathematical modelling ($n = 1$), Justi and Gilbert 's educational framework ($n = 1$), and reader response theory ($n = 1$) were used as frameworks.

Co-Occurrence Analysis of TPACK Dimensions and Thematic Codes (RQ2)

To explore the interconnections between different knowledge domains and thematic aspects of 3D modelling and printing in teacher education, we conducted a co-occurrence analysis utilising Atlas.ti. The results are presented in Fig. 6, which maps the frequency of co-occurrences between the core TPACK dimensions (Content Knowledge, Pedagogical Knowledge, and Technological Knowledge) and thematic codes that appeared more than 20 times in our review.

Figure 6 visually represents these relationships through a Sankey diagram (Schmidt, 2008), highlighting the connections between TPACK dimensions and

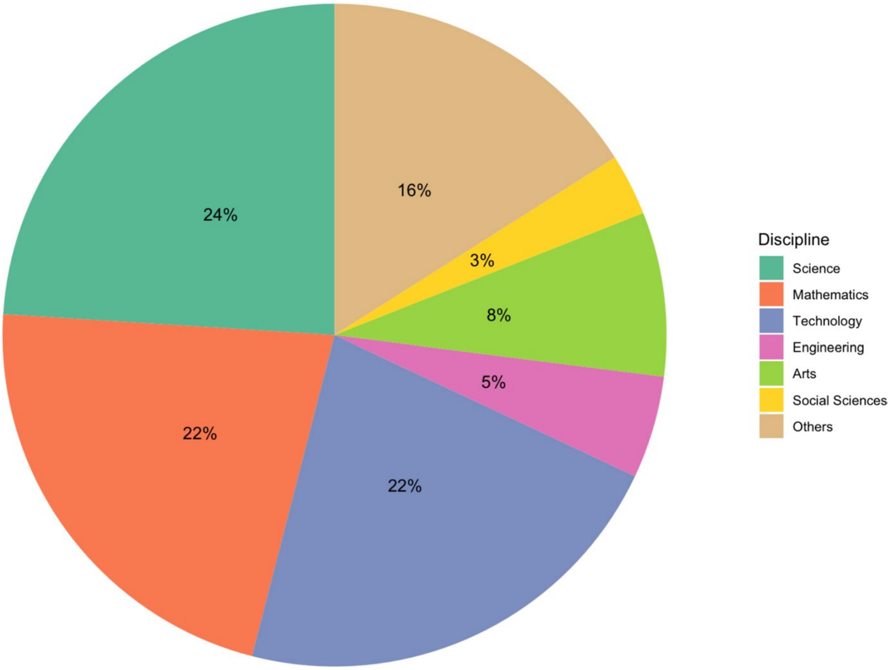


Fig. 5 Discipline focus of the studies (in percentage)

thematic codes. The nodes on the left-hand side represent the TPACK dimensions (CK, PK, and TK), while the right-side nodes represent the thematic codes identified in our analysis (e.g., skill development, hands-on experience, and self-efficacy). The bands connecting the nodes display the frequency of co-occurrence between a knowledge domain and a thematic code, with thicker bands indicating more frequent connections. The colour-coding of the bands reflects the TPACK dimensions, allowing us to track the flows and identify co-occurrence patterns visually. For example, the prominence of connections between CK and Skill Development highlights the importance of this theme in content knowledge. Likewise, PK and TK demonstrate strong ties to Hands-On Experiences and Self-Efficacy, reflecting their pedagogical and technological significance.

An analysis of the co-occurrence highlights that skill development (e.g., Benzer & Yildiz, 2019; Carmona-Medeiro et al., 2021), school integration (e.g., Song, 2018; Verner & Merksamer, 2015), and hands-on experiences (e.g., Ng & Chan, 2021; Wan & Ivy, 2022) are crucial components of teacher education programs in content knowledge (CK), pedagogical knowledge (PK), and technological knowledge (TK). These elements appear closely interconnected, emphasising the need for a holistic approach to their integration. Teachers need to combine and apply these knowledge domains, which can be achieved by enhancing their skills, integrating them into the school environment, and providing practical experiences.

While self-efficacy relates to teachers' CK, PK, and TK, there is often a greater emphasis on PK and TK. This focus aligns with the goals of many teacher

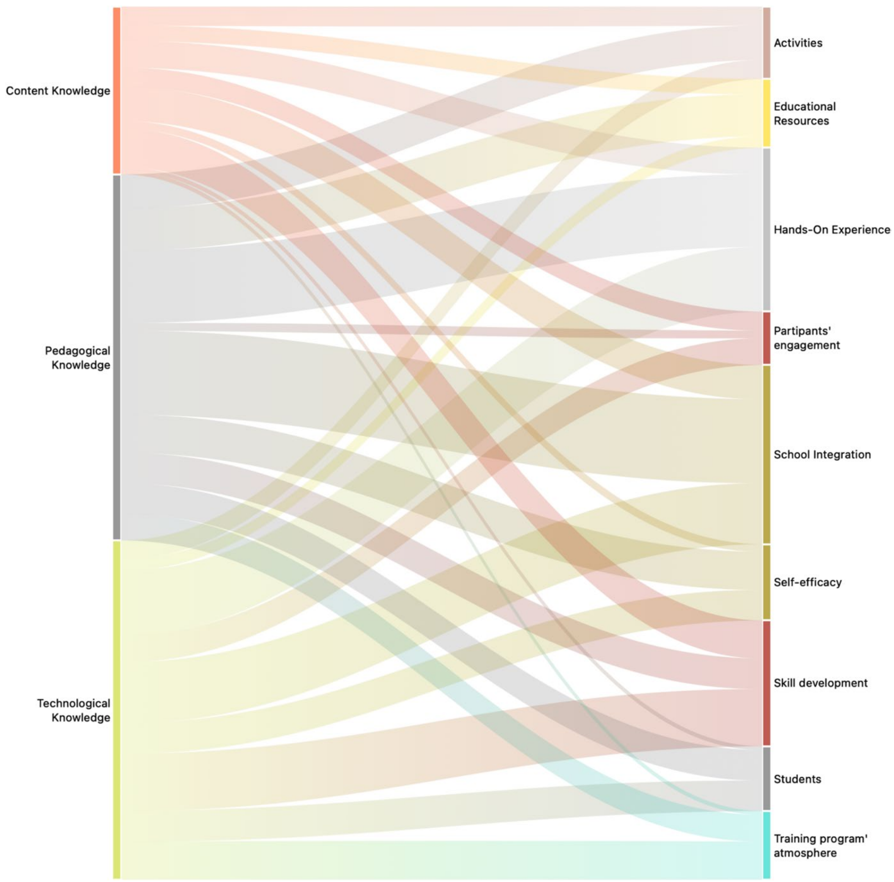


Fig. 6 Sankey diagram of the co-occurrence analysis

preparation programs, which provide examples of students' work and school integration to enhance participants' pedagogical and technological knowledge (Asempapa & Love, 2021). However, these programs may have a limited impact on participants' content knowledge. Consequently, while teachers feel confident in their ability to teach and integrate technology, gaps in CK might persist (Karaismailoglu & Yildirim, 2024; Guler et al., 2019). Addressing this imbalance through a more integrated approach that includes targeted content knowledge resources could better support teachers in delivering comprehensive instruction. Integrating educational resources, hands-on experiences, and activities that balance CK, PK, and TK can enhance teacher preparation (Alimisi et al., 2020). While technology knowledge is central to these 3DMP programs, preservice teachers face challenges simultaneously mastering content, pedagogical methods, and strategies for fostering student learning (Karaismailoglu and Yildirim, 2024; Song, 2018). By addressing all three areas, educational institutions can ensure teachers are well-prepared to meet diverse classroom needs and improve outcomes. Table 5 summarises the TPACK dimensions and thematic connections of our review.

By addressing these dimensions, teacher education programs can better prepare educators to integrate 3DMP into their teaching practices, ultimately enriching their students' experiences. The analysis offers insights into the topic, informing the interconnectedness of different knowledge domains and thematic elements in teacher education for 3DMP.

Co-occurrence Analysis of Reported Benefits, Challenges, and Needs (RQ 3)

Building on our previous analysis, which explored the interconnections between TPACK dimensions and various emerging themes, we further examined the reported benefits, challenges, and needs of 3DMP in teacher education. The results, presented in Table 6, reveal significant insights into how different aspects contribute to the overall success of these training programs.

In the following sections, we present a detailed view of the benefits, challenges, and needs of the training programs discussed in the studies. While the categorisation may appear subjective, it aligns with the overarching patterns observed in the results. Notably, most themes are referenced in at least two identified categories, showing the complexity of including emerging technologies in teacher education.

Table 5 TPACK dimensions and related emerging themes

TPACK dimension	Thematic connections
Content knowledge	This dimension primarily co-occurs with themes such as *skill development (n = 10)*, *school integration (n = 9)*, and *hands-on experience (n = 7)*. These connections indicate that a strong foundation in subject-specific content is closely linked to the practical aspects of teaching, including the implementation of activities and utilisation of educational resources to enhance learning experiences
Pedagogical knowledge	This dimension links significantly with *school integration (n = 22)*, *hands-on experience (n = 19)*, *educational resources (n = 11)*, *self-efficacy (n = 10)*, *activities (n = 9)*, *students (n = 8)*, and *skill development (n = 8)*. These associations highlight the importance of pedagogical strategies in fostering engagement, integrating new technologies into school curricula, and developing teachers' self-efficacy and skills. This suggests that pedagogical knowledge is essential for successfully incorporating 3D modelling and printing into educational contexts
Technological knowledge	This dimension is strongly associated with *hands-on experience (n = 17)*, *school integration (n = 16)*, *skill development (n = 15)*, *the training program's atmosphere (n = 10)*, *students (n = 8)*, and *participants' engagement (n = 7)*. The co-occurrence with *students* indicates a direct impact of technological proficiency on student outcomes. Additionally, the link with skill development underscores teachers' need for a robust understanding of technological tools to facilitate skill acquisition. The connection with the training program's atmosphere suggests that the technological aspect also plays a role in shaping the overall learning environment

Table 6 Co-occurrence of benefits, challenges and needs with the emerging themes

Themes	Benefits (N=169)	Challenges (N=71)	Needs (N=63)
Accessibility (N=20)	5	12	2
Activities (N=30)	12	4	10
Educational resources (N=27)	8	0	15
Hands-on experience (N=42)	17	2	13
Interdisciplinary (N=9)	7	0	2
Participants ' active learning (N=13)	12	0	1
Participants ' engagement (N=33)	31	0	3
Pedagogical approaches (N=20)	11	4	1
Physical and digital connection (N=7)	8	0	0
School integration (N=35)	12	6	8
Self-efficacy (N=31)	18	8	1
Skill development (N=43)	33	3	5
Students (N=24)	16	2	1
Time (N=15)	0	11	4
Training program's atmosphere (N=34)	14	3	8

Main Benefits Of the Reviewed Training Programs

Skill development is the most frequently reported benefit (33), indicating that these programs enhance teachers ' 3DMP abilities and other general competencies. Skill development is related to all TPACK dimensions (Table 5). The skills mentioned are communication, critical thinking, life-long learning, spatial thinking, analytical thinking, and problem-solving (e.g., Levin and Verner, 2021; Benzer & Yildiz, 2019; Guler et al., 2019; Schelly et al., 2015). Some studies have indicated that the design of teacher education programs significantly impacts teachers' skills (e.g., Asempapa & Love, 2021; Benzer & Yildiz, 2019). Additionally, some studies have employed qualitative research methods, such as interviews, to assess the impact of training on preservice teachers' skills (e.g., Guler et al., 2019). However, skill development is also noted as a challenge (3) and a need (5), suggesting that while many preservice teachers improve their skills, a significant subset still faces difficulties, underscoring the necessity for ongoing support and tailored training strategies (e.g., Sun and Okojie, 2020).

Participants ' engagement, a key benefit (31), demonstrates that the training programs successfully motivate teachers. However, it is also reported as a need in three studies, which shows that not all programs achieve this uniformly. Our previous findings indicate that participants' engagement is related to their technological knowledge (see Table 4). This suggests that designing a teacher education program according to participants' technological knowledge may affect their engagement.

Hands-on experience (17) allows teachers to apply what they learn directly. Nevertheless, its occurrence as a challenge (2) and a need (13) suggests that while beneficial, its implementation may be inconsistent. It is recommended that participants be provided with opportunities for hands-on experiences to learn how to use 3DMP in real classroom practices and to guide their students. In addition, it is suggested that teachers become the first learners to create, design, and produce materials before their students and integrate them into the curriculum (Ng & Chan, 2021; Wan & Ivy, 2022). Therefore, ensuring more hands-on opportunities is crucial for maximising the benefits of these training initiatives.

Self-efficacy was presented as a benefit in several studies (18). Preservice teachers have indicated that they feel confident in their ability to utilise 3DMP following attendance at a workshop (Ucgul and Altiok, 2023; Novak & Wisdom, 2018). However, some studies (e.g., Alimisi et al., 2020) have identified challenges associated with its implementation. If they perceive it as futile, it is challenging to alter preservice teachers' confidence in utilising 3D modelling and printing in their classrooms (Arslan & Erdogan, 2021). One paper (Sullivan & McCartney, 2017) identified self-efficacy as a requisite because their participants indicated they would be confident if they could gain experience using 3DMP in a real classroom setting.

Moreover, consideration of students in training future teachers is reported to be a significant benefit (16). This underscores the positive impact of 3D modelling and printing on student learning experiences. Understanding the complexity of school integration, pedagogical approaches, and the effect on students is crucial for improving the outcomes of teacher education programs on 3DMP.

Challenges for the Integration of 3DMP in Teacher Education

Accessibility is reported as a challenge (12) and a need (2), highlighting barriers related to the availability and reach of training programs and technologies. The term "accessibility" describes the ability to utilise technological tools in the classroom for learning and teaching purposes. Some studies have indicated that preservice teachers need more resources to continue their development following the training and have limited classroom access to integrate these technologies into the curriculum (e.g., Alimisi et al., 2020). These barriers include cost (e.g. Ucgul and Altiok, 2023; Arslan & Erdogan, 2021; Carmona-Medeiro et al., 2021; Song, 2018), language difficulties associated with software (e.g. Ucgul and Altiok, 2023), technological access (e.g., Arslan & Erdogan, 2021; Wargo et al., 2022), resource unavailability (e.g., Song, 2020; Wargo et al., 2022), time limitations (e.g., Arslan & Erdogan, 2021), complexity in classroom use (e.g., Carmona-Medeiro et al., 2021; Song, 2018), and challenges to school implementation (e.g., Song, 2018).

Similarly, time is noted exclusively as a challenge (11) and a need (4), indicating that participants struggle to find sufficient time within their schedules to engage in training programs. Moreover, should they identify a suitable time frame within their schedules, becoming acquainted with the technologies in question is lengthy, encompassing integration and incorporation (e.g., Alimisi et al., 2020; Wan & Ivy, 2021). Furthermore, printing is also a time-consuming process that affects the workshop (e.g., Wan & Ivy, 2021). The design of a 3D model necessitates the utilisation of three-dimensional thinking and spatial ability, resulting in a prolonged design process during the workshop (e.g., Song, 2018). Time is a significant challenge not only in the context of training but also in integrating these skills within the school curriculum. Future teachers and students may also encounter a similar barrier in the classroom. This issue is compounded by the demands of their regular responsibilities, making it difficult for them to dedicate adequate time to learning 3D modelling and printing and to allocate time in their daily teaching to include 3DMP. Addressing these logistical challenges ensures that all preservice teachers benefit from these programs.

Needs of the Training Programs Reported in the Studies

Educational resources refer to any curriculum material that participants can use in their teaching practice, such as lesson plans, activities, materials, student worksheets or teacher guidelines. Participants attending training generally shared that it would be better if they had an opportunity to access free and open educational resources after the training sessions either to use in their classroom or to help them design a new activity (e.g., Arslan and Erdogan, 2021; Alimisi et al., 2020). While highlighted as a benefit (8), educational resources are even more frequently reported as a need (15). This discrepancy suggests a gap between the resources provided and what preservice teachers feel is necessary. Addressing this gap by enhancing the availability and quality of resources is a necessity that can significantly empower future teachers.

The training program's atmosphere is beneficial (14) but also reported as a challenge (3) and a need (8). This highlights that while a positive atmosphere is advantageous, creating a conducive learning environment is essential but only sometimes achieved. Emphasising a supportive, communicative and collaborative atmosphere can enhance program success (e.g., Schelly et al., 2015). Participants generally reported that learning from other participants or discussions with other participants and trainers helps motivate them to attend the training and support their learning (Sullivan & McCartney, 2017; Verner & Merksamer, 2015). Some papers reported that participants need to be part of a group to complete the task, support from a mentor and guide to overcome difficulties, and feedback or review of their work (e.g., Wan & Ivy, 2021, 2022).

School integration stands out as a theme that is simultaneously a benefit (12), challenge (6), and need (8), reflecting the complexity of embedding 3DMP into school curricula. School integration refers to the integration of technology into real classrooms. Successful integration can enhance educational practices and engagement, as evidenced by its benefits. Most studies argue that training programs are essential in connecting technological skills with classroom practices (e.g., Sun and Okojie, 2020; Verner & Merksamer, 2015). In addition, several papers highlighted the importance of school integration as part of a teacher education program to improve preservice teachers ‘ skills in pedagogical methods and curriculum adaptation (e.g., Song, 2018). However, some papers reported challenges to doing this, such as cost, time, equipment, and curriculum (e.g., Alimisi et al., 2020; Ucgul & Altiok, 2023). The challenges highlight the difficulties in aligning new technologies with existing school structures and resources. The frequent mention of school integration as a need indicates that more structured support and planning are essential for smoother implementation.

When the authors connect school integration and pedagogical approaches, they generally emphasise the pedagogical methods in the real classroom (e.g., Verner & Merksamer, 2015; Wargo et al., 2022). Pedagogical approaches help preservice teachers explain their pedagogical and technological knowledge to integrate technology into their teaching practice. It is crucial to create a learning environment for participants to improve their skills, support them in applying their knowledge and enhance the lesson by incorporating 3DMP (e.g., Song, 2021; Novak & Wisdom, 2018). Many papers reported that pedagogical approaches are a benefit (11) of a teacher education program as they link educational goals and teaching methods (e.g., Wan & Ivy, 2022). On the other hand, it can be a challenge (4) if the educational goals are unclear to the participants (e.g., Alimisi et al., 2020). These findings highlight the importance of appropriate teaching methods when using 3D technologies, although adapting these methods to new tools can be difficult.

Other Significant Aspects of the Training Interventions

Activities in teacher education programs for 3D modelling and printing serve as a general umbrella, encompassing various aspects that can be perceived as benefits, challenges, or needs, depending on their characteristics. The term *activity* describes an educational resource, materials, tools, or experiments made available to participants during training. Practical activities that engage participants in active learning, facilitate physical and digital connections, and incorporate interdisciplinarity are particularly beneficial for training outcomes. For instance, activities identified as beneficial (12) frequently comprise interactive and hands-on components that actively engage preservice teachers in learning (e.g., Alimisi et al., 2020), facilitating a more profound understanding of learning and technology utilisation (e.g., Alimisi et al., 2020; Arslan & Erdogan, 2021) and skill acquisition (e.g., Benzer & Yildiz, 2019; Sullivan & McCartney, 2017). However, activities lacking these qualities can become challenges (4) or unmet needs (10), indicating a need for better-designed training activities.

It was observed that the active learning of participants was a crucial element that contributed to the success of the activities. As evidenced by the benefits reported (12), preservice teachers are more likely to retain information and apply new skills when actively involved in their learning process. Schelly et al. (2015) assert that participants engage actively through designing and printing models associated with physical objects. The interconnection between the physical and digital worlds, as evidenced by its correlation with the enumerated benefits (8), is pivotal. These connections facilitate the integration of 3DMP technologies into pedagogical practices, combining physical, hands-on experiences with digital tools and resources (e.g., Arslan & Erdogan, 2021), promoting visual and spatial thinking (e.g., Karaismailoglu and Yildirim, 2024), and motivating participants to engage with the training (e.g., Ucgul and Altiok, 2023). Conversely, activities devoid of these attributes may prove problematic if they lack discernible educational objectives (e.g., Ucgul and

Altiok, 2023; Alimisi et al., 2020) or exhibit a lack of cognitive demands on participants (e.g., Asempapa and Love, 2021).

Incorporating interdisciplinary approaches enhances the quality of training activities by enabling educators to establish linkages between different subject areas and utilise 3D technologies in multiple settings. It is recommended that mathematical modelling be taught through 3D printing in the context of mathematics and science education as a STEM or STEAM learning experience (e.g., Asempapa and Love, 2021; Schelly et al., 2015). Furthermore, Verner and Merksamer (2015) observed that incorporating engineering content and collaboration with industrial partners can facilitate the development of technology-focused pedagogical skills among future educators. Such methodologies have been demonstrated to enhance preservice teachers' attitudes towards integrating technology in the classroom (Novak & Wisdom, 2018). It permits the expansion of participants' knowledge and competence and the modification of the curriculum and pedagogical development (Song, 2018).

In summary, emphasising active learning, interdisciplinary connections, and hands-on experiences in teacher education are crucial for preparing preservice teachers to integrate 3D modelling and printing into their educational practices. Activities that engage participants in active learning, foster physical and digital connections, and integrate interdisciplinary approaches are particularly favourable for 3DMP in teacher education. Ensuring that training programs emphasise these aspects can help overcome challenges and meet future teachers' needs, ultimately enhancing their capability to incorporate new technologies into their teaching practices.

Discussion

In this review, we systematically investigated the current research in 3D modelling and printing in teacher education. Our analysis provides insights into the characteristics of current research, the elements of the reported teacher training programs, and the benefits, challenges, and needs associated with designing and implementing 3DMP training in teacher education.

Current State of the Art of 3DMP in Teacher Education

A notable increase in publications was observed in the last years, with a peak in 2021. During this period, the global pandemic led to the implementation of remote education in many educational institutions, which may have influenced the publication trends in this field. This trend suggests a growing emphasis on preparing preservice teachers for emerging technological demands, although a slight decline in publication volume was noted in subsequent years. Furthermore, most of the reviewed papers used a qualitative approach and were exploratory (Table 4). Examining sample sizes (Table 3) reveals that participant numbers were predominantly between 21 and 50. This pattern reflects the focus of the majority of studies, which primarily explored preservice teachers within small classroom settings. These findings highlight the early research stage in this area and the need for further theoretical and practical developments that could expand research and practice in emerging technologies integration in teacher education.

Regarding disciplinary focus, approximately 73% of the studies were directly related to STEM areas, and this figure increased to 81% when STEAM disciplines were included. These findings align with the interdisciplinary potential of 3DMP, as highlighted by Anđić et al. (2024), who note its use in creating biological models that integrate art and technology to enhance learning experiences. Additionally, Ulbrich et al. (2024) emphasise that 3DMP is highly suitable for interdisciplinary environments and problem-based learning. Moreover, several reviewed studies reported that 3DMP supports the development of critical 21st-century skills, including communication, critical thinking, spatial reasoning, and problem-solving (e.g., Levin and Verner, 2021; Benzer & Yildiz, 2019; Guler et al., 2019; Schelly et al., 2015).

Another significant finding relates to the use of theoretical and conceptual frameworks. While nearly half of the reviewed studies did not explicitly employ a framework, the TPACK framework was prominently among those that employed a framework. Given TPACK's established role in educational research (Schmid et al., 2024; Ortiz Colón et al., 2023; Irwanto, 2021; Willermark, 2018), its application in studies on 3DMP reflects its relevance for planning the integration of emerging technologies into teacher education. These insights establish the context for a detailed breakdown of the technological, pedagogical, and content knowledge dimensions in 3DMP research within teacher education.

Pedagogical, Technological, and Content Knowledge in 3DMP Teacher Education

By addressing TPACK dimensions (Table 5), teacher education programs can better prepare future educators to integrate 3DMP into their teaching practices, ultimately enriching the educational experiences of their students (Alimisi et al., 2020). Accordingly, a well-designed 3D modelling and printing teacher education program should:

- Integrate content knowledge with practical applications: Emphasise using hands-on activities and educational resources that leverage preservice teachers' content expertise.
- Enhance pedagogical strategies: Focus on methods to increase participant engagement, propose model activities that facilitate school integration of 3D technologies, and boost preservice teachers' self-efficacy and skills.
- Build technological proficiency: Ensure preservice teachers are well-versed in the technological aspects by creating a conducive training atmosphere that directly impacts their learning and skill development.

These findings highlight the need for comprehensive teacher education programs that integrate content, pedagogical, and technological knowledge to maximise the benefits for future educators and students alike. Research by Alimisi et al. (2020)

and Arslan and Erdogan (2021) highlights that programs that address these areas simultaneously are essential for integrating 3DMP.

By focusing on the identified benefits and addressing the reported challenges and needs, training programs can equip future teachers with the skills, confidence, and resources they need to integrate 3DMP into their educational practices. Integrating content knowledge with technological practices is crucial to overcoming challenges in adapting to new educational technologies, as seen in Wan and Ivy's (2021) study. The study emphasised the need for teachers to first experience technologies as learners, which aligns with the proposal of Ruthven and Lavicza (2011). Schelly et al. (2015) further emphasise that hands-on engagement with technology, like building and using 3D printers, empowers teachers and enhances interdisciplinary learning by applying these tools across various STEM subjects. Ultimately, this approach ensures that preservice teachers are proficient in 3DMP and can utilise these skills to enhance their future students ' learning experiences, thereby achieving a more innovative educational environment. This comprehensive approach can foster critical thinking and creativity among students, allowing them to engage more deeply with the learning material and explore new avenues for problem-solving (Arslan & Erdogan, 2021).

Implications of 3DMP in Teacher Education

To maximise the benefits of 3DMP in teacher education, it is crucial to ensure more hands-on opportunities (Graham et al., 2021; Lin et al., 2018; Urbina & Polly, 2017), alongside establishing ongoing support mechanisms that can help participants build and maintain confidence in their teaching abilities. Workshops that prioritise experiential learning, as highlighted by Alimisi et al. (2020) and Asempapa and Love (2021), emphasise the value of teachers engaging directly with technologies, allowing them to explore both the technological and pedagogical implications of integrating tools like 3D printing into the classroom. The hands-on nature of these workshops, combined with project-based learning and collaborative environments (e.g., Benzer and Yildiz, 2019), enhances teachers' understanding of how 3D printing can support STEM education.

The utilisation of software for three-dimensional modelling offers a significant challenge for educators (Anđić et al., 2024; Song, 2018). Therefore, assessing preservice teachers' content knowledge, technological skills, and prior experiences with 3D modelling and printing is a crucial first step (Novak & Wisdom, 2018). Beginning with user-friendly software like TinkerCAD ensures a comprehensive understanding of the modelling process (Karaismailoglu and Yildirim, 2024; Wan & Ivy, 2021). This approach allows educators to build confidence and engagement by addressing their diverse needs through customised pedagogical strategies, such as differentiated instruction, culturally responsive teaching practices, and adaptive learning technologies (Alimisi et al., 2020). Starting with accessible tools establishes a robust foundation for progressing to more sophisticated 3D modelling software (Ulbrich et al., 2024). Additionally, improving the availability, quality, and variety of educational resources bridges the gap between provided and needed materials, better supporting preservice teachers (Sun & Okojie, 2020). These strategies reinforce foundational skills and engagement, ensuring the successful and sustainable integration of emerging technologies like 3DMP into teaching practices.

Creating a supportive and collaborative training environment is critical for effectively integrating 3D technologies into teacher education. This can be achieved by fostering a community of practice among participants, presenting mentorship opportunities, and designing interactive and inclusive training sessions (Sullivan & McCartney, 2017; Schelly et al., 2015; Verner & Merksamer, 2015). Handling logistical issues is also critical, such as offering flexible training schedules, providing online or hybrid training options, and ensuring accessibility, regardless of participants' geographic location or time constraints (Alimisi et al., 2020). Additionally, structured support and strategic planning are key in facilitating the seamless adoption of 3D technologies into school curricula (Song, 2018). Effective strategies may include providing follow-up support after training, offering accessible integration guides, and collaborating with school administrators to align 3DMP with school goals and resources. By addressing these practical and pedagogical aspects, training programs can better equip educators to integrate 3D technologies into their teaching, ultimately enhancing teacher confidence and student learning outcomes.

Incorporating interdisciplinary approaches into teacher education programs, particularly through integrating 3DMP, can significantly enhance the quality of training by fostering connections across various subject areas. By utilising 3D technologies within STEM education, educators can create dynamic learning experiences that bridge mathematics, science, and technology education (Asempapa and Love, 2021; Schelly et al., 2015). Additionally, as Novak et al. (2021) point out, expanding STEM to include other disciplines, such as history and architecture, can provide broader career opportunities related to STEM fields, creating a more diverse learning experience for preservice teachers. This approach enriches content knowledge and prepares future educators to engage in real-world, interdisciplinary problem-solving scenarios.

Based on the discussed implications, we propose the following actions for 3DMP integration in teacher education:

- Conduct comprehensive needs assessments before training to tailor programs to participants' needs (e.g., preliminary activities or surveys).
- Start with user-friendly 3D modelling software before progressing to more complex tools (e.g., TinkerCAD).
- Offer hands-on activities during training sessions (e.g., apply and analyse K-12 learning projects)
- Encourage the integration of 3DMP across various disciplines to create holistic and diverse learning experiences (e.g., implementing STEM and STEAM projects)
- Promote the use of 3DMP to foster critical 21st-century skills (e.g., proposing collaborative problem-solving tasks)
- Improve the availability and quality of educational materials to bridge resource gaps (e.g., ready-made lesson plans).

- Foster a supportive learning environment through communities of practice and mentorship (e.g., online resource-sharing community).
- Develop structured support for curriculum integration, including collaboration with school administrators (e.g., collective lesson planning).
- Offer flexible training options to address logistical challenges and ensure accessibility (e.g., hybrid format training).

These insights provide a framework for implementing effective 3DMP integration in teacher education programs. They address the challenges and capitalise on the abovementioned benefits while highlighting the necessity for more carefully designed training activities that consider the participants' specific needs. Participants require the opportunity to engage in a goal-oriented, well-planned training program (Ucgul and Altiok, 2023; Alimisi et al., 2020; Asempapa and Love, 2021; Benzer & Yildiz, 2019; Song, 2018).

Limitations and Future Directions

This study highlights the growing interest and potential of 3DMP within teacher education, offering valuable insights into its integration. However, it is important to acknowledge several limitations in this study. Firstly, despite significant advancements in research on 3DMP within teacher education, the current body of work reveals limitations due to geographic concentration and the predominance of exploratory studies. Many studies have been conducted in recent years, allowing us to look at the big picture of 3DMP within teacher education. Nevertheless, the concentration of research in certain countries, which could be attributed to their size, investment in research, and technological infrastructure, narrows the relevance of conclusions. To expand the field of study, researchers, educators, and policymakers worldwide should consider the cultural contexts associated with each technological development to deepen their knowledge of the topic and understand the opportunities and challenges of different settings (Ulbrich et al., 2024; Pearson & Dube 2022).

Secondly, our search was limited to five databases, and we specifically focused on articles published in English. Additionally, we conceptualised teacher education as preservice teacher training, and thus, our analysis focused on preservice teacher training. We recognise this as a limitation and suggest that future studies consider the differences in educational settings across countries. This would allow for a more comprehensive examination of the teacher education continuum, including pre- and in-service teachers, and the intersections between these groups. We emphasise the importance of conducting systematic reviews on in-service teachers or professional development programs. Moreover, given that this study is limited to preservice teachers, it does not address the design and practical implementation of 3DMP within K-12 classrooms. Nonetheless, we acknowledge that the challenges inherent in classroom teaching environments are critical in shaping teacher education. Consequently, we recommend that future research explore the reflections and impacts of 3DMP in K-12 learning settings, as these investigations may provide valuable insights for refining teacher education programs. While reviewing the studies, we observed some included syllabi for their training programs. Although we did not incorporate this in our study, future research could benefit from examining the syllabi of training programs to provide a more comprehensive understanding of teacher education initiatives.

Based on our findings, we highlight key actions for integrating 3DMP into teacher education. We recommend that future empirical studies incorporate these actions to design well-structured training courses that meet the needs of preservice teachers. Furthermore, we observed that STEM and STEAM disciplines dominate the field of 3DMP research in teacher education. We believe exploring these developments in other countries and comparing results across cultures would be valuable. Future studies should also identify the differences and similarities between the various approaches to integrating 3DMP into the classroom and teacher education across different countries or cultures.

Moreover, another possible direction for future research concerns the role of teacher educators. The majority of the studies in this analysis focus on the knowledge and experience of preservice teachers during these interventions, while none pay significant attention to the trainers. As Novak et al. (2021) have previously highlighted, there is a need for 3DMP professional development targeting postsecondary faculty. Understanding these dynamics is essential as we focus on the specific benefits and needs that teacher education programs must address in integrating 3DMP.

Conclusions

This study investigated the integration of 3D modelling and printing in teacher education through the lens of three research questions, providing insights into the field's current state, the interplay of knowledge domains, and the practical implications for teacher training programs. We have recognised critical trends and gaps by analysing the existing studies, how technological, pedagogical, and content knowledge are addressed, and the benefits and challenges of implementation. These findings provide valuable guidance for future research and the development of more effective teacher education programs that leverage 3DMP.

The analysis of research on 3D modelling and printing in teacher education highlights promising advancements and notable limitations. While interest in 3DMP has grown, with an increasing number of studies in recent years, the geographic concentration of research and the predominance of exploratory, qualitative studies indicate the field is still in its early stages. Most studies focus on preservice teachers, leaving gaps in understanding the role of teacher educators in implementing 3DMP. Notably, the discipline focus of the studies emphasises the centrality of science, mathematics, and technology, which account for the majority of research contexts. This alignment with STEM disciplines highlights the potential of 3DMP to support STEM literacy through hands-on, inquiry-based approaches that engage teachers and students in interdisciplinary learning.

The analysis of studies on 3D modelling and printing (3DMP) in teacher education shows how technological, pedagogical, and content knowledge (TPACK) are addressed, indicating strengths and limitations. Pedagogical and technological knowledge are emphasised in most studies, mainly through hands-on experiences and school integration. These themes stress efforts to enhance teachers' confidence and ability to integrate technology into teaching practices. However, content knowledge receives comparatively less attention, with fewer studies providing explicit resources or activities to strengthen subject-specific expertise. This imbalance indicates a partial approach to the TPACK dimensions, where content knowledge is underexplored relative to technological and pedagogical knowledge.

The multifaceted nature of 3D modelling and printing in teacher education requires a comprehensive approach integrating content, pedagogical, and technological knowledge. Our analysis indicates that while skill development, participant engagement, and hands-on experience are critical benefits, they also present significant challenges. Programs must adapt training to varying skill levels, incorporate engaging elements, and provide support mechanisms to build teacher confidence. Additionally, addressing the need for educational resources and fostering a supportive training atmosphere are essential for successful implementation. These findings emphasise the opportunity for 3DMP programs to enhance STEM literacy by preparing teachers to integrate interdisciplinary, hands-on activities that foster inquiry and innovation in science, technology, engineering, and mathematics. By adopting a holistic approach that accentuates practical applications, enhances pedagogical strategies, and builds technological proficiency, teacher education programs can better equip educators to enrich students' learning experiences and create more innovative STEM learning environments.

Through this study, we provide actionable recommendations for integrating 3DMP into teacher education, specifically targeting the challenges and needs identified in our research. We anticipate that these recommendations will facilitate the successful integration of 3DMP, overcoming current barriers and promoting its broader use in teacher education programs. Overall, our findings offer valuable insights for researchers and educators to guide the integration of 3DMP into teacher education programs.

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Data Availability The data supporting the findings of this systematic literature review were obtained from four databases: ERIC, Web of Science, Scopus, and IEEE Xplore. The methodology section details the search strings and eligibility criteria applied in each database, ensuring transparency and reproducibility.

The PRISMA framework guided the selection and screening process, as illustrated in Fig. 2. For further details regarding the search strategy or screening methodology, please contact the corresponding author.

Declarations

Competing Interests The authors declare no competing interests.

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