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The Relationship Between 3D Printing Technology and STEM Education Outcomes: The Moderating Role of Institutional Infrastructure in Ethiopian Secondary Schools

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Abstract

The integration of 3D printing technology (3DPT) into STEM education has transformed teaching and learning through experiential and design-based approaches. However, the effectiveness of this technology is largely shaped by the institutional environment in which it is implemented. This study investigates the moderating role of institutional infrastructure in the relationship between 3DPT and STEM education outcomes (STEMO) in Ethiopian secondary schools. A quantitative cross-sectional survey design was employed, involving 368 participants from secondary schools equipped with STEM and 3D printing facilities. Data were analyzed using Structural Equation Modeling (SEM). The results indicate that the dimension of 3DPT are positively associated STEMO, with frequency of use, instructional integration, and access to digital resources showing stronger associations than availability alone. In addition, both human and digital infrastructures were positively associated with STEMO. The significant interaction effects further indicate that institutional infrastructure moderates the association between 3D printing technology and STEM education outcomes. The study contributes to educational technology literature by integrating constructivism, experiential learning, socio-technical systems theory, and connectivism into a unified explanatory framework. The findings provide empirical evidence from a developing-country context and highlight the importance of institutional readiness in maximizing the educational benefits of 3D printing technology in STEM education.

Keywords: 3D printing technology; STEM education outcomes; institutional infrastructure; structural equation modeling; educational technology; socio-technical systems; constructivist learning

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1. Introduction

The rapid advancement of digital technologies associated with the Fourth Industrial Revolution (Industry 4.0) has significantly transformed modern educational systems worldwide (Shahroom & Hussin, 2018). Among these emerging technologies, 3D printing technology (additive manufacturing) has attracted growing attention in education due to its ability to transform digital designs into tangible objects through layer-by-layer fabrication (Ford & Minshall, 2019). This technology offers substantial pedagogical potential by enabling experiential, interactive, and learner-centered instructional approaches,

particularly in Science, Technology, Engineering, and Mathematics (STEM) education (Nedungadi et al., 2026).

In STEM disciplines, students often experience difficulties in understanding abstract and complex concepts through traditional lecture-based instruction. In this regard, 3D printing technology provides an innovative pedagogical approach by enabling learners to visualize, manipulate, and construct physical models that enhance conceptual understanding and active engagement (Lin et al., 2018; Kefalis et al., 2024). Prior studies have shown that 3D printing improves learning outcomes in various STEM subjects, including chemistry, mathematics, and engineering education (Wisdom & Novak, 2020; To et al., 2024). In addition, it contributes to the development of essential 21st-century competencies such as creativity, critical thinking, collaboration, problem-solving, and digital literacy (Sun & Li, 2018). Pantazis et al. (2021) further emphasized that 3D printing serves as an effective tool for stimulating innovation and creativity, while also improving student motivation and learning success (Bonorden & Papenbrock, 2022).

On the other hand, teaching and learning can be seen as something that happens because of the way people think, feel and interact with others. It also includes the environments where learning takes place such as schools. This idea comes from research done by Cappon and Kennette in 2022 (Cappon & Kennette, 2022). In technology-enhanced STEM education, these same areas might show up in how students think and feel about their learning, how teachers teach, and what kind of support the school gives. This study mainly looks at the social parts as well as the technology and school environment, instead of looking at biology directly. As a result, the study focuses on how students feel about their STEM education as a learning-related part. It examines printing technology, school equipment, the technology-teaching methods, and the learning environments that associated with these results.

Despite these advantages, the effectiveness of 3D printing in education is not solely determined by the technology itself but also by the institutional environment in which it is implemented. The recent systematic review by Tejera et al. (2026) directly identifies resource availability, teacher training, and school integration as major challenges, while Ford and Minshall (2019) provide a broader review of 3D-printing integration in education. In particular, contextual and environmental factors play a decisive role in shaping the effectiveness of 3D printing in educational settings (To et al., 2023). However, much of this literature has primarily recognized these factors as general requirements for technology integration, with limited empirical attention to how institutional infrastructure moderates the relationship between 3D printing technology and STEM education outcomes. In particular, insufficient emphasis has been placed on the role of institutional infrastructure as a moderating factor, including digital facilities, internet access, laboratory resources, technical support, teacher competence, and training opportunities. Moreover, most existing studies have been conducted in developed countries, resulting in limited empirical evidence from secondary education systems in developing countries.

This gap is particularly evident in the Ethiopian educational context, where infrastructural and technological challenges continue to affect the integration of emerging technologies in education (MoE, 2023). Reports from the Ethiopian Ministry of Education and the World Bank indicate that many secondary schools lack adequate computer-based learning materials, functional laboratories, reliable internet access, and sufficient teacher preparation for technology-integrated instruction. These limitations contribute to ongoing concerns regarding the quality and effectiveness of STEM education. Although variations in student achievement have been observed in relation to exposure to educational technologies, such variations cannot be interpreted as causal due to the presence of multiple confounding factors (Tamim et al., 2011; Sung et al., 2016).

To address these gaps, this study develops and empirically tests a socio-technical framework that examines both the direct effect of 3D printing technology on STEM education outcomes and the moderating role of institutional infrastructure. The framework integrates technological, pedagogical, and infrastructural dimensions to provide a more comprehensive and context-sensitive explanation of technology-enhanced learning effectiveness. Specifically, the study conceptualizes 3D printing technology as a multidimensional construct comprising availability, frequency of use, instructional integration, and access to digital resources, while institutional infrastructure is modeled through human and digital dimensions.

The study contributes to the literature in several important ways. Theoretically, it extends educational technology research by positioning institutional infrastructure as a moderating mechanism that explains the conditions under which 3D printing technology becomes more or less effective in improving STEM education outcomes. Empirically, it provides evidence from Ethiopian secondary schools, a context that remains underrepresented in the literature. Methodologically, it applies Structural Equation Modeling (SEM) to test a multidimensional and moderated framework, offering a more robust analytical approach than prior studies that focus primarily on direct relationships. Practically, the findings offer valuable insights for policymakers, school administrators, and educators to strengthen institutional capacity and enhance the integration of emerging technologies into STEM education.

This study addresses the following research questions:

(1) To what extent does 3D printing technology influence STEM education outcomes in secondary schools?
(2) How does institutional infrastructure moderate the relationship between 3D printing technology and STEM education outcomes?

Addressing these questions provides important insights into the contextual conditions necessary for the successful implementation of emerging educational technologies in resource-constrained environments.

The novelty of this study lies in the development and empirical validation of a context-sensitive socio-technical framework that explains how institutional infrastructure moderates the relationship between multidimensional 3D printing technology adoption and STEM education outcomes in Ethiopian secondary schools using SEM. Unlike previous studies, this research integrates 3D printing technology, institutional factors, and STEM education outcomes into a unified conceptual model and empirically tests the proposed relationships. To the best of the authors' knowledge, limited empirical research has examined these constructs jointly within a single empirical framework, particularly at the secondary-school level in Ethiopia. The findings contribute to the body of scientific knowledge by providing an empirically validated framework that enhances understanding of how institutional factors strengthen the impact of 3D printing technology on STEM education outcomes.

2. Literature Review

2.1. 3D Printing Technology and STEM Education

The technology of 3D printing is a revolutionary invention in modern times in educational practice, especially in the context of STEM. It acts as a digital fabrication tool used in learning processes whereby users create physical prototypes of any object from digital designs through the accumulation of layers of materials (Wisdom & Novak, 2020). This approach conforms to the notion of inquiry-based learning or active learning, which entails students interacting with learning content. Empirical research studies demonstrate the effectiveness of 3D printing in enhancing learners' comprehension of difficult scientific and mathematical concepts by providing a tangible form of these ideas (Lin et al., 2018; Song &

Wen, 2018). In their findings, Lin et al. (2018) and Song and Wen (2018) argue that digital fabrication tools greatly increase student engagement and enhance academic performance in STEM education. According to Murat (2026), project-based teaching approach effectively bridges theory and practice and provides a scalable model for including 3D printing into engineering curricula.

Apart from the development of conceptual knowledge, there are studies proving that 3D printing can encourage the formation of higher-level cognitive abilities such as creative and spatial thinking, problem solving, and design thinking. The skills mentioned above are particularly vital for modern STEM education, in which the focus lies on innovation and practice. According to existing research, the implementation of 3D printing into learning through inquiry- and project-based methods can improve the skills related to the process of designing and collaborative problem solving among learners (Seyda & Funda, 2025; Flowers, 2025).

Abu Khurma et al. (2023) in their study explored the perceptions of students and teachers towards the integration of 3D printing technology in STEM teaching and learning within United Arab Emirates elementary schools. Their findings revealed the positive perceptions of students and teachers regarding the interdisciplinary integration of 3D printing technology in teaching and learning. The study by Inoma et al. (2020) evaluated the necessity of introducing 3D printing into science and engineering education in Nigeria. According to their study, this technology brings opportunity for new teaching practices in science and engineering programs in a developing country. In addition, in the context of smart education, which broadly refers to the use of interconnected digital technologies and intelligent systems to support flexible, personalized, and technology-enhanced teaching and learning, integrating 3D printing technology can provide additional opportunities for hands-on and learner-centered STEM learning (Kerimbayev et al., 2023).

2.2. Constructivist and Constructionist Perspectives in Technology-Enhanced Learning

There are many educational benefits associated with the use of 3D printing technology in teaching, as evidenced by several theories and models supporting the pedagogical role of this technology. One such theory is the Constructivist Learning Theory, based on the idea that knowledge is actively constructed by learners in response to interactions within their environments, rather than received passively (Almulla, 2023). In this respect, 3D printing can be viewed as a valuable tool facilitating constructive and inquiry-based learning, promoting cognitive engagement, and encouraging knowledge acquisition in a meaningful manner. The process of using this technology to create material objects based on abstract science or math concepts contributes to better comprehension and application of these concepts. Numerous studies have shown that constructivist technology-supported learning environments positively affect student engagement and learning outcomes in STEM fields (Bou Saad et al., 2025; Seyda & Funda, 2025; Jekabsone et al., 2025). Additionally, 3D printing has been linked to better problem-solving skills, spatial visualization, and motivation, among other benefits (Buehler et al., 2016; Ford & Minshall, 2019).

Another concept that is highly associated with constructivism is the constructionism theory, which suggests that learning takes place best when learners construct physical objects. The creation of 3D models through designing and making them results in an innovative and creative approach to learning known as "learning by making." Access to computer-aided design tools makes this possible for students to imagine their ideas and work on them before actually creating them (Omer et al., 2023). Research studies on technology-enhanced learning environments have shown that constructionist approaches combined with digital fabrication tools increase students' motivation and engagement (Jennifer, 2014; Seyda & Funda, 2025).

2.3. Experiential Learning and Interactive Technologies

Incorporation of 3D printing in the educational setting is highly encouraged by experiential learning theory, which views learning as a cyclic process that comprises concrete experience, reflective observation, abstract conceptualization, and active experimentation. Under this theory, 3D printing facilitates active participation in the entire cycle of learning as students design, produce, test, and improve physical prototypes. This approach helps deepen theoretical knowledge while developing practical skills and fostering creative problem-solving techniques.

Empirical research shows that experiential learning facilitated by modern technology, specifically by digital fabrication technologies, significantly increases students' engagement, retention, and performance within the framework of STEM education (Buehler et al., 2016; Ford & Minshall, 2019; Seyda & Funda, 2025). There is also evidence that 3D printing stimulates cognitive engagement, spatial thinking, and students' motivation due to its facilitation of experimental and iterative processes in learning (Kerimbayev et al., 2023; Voogt & Roblin, 2012). Moreover, research reports mentioned in Buehler et al. (2016) and Anđic et al. (2023) state that visualized learning helps students comprehend complex concepts of science better.

The interactive nature of technologies like 3D printing is extremely important because it promotes experiential learning through hands-on interaction with problems. According to the studies carried out by Wang et al. (2024), experiential and project-based learning contributes to greater retention, engagement, and critical thinking among participants. The interactive nature of learning technologies can be especially effective in smart learning settings where such tools are connected with digital platforms which help with feedback and cooperation between learners (Kerimbayev et al., 2023).

2.4. Technology Adoption and Pedagogical Integration

The effectiveness of 3D printing technology in education does not only hinge on its accessibility but also on its adoption and incorporation into the teaching process. The Technology Acceptance Model (TAM) provides an important theoretical foundation for understanding how people accept and use technology. This model states that perceived usefulness and perceived ease of use are critical factors behind user technology acceptance and adoption behaviors. Similarly, according to Bayaga and du Plessis (2024), for the purposes of analyzing technology adoption and use in educational settings, TMA presents an important theoretical foundation. Thus, in education, this perspective suggests that teachers are more likely to adopt and use 3D printing when they perceive it as useful for teaching and learning and sufficiently easy to use. Accordingly, teachers' perceptions of the usefulness and usability of 3D printing may influence their willingness to incorporate the technology into instructional activities. Earlier studies have also highlighted the importance of users' attitudes, perceptions and technological skills, in the adoption of educational technologies (Buehler et al., 2016; Bond et al., 2020; Tejera et al., 2026; Wang et al., 2024). Yet technology acceptance alone does not show whether technology is used well in practice. A teacher may use a 3D printer but may not have the knowledge needed to choose good instructional strategies, link technology with subject content or create meaningful learning activities. Thus another theoretical view is needed to explain the pedagogical integration of technology.

On the other hand, the Technological Pedagogical Content Knowledge (TPACK) model, developed by Mishra and Koehler (2006), proposed the combination of pedagogical content and technological competencies required for teachers to provide the most comprehensive educational experiences to students. TPACK provides a comprehensive model that explains how technological, pedagogical, and content knowledge support effective instruction (Ruth

et al., 2026). According to Ruth et al. (2026), the integration of digital tools into classroom teaching and learning can enhance learning experiences. From this perspective, effective integration of 3D printing technology requires more than technical ability to operate this digital technology. Teachers need to understand how 3D printing can be connected with particular STEM concepts and how appropriate pedagogical approaches can be used to design, produce, test, and evaluate 3D-printed learning activities.

Thus, TAM and TPACK address complementary but distinct dimensions of educational technology integration. TAM primarily explains whether and why users accept and use a technology, whereas TPACK explains how teachers integrate technology with pedagogy and subject content in instructional practice. This distinction is important in the context of 3D printing technology because acceptance and use of the technology do not necessarily guarantee effective pedagogical integration. Research on TPACK also emphasizes that technology integration is situated within teachers' instructional contexts and depends on the interaction of technological, pedagogical, content, and contextual factors (Tondeur et al., 2016/2017). Accordingly, this study uses TAM and TPACK as complementary theoretical perspectives rather than treating one as a replacement for the other. TAM provides a basis for understanding the technology-adoption dimension, while TPACK provides a basis for understanding the pedagogical integration of 3D printing into STEM teaching. Together, these perspectives help explain why the educational value of 3D printing depends not only on access to and acceptance of the technology but also on teachers' capacity to connect the technology with appropriate pedagogical strategies and STEM content.

2.5. Institutional Infrastructure and Smart Learning Environments

Institutional infrastructure is a crucial element that influences the extent to which technology can be effectively used in teaching and learning. According to socio-technical systems theory, the success of any system depends on the interdependence and interaction of its social and technical elements. Social systems include people and their competencies, skills, knowledge, and organizational culture, whereas technical systems involve the technologies, infrastructure, and processes required to perform tasks. Thus, effective technology integration in education requires both appropriate technological infrastructure and organizational support (Appelbaum et al., 2023).

In educational settings, institutional infrastructure encompasses both human and digital dimensions. The human dimension includes teacher proficiency, training, and technical assistance, while the digital dimension covers internet connectivity, software, and digital learning resources. These elements provide the enabling conditions necessary for effective technology-supported teaching and learning. In this context, a smart learning environment refers to a physical and digital learning environment that integrates interconnected technologies, digital resources, and institutional support to facilitate flexible, personalized, interactive, and technology-enhanced learning. Within this broader context, 3D-printing-integrated classrooms represent a specific form of technology-enhanced learning rather than a synonym for smart learning environments. While 3D printing can be incorporated into a smart learning environment to support visualization, prototyping, hands-on activities, and learner-centered STEM instruction, a smart learning environment encompasses a wider range of technological, human, and organizational resources. Consistent with socio-technical systems theory, technologies such as 3D printing are therefore more likely to be effectively utilized when the relevant social and technical elements of the educational environment are appropriately aligned (Bond et al., 2023).

It is evident from empirical studies that institutions having well-built organizational structures can effectively adopt emerging educational technologies including 3D printers. However, insufficient infrastructure would not enable effective use of technology and

would hinder its pedagogical potential. Recent literature indicates that the readiness of an institution has a positive impact on the success of use of digital fabrication tools for STEM learning (Tejera et al., 2026; Wang et al., 2024). Digital infrastructure along with the readiness of teachers plays a critical role in the integration of technological advances in teaching processes (Bond et al., 2020; Zawacki-Richter et al., 2022). Moreover, the concept of smart education places importance on the role of technology and pedagogy integrated into a supportive organizational environment (Kerimbayev et al., 2023; Zhang et al., 2024).

2.6. Digital Connectivity and Networked Learning

Connectivism is one theoretical perspective from which learning in digitally connected settings can be examined. Connectivism suggests that knowledge is dispersed amongst individuals, digital technology, and various information sources, while learning takes place when one creates and explores networks. In other words, from the connectivist perspective, learning is a continual process through which one accesses, connects, and updates their knowledge via interactions with digital technologies and technologically mediated resources. This theory is applicable to the application of advanced technologies in educational processes, including the use of 3D printing in the educational process when students access information in digital design software, databases, and other collaborative tools (Goldie, 2016). As far as 3D printing is concerned, digital infrastructure allows learners to use online design databases, simulation systems, and learning materials, and to collaborate with their fellow students and teachers. Digital networks create conditions for creativity, co-creation, problem-solving skills development, and other aspects of successful STEM teaching and learning. As shown by empirical studies, digital connectivity substantially increases the efficiency of technology-enabled learning due to improved interaction, engagement, and opportunities for lifelong learning (Tejera et al., 2026; Wang et al., 2024). At the same time, as pointed out by Bond et al. (2020) and Zawacki-Richter et al. (2022), strong digital infrastructure facilitates collaboration, knowledge exchange, and higher levels of engagement in online and blended learning settings.

2.7. STEM Education Performance Measuring Factors

Performance of STEM education within the integration of 3D printing can be assessed through several indicators that have been found in previous studies. These include academic achievements, conceptual understanding, student engagement, creativity, problem solving, critical thinking, collaboration, and motivation. Academic achievements and conceptual understanding are indicators of the intellectual outcomes of learning. Engagement, creativity, and motivation are indicators of behaviors and attitudes toward learning. Moreover, problem solving and critical thinking skills are higher cognitive outcomes, while collaboration is an indicator of working in teams (Voogt & Roblin, 2012; Levin & Verner, 2020; Avinal & Aydın, 2022; Xu & Ouyang, 2022).

Generally, educational outcomes in STEM learning within this study are measured using both cognitive and affective-behavioral dimensions. Cognitive outcomes such as academic performance, conceptual understanding, problem-solving, and critical thinking represent learners' intellectual development, while affective and behavioral outcomes such as creativity, engagement, teamwork, and motivation reflect learners' attitudes and learning behaviors. All constructs are operationalized into measurable variables using a Likert-scale questionnaire, enabling the transformation of both cognitive and affective-behavioral indicators into quantitative data for statistical analysis.

2.8. Research Gaps

Despite the emerging academic discourse about the importance of 3D printing in STEM education, a number of important gaps can be found. First, previous studies have largely examined the general educational benefits of 3D printing, particularly students' engagement, motivation, and learning outcomes, while comparatively less attention has been given to examining distinct dimensions of 3DPT, such as AVL, FUT, IIP, and associated digital tools, and their relationships with STEMO. Second, although previous research has recognized the importance of institutional conditions for educational technology integration, limited empirical attention has been given to how human and digital infrastructure may shape the relationship between 3DPT and STEMO, particularly at the secondary-school level.

Third, the available literature has predominantly relied on empirical data collected from higher education institutions and laboratory settings. Although research on 3D printing in education has expanded, empirical studies focusing specifically on secondary schools remain comparatively limited, particularly in contexts with emerging 3D-printing infrastructure. Previous studies have investigated the use of 3D printing in secondary education in contexts such as Montenegro (Anđic et al., 2023), while research from an African context has examined the perception and deployment of 3D printing in Nigeria (Inoma et al., 2020). Nevertheless, comparatively limited empirical evidence is available on the integration of 3D printing into secondary-school STEM education and its relationship with educational outcomes in Ethiopia. This gap highlights the need for context-specific empirical research examining the integration of 3D printing into secondary-school STEM education and the institutional and instructional factors associated with its educational outcomes. Fourth, relatively few studies have employed an integrated theoretical and empirical framework to examine the relationships among multiple dimensions of 3D printing technology, institutional infrastructure, and STEM education outcomes. In response to these gaps, this study examines the direct relationships between the dimensions of 3D printing technology and STEM education outcomes and the moderating role of institutional infrastructure in the Ethiopian secondary-school context. The study therefore provides context-specific empirical evidence without claiming to be the first study to investigate these constructs.

3. Conceptual Framework and Hypotheses Development

3.1. Conceptual Framework

In this research, the conceptual framework presented in Figure 1 integrates 3DPT, institutional infrastructure, and STEM education outcomes (STEMO). 3DPT is represented by availability (AVL), frequency of usage (FUT), instructional integration (IIP), and access to digital resources (ASD), while STEMO comprises cognitive outcomes (COA) and affective-behavioral outcomes (ABO).

Constructivism, constructionism, and experiential learning theory provide the pedagogical foundation for the proposed positive relationship between 3DPT and STEMO by emphasizing active, hands-on, and experiential learning. TAM and TPACK provide complementary support for understanding technology acceptance and teachers' ability to integrate 3D printing with pedagogy and STEM content.

Furthermore, socio-technical systems theory and connectivism provide the theoretical basis for the moderating role of institutional infrastructure. Human infrastructure (HUL), including teacher competence, training, and technical support, and digital infrastructure (DII), including connectivity, software, and digital learning resources, are proposed to strengthen or weaken the relationship between 3DPT and STEMO. Thus, the framework proposes that 3DPT positively influences STEMO, while the strength of this relationship depends on the availability of adequate human and digital institutional infrastructure.

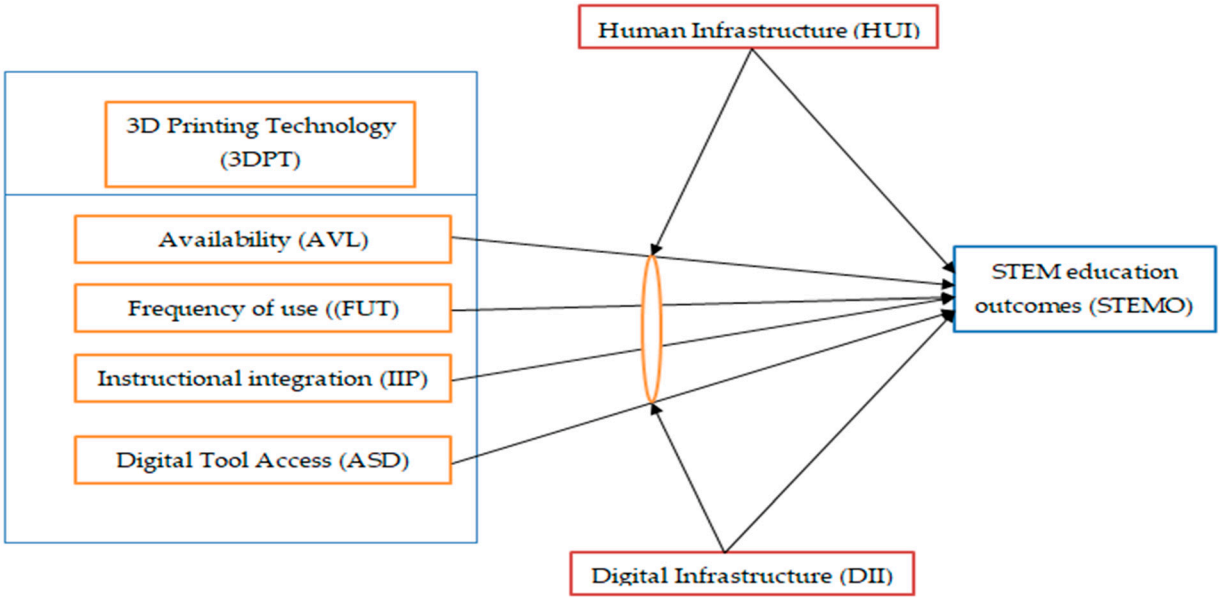


Figure 1. Conceptual framework showing the relationships between 3DPT, IIP, and STEMO.

3.2. Hypotheses Development

3.2.1. Effect of 3DPT on STEMO

The use of 3DPT aids in improving the results of education in STEM fields due to visualization, experiential learning, and development of critical thinking among learners. Theories of constructivism and experiential learning emphasize that knowledge is constructed better by active involvement of learners. Scientific research has proven the positive relationship between the use of digital fabrication technologies and education in STEM fields (Wang et al., 2024; Tejera et al., 2026). The relationship between 3DPT and STEMO can therefore be explained through constructivism, constructionism, and experiential learning theory, which emphasize active knowledge construction, learning-by-making, and learning through concrete experiences (Pearson & Dubé, 2026). However, the educational contribution of 3DPT may depend on how the technology is accessed and used within instructional settings. In particular, availability, frequency of use, instructional integration, and access to supporting digital design tools represent important dimensions that may influence STEMO.

Availability: The availability of 3DPT provides teachers and students with opportunities to transform digital designs into tangible models and educational objects. From constructivist and constructionist perspectives, access to such technology supports active learning, hands-on experimentation, and knowledge construction through making. According to Lin et al. (2018) and Anđic et al. (2023), in STEM education, 3DPT can facilitate visualization, modeling, prototyping, and project-based learning. On the other hand, limited access may constrain students' opportunities to engage in practical and artifact-based learning activities (To et al., 2024; Tejera et al., 2026). Therefore, greater availability of 3D printing technology is expected to be positively associated with STEM education outcomes.

H1a. *Availability of 3DPT is significantly and positively associated with STEMO.*

Frequency of Usage: The frequency of 3DPT use represents how often students engage with the technology during STEM learning activities. Based on experiential learning theory, repeated cycles of designing, producing and testing prototypes provide opportunities for concrete experience, experimentation, and reflection. Frequent use of 3DPT can therefore strengthen practical knowledge, problem-solving, creativity, and understanding of STEM

concepts (Ferlyn et al., 2025; Tejera et al., 2026). Therefore, it is anticipated that increased use of 3DPT will be positively correlated with STEMO.

H1b. *Frequency of 3DPT use in teaching is significantly and positively associated with STEMO.*

Instructional Integration: Instructional integration of 3DPT refers to the purposeful incorporation of the technology into teaching and learning activities. The TPACK framework emphasizes that effective educational technology use requires alignment among technology, pedagogy, and content (Mishra & Koehler, 2006). When integrated into STEM instruction, 3DPT can support visualization, prototyping, engineering design, experimentation, and project-based learning (Lin et al., 2018; Anđic et al., 2023). Thus, effective instructional integration of 3DPT is expected to be positively associated with STEM education outcomes.

H1c. *Instructional integration of 3DPT is significantly and positively associated with STEMO.*

Access to digital resources: Access to digital tools, such as CAD software, modeling platforms, and simulation tools, enables students to create, modify, and prepare digital models for 3DPT (Charles et al., 2018). These tools connect conceptual ideas with physical prototypes and support constructionist learning through designing and creating artifacts. The availability of appropriate digital and technical resources is also important for effective 3DPT integration in STEM education (Mishra & Koehler, 2006; Anđic et al., 2023; Tejera et al., 2026). Therefore, access to supporting digital design tools is expected to be positively associated with STEMO.

H1d. *Access to supporting digital design tools is significantly and positively associated with STEMO.*

3.2.2. Institutional Infrastructure and STEM Education Outcomes

The socio-technical systems theory states that for an organization to perform well, there should be harmony between the social and technical systems. In education, the institutional structure, which includes the proficiency of teachers, training, ICT and internet provision, and software availability, is crucial in ensuring the success of technology-based education. Evidence shows that institutions with good infrastructure are far better at implementing technology-assisted learning (Bond et al., 2020).

Human infrastructure: Human infrastructure, including teachers' technological proficiency, training, and pedagogical capacity, enables educators to effectively implement and integrate 3DPT into STEM instruction. According to Endale et al. (2022) and Tonkolu et al. (2026) teachers' technological and pedagogical competencies and in-service training are important factors in effective technology integration. Therefore, stronger human infrastructure is expected to enhance STEMO.

H2a. *Human infrastructure has a significant positive effect on STEMO.*

Digital infrastructure: Digital infrastructure, including ICT facilities, internet connectivity, software, and other digital resources, provides the technical environment required to support technology-enhanced STEM learning. Adequate digital infrastructure facilitates access to digital learning resources, design tools, and communication platforms, thereby supporting effective implementation of technology-based instruction (Bond et al., 2020; Zawacki-Richter et al., 2022). Thus, stronger digital infrastructure is expected to enhance STEMO.

H2b. *Digital infrastructure has a significant positive effect on STEMO.*

3.2.3. Moderating Role of Human and Digital Infrastructure: (TPACK and Connectivism Perspectives)

The application of the TPACK model indicates that the efficient use of technology in education requires the integration of technological, pedagogical, and content knowledge by educators (Mishra & Koehler, 2006). In the framework, human infrastructure, including teachers' ICT competence, professional development, pedagogical preparedness, and technical assistance, plays a critical role in evaluating the efficiency of technology-based teaching and learning experiences (Tondeur et al., 2016/2017). Teachers with high TPACK can efficiently develop meaningful learning exercises through the use of 3DPT to visualize, experiment, and solve problems in STEM classes. Likewise, teachers' competence acts as a primary factor in integrating technology and academic success in technology-enabled learning environments (Bond et al., 2020; Mishra & Koehler, 2006). Thus, human infrastructure may strengthen the contribution of 3DPT to STEMO (Tejera et al., 2026; Wang et al., 2024). Accordingly, the positive relationship between 3DPT and STEMO is expected to be stronger when human infrastructure is adequate.

Moreover, the theory of connectivism offers a theoretical basis for understanding the moderating role of digital infrastructure. According to connectivism, learning takes place via digital networks, communication, and collaboration platforms rather than through individuals alone (Siemens, 2005). In this sense, digital infrastructure, such as internet connectivity, software provision, digital simulation platforms, and other digital learning materials, provides the technical environment necessary for students and teachers to effectively use 3DPT. Adequate digital infrastructure plays a key role in boosting engagement, collaboration, and knowledge creation in blended and technology-enabled learning contexts (Zawacki-Richter et al., 2022; Tejera et al., 2026). Therefore, the positive relationship between 3DPT and STEMO is expected to be stronger when digital infrastructure is adequate. Hence, based on these theoretical arguments, human and digital infrastructures are expected not only to have direct effects on STEMO but also to condition the strength of the relationship between 3DPT and STEMO.

H3a. *Human infrastructure significantly moderates the relationship between 3DPT and STEMO.*

H3b. *Digital infrastructure significantly moderates the relationship between 3DPT and STEMO.*

4. Materials and Methods

This study employed a quantitative cross-sectional survey design to examine the relationships among 3DPT, institutional infrastructure, and STEMO in Ethiopian secondary schools equipped with STEM centers and 3D printing laboratories. This design is appropriate for testing complex theoretical models involving both direct and moderating relationships using SEM.

The target population comprised teachers and stakeholders involved in STEM education. A total of 368 respondents from eight secondary schools participated in the study. The selection of schools was conducted using purposive sampling, based on the availability of STEM programs and 3D printing facilities. Within the selected schools, respondents were selected using simple random sampling to enhance representativeness and reduce selection bias. The sample size is considered adequate for SEM analysis, in line with recommendations by Hair et al. (2019). Data were collected using a structured questionnaire whose items were contextually developed based on previous theoretical and empirical studies and tailored to the Ethiopian secondary-school context. The questionnaire comprised eight constructs: AVL, FUT, IIP, ASD, HUI, DII, COA, and ABO. All items were measured using a five-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree), a commonly

adopted scale in educational research for capturing respondents' perceptions, attitudes, and experiences toward the studied phenomena. Prior to the main survey, a pilot study was conducted with 30 respondents from comparable secondary schools. The purpose of the pilot study was to assess the clarity, relevance, and reliability of the measurement instrument. Based on the pilot results, minor refinements were made to improve item wording and contextual appropriateness.

Content validity was established through expert evaluation, whereas the construct validity was tested using Confirmatory Factor Analysis (CFA). The reliability of the variables was established through Cronbach's alpha values above 0.70, and the convergent validity was determined using Composite Reliability (CR above 0.70) and Average Variance Extracted (AVE above 0.50). A discriminant validity test was performed based on the Fornell–Larcker criterion (Brown, 2015). Statistical analysis was conducted using SEM, where AMOS Version 25 was used to conduct the analysis in a two-step manner (measurement and structural model analysis). Model fitness was determined using conventional model fit indices (CFI, TLI, GFI $\geq$ 0.90; RMSEA and RMR $\leq$ 0.08; χ^2/df 2–5) as recommended by Hair et al. (2022).

In addition, because the study employed a cross-sectional survey in which the predictor, moderator, and outcome variables were measured using self-reported Likert-scale items, the potential for common-method bias (CMB) was considered. Harman's single-factor test was employed to assess whether a single underlying factor accounted for a substantial proportion of the variance among the measurement items. The test was conducted using all 29 retained measurement items presented in Appendix A. Principal component analysis (PCA) was performed without rotation, and the variance explained by the first unrotated component was examined against the commonly applied 50% criterion.

For the moderation analysis, 3DPT was operationalized as a composite variable (M3DPT) derived from its four dimensions (AVL, FUT, IIP, and ASD). Thus, M3DPT was treated as an aggregated multidimensional construct rather than as a higher-order latent construct in the moderation analysis. The composite scores for M3DPT, HUI, and DII were mean-centered before creating the interaction terms to reduce potential multicollinearity. Two interaction terms, M3DPT $\times$ HUI and M3DPT $\times$ DII, were then computed by multiplying the corresponding centered variables. The moderation effects were estimated in AMOS by including these interaction terms as predictors of STEMO. A significant interaction coefficient was interpreted as evidence that the corresponding infrastructure dimension significantly moderates the relationship between 3DPT and STEMO.

5. Results

5.1. Respondents Demographic Profile Result

The demographic characteristics of the study participants (N = 368) in Table 1 show that 68.21% of the respondents were male, while female respondents constituted 31.79%. With respect to age distribution, the highest proportion of respondents belonged to the age range of 31–40 (64.95%), followed by 20–30 (19.84%) and 41–50 (15.22%). It suggests that the study was conducted on relatively young and professional teachers. As far as education is concerned, almost half of the respondents had at least a master's degree (48.37%), while 42.66% had a bachelor's degree and only 8.97% possessed a diploma. This demonstrates a comparatively high educational qualification of the participants. As regards their teaching experience, over 55.71% of the respondents were teachers with over 10 years of experience.

Regarding their occupational positions, most of the participants were teachers in classrooms (95.65%), while only a few were coordinators (2.17%) and administrative staff members (1.63%). Thus, the results obtained represent the practical realities of teaching practices at the classroom level. Lastly, 60.05% of the participants stated that they received

training in ICT and 3D printing technologies, while the remaining 39.95% lacked the relevant training, implying that there is a reasonable amount of preparation for technology among the participants from the sample schools.

Table 1. Respondents' demographic profile.

Variable	Category	Frequency	Percentage (%)
Gender	Male	251	68.21
	Female	117	31.79
Age	20–30	73	19.84
	31–40	239	64.95
	41–50	56	15.22
Education Level	Diploma	33	8.97
	Bachelor	157	42.66
	Master and above	178	48.37
Experience	<5 years	53	14.40
	5–10 years	112	30.43
	>10 years	205	55.71
Position	Teacher	352	95.65
	Coordinator	8	2.17
	Administrator	6	1.63
ICT/3D Training	Yes	221	60.05
	No	147	39.95

5.2. Reliability and Measurement Model Fit Test Analysis

According to the analysis results presented in Table 2, the Cronbach's alpha (α) values for each construct ranged from 0.906 to 0.970. This finding shows that all constructs had Cronbach's alpha (α) values higher than the acceptable level of 0.70 suggested in the literature, for instance by Kline (2011). This result showed that there is strong internal consistency among all the items in each of the study's constructs. Similarly, the factor loading results in the same table shows that the items under each relevant construct have stronger connections. In addition, all factor loadings are above 0.7 (ranging from 0.819 to 0.982), which shows a strong association with their respective constructs.

Although some reliability coefficients, particularly Cronbach's alpha and CR, exceeded 0.95, the measurement model was carefully re-examined for potential item redundancy. The retained indicators were theoretically relevant and demonstrated acceptable factor loadings. In addition, discriminant validity was assessed using both the Fornell–Larcker criterion and the heterotrait–monotrait (HTMT) ratio.

Convergent and discriminant validity tests were run following the reliability analysis test. Based on the CFA results, AVL1, FUT1, FUT2, and IIP1 were removed during the measurement-model refinement, and the remaining indicators were retained for the final model. As a result, as demonstrated in Table 3, the values of AVE and CR for each of the constructs, respectively, surpass the cutoff limits of 0.5 and 0.7, respectively, showing that the results provide evidence of adequate convergent validity (Hamid et al., 2017). In addition, the discriminant validity of the concepts used in this study is reflected in Table 3. As stated by the Fornell–Larcker criterion (Brown, 2015), discriminant validity is achieved when the square root of AVE in every concept is greater than the inter-construct correlation of this concept with any other concept. All the numbers on the diagonal

of Table 3, AVL (0.883), FUT (0.912), IIP (0.945), ASD (0.901), HUI (0.959), DII (0.909), COA (0.861), and ABO (0.851), are considerably higher than the off-diagonals of the same table. This shows that the construct has a higher variance compared to others since it is shared between its indicators and itself. Additionally, inter-construct correlation coefficients are low, and the highest correlation is shown between IIP and ASD (r = 0.496), which is lower than the square roots of AVE of the two concepts. Thus, discriminant validity is proven since constructs are unique. Similarly, HTMT analysis results presented in Table 4 indicate satisfactory discriminant validity among all constructs. All HTMT values were below the recommended threshold of 0.85 (Henseler et al., 2015), with the highest value being 0.486 between IIP and ASD. This confirms that the constructs are sufficiently distinct from one another and supports the adequacy of the measurement model for subsequent structural analysis.

Table 2. Reliability and convergent validity results.

Constructs	Items	FL	α-Value	CR	AVE
AVL	AVL2	0.810	0.906	0.914	0.780
	AVL3	0.957			
	AVL4	0.877			
FUT	FUT3	0.773	0.932	0.937	0.833
	FUT4	0.982			
	FUT5	0.968			
IIP	IIP2	0.902	0.970	0.971	0.894
	IIP3	0.945			
	IIP4	0.967			
	IIP5	0.966			
ASD	ASD1	0.928	0.921	0.929	0.813
	ASD2	0.950			
	ASD3	0.822			
HUI	HUI1	0.943	0.956	0.972	0.921
	HUI2	0.963			
	HUI3	0.973			
DII	DII1	0.876	0.964	0.960	0.827
	DII2	0.931			
	DII3	0.946			
	DII4	0.903			
	DII5	0.888			
COA	COA1	0.950	0.927	0.919	0.742
	COA2	0.760			
	COA3	0.958			
	COA4	0.756			
ABO	ABO1	0.884	0.937	0.919	0.741
	ABO2	0.954			
	ABO3	0.836			
	ABO4	0.757			

Table 3. Discriminant validity assessment using the Fornell–Larcker criterion.

	AVL	FUT	IIP	ASD	HUI	DII	COA	ABO
AVL	0.883							
FUT	0.102	0.913						
IIP	0.069	0.323	0.945					
ASD	−0.048	0.151	0.496	0.902				
HUI	0.004	0.264	0.275	0.062	0.960			
DII	−0.020	−0.150	0.148	0.250	0.355	0.909		
COA	0.003	−0.110	0.071	0.158	0.072	0.296	0.862	
ABO	0.062	−0.012	−0.068	0.128	0.023	0.103	0.090	0.861

Table 4. Discriminant validity assessment using HTMT ratio.

	AVL	FUT	IIP	ASD	HUI	DII	COA	ABO
AVL	1.000							
FUT	0.121	1.00						
IIP	0.064	0.284	1.00					
ASD	0.039	0.153	0.486	1.00				
HUI	0.051	0.251	0.290	0.064	1.00			
DII	0.031	0.187	0.158	0.245	0.340	1.00		
COA	0.022	0.129	0.064	0.157	0.055	0.305	1.00	
ABO	0.040	0.027	0.053	0.155	0.044	0.120	0.175	1.000

On the other hand, the measurement model test result shown in Figure 2, illustrates that the created measurement model fits well, meeting the recommended cutoff points (Mia et al., 2022) with the goodness-of-fit indices of χ 2/df = 3.73, GFI = 0.921, IFI = 0.928, TLI = 0.913, CFI = 0.927, RMR = 0.02 and RMSR = 0.086. These fit indices confirmed that there is a good fit between the collected data and the created conceptual framework.

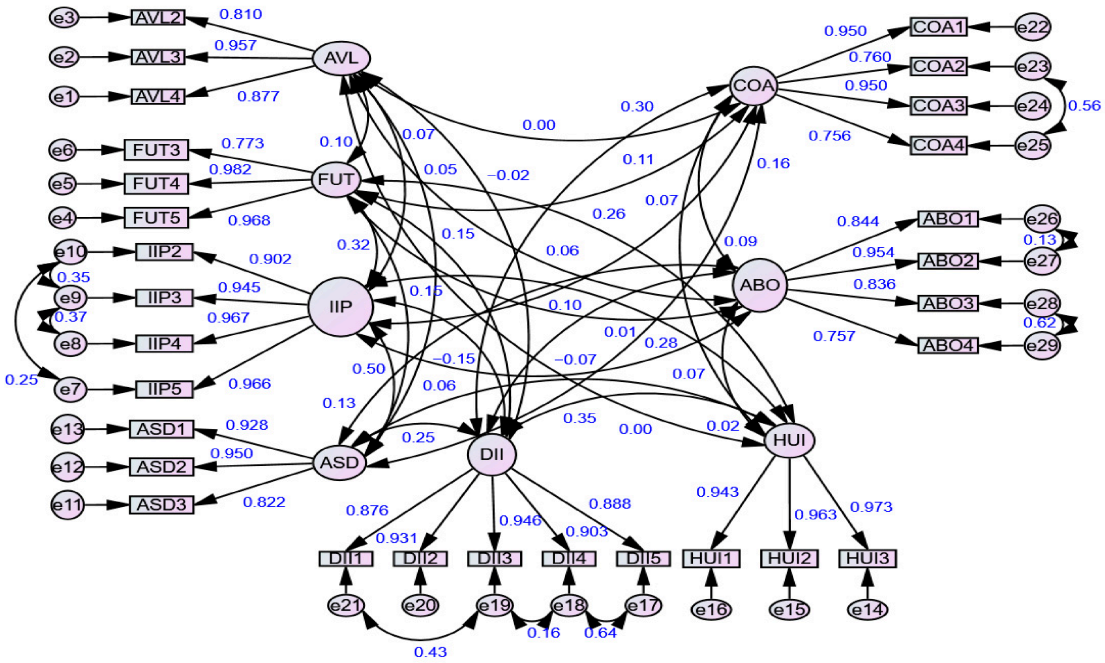


Figure 2. Measurement model fit test result.

5.3. Common-Method Bias Assessment Result

The results of Harman's single-factor test in Table 5 showed a KMO value of 0.759, while Bartlett's test of sphericity was significant ($\chi^2(406) = 12{,}834.244$, $p < 0.001$), indicating that the correlation matrix was suitable for factor analysis. The first unrotated component accounted for 22.729% of the total variance, which is considerably below the commonly applied 50% criterion. Thus, no single factor accounted for the majority of the variance among the measurement items, suggesting that common-method bias is unlikely to be a serious threat to the findings. Nevertheless, Harman's single-factor test cannot completely rule out the possibility of common-method effects; therefore, the cross-sectional and self-reported nature of the data is acknowledged as a methodological limitation.

Table 5. Harman's single-factor test for common-method bias.

Indicator	Result
Number of measurement items	29
KMO	0.759
Bartlett's Test of Sphericity (χ^2)	12,834.244
Degrees of freedom (df)	406
Significance (p)	<0.001
Variance explained by the first unrotated component (%)	22.729
Commonly used threshold (%)	50.000

5.4. Assessment of School-Level Clustering and Between-School Differences

Because the respondents were nested within eight secondary schools, school-level clustering was examined before conducting the structural model analysis. ICC(1), design effects, and between-school F-tests were calculated for the study constructs. The results are presented in Table 6. School-level clustering was generally limited across the constructs. The ICC values ranged from −0.008 to 0.031, while the design effects ranged from 0.63 to 2.40. DII showed the largest school-level variation (ICC = 0.031; DE = 2.40) and significant differences between schools, $F(7, 360) = 11.864$, $p = 0.001$. HUI also showed a statistically significant between-school difference, $F(7, 360) = 2.299$, $p = 0.026$, although its ICC was low (0.027). These findings were considered when interpreting the subsequent structural and moderation analyses.

Table 6. Assessment of school-level clustering and between-school differences.

Construct	ICC(1)	Design Effect	F	p-Value
3DPT	0.000	1.00	1.002	0.429
HUI	0.027	2.24	2.299	0.026
DII	0.031	2.40	11.864	0.001
STEMO	−0.008	0.63	0.621	0.739

5.5. Structural Model and Hypothesis Analysis Result

The measurement model's validity and reliability were demonstrated; thus, the next step was to examine the structural model and validate the presented hypotheses using SEM (Malik et al., 2024) with AMOS. This study employed SEM as it allows for simultaneous analysis, which leads to more accurate estimations and is the highest probability approach for investigating the correlations between variables. Figure 3 displays the results of the structural model's goodness of fit assessment and path analysis. The model has an excellent

fit to the data, with a χ^2/df ratio of 3.52. This is below the usual criterion of fit (less than 5), indicating a robust fit. The model fit indices also offered corroborative evidence, with RMSEA at 0.083 and RMR at 0.029, both considerably below the proposed limit of 0.08 as suggested by Brown (2015). Furthermore, the TLI = 0.944, CFI = 0.957, GFI = 0.908 and IFI = 0.958 fulfilled the acceptance level as recommended by Brown (2015). The findings show the degree to which the SEM matches the empirical data, providing a solid foundation for further evaluation of the hypotheses.

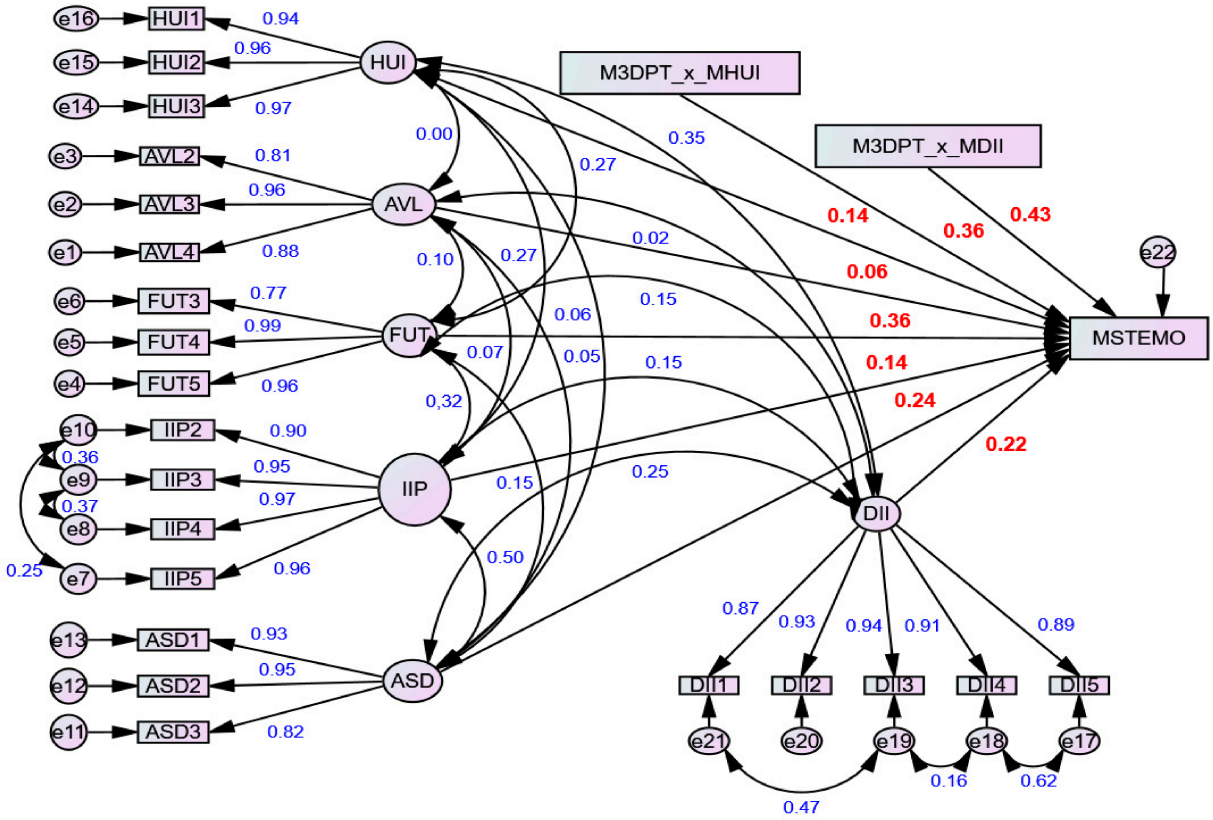


Figure 3. Structural model and path analysis results.

From the analysis presented in Table 7, it can be seen that the hypothesized relationships were statistically supported. First, the availability of 3D printing technology (AVL) was found to have a statistically significant positive relationship with STEM education outcomes (β = 0.06, p = 0.001), supporting H1a. However, the relatively small standardized coefficient indicates that the direct contribution of availability to STEM education outcomes is limited. In turn, the frequency of use (FUT) was discovered to have the strongest effect (β = 0.36, p = 0.001) which implies that using 3D printing technology more frequently is crucial for enhancing results. Integration into teaching processes (IIP) (β = 0.14, p = 0.031) and availability of other digital technologies (ASD) (β = 0.21, p = 0.000) positively affects MSTEMO as well.

Similarly, institutional infrastructure variables demonstrate statistically significant positive associations with STEMO. Human infrastructure (HUI) (β = 0.14, p = 0.000) and digital infrastructure (DII) (β = 0.22, p = 0.000) are positively associated with educational outcomes. These findings suggest that teacher competence, training, and access to digital resources may facilitate the effective integration of technology into classroom learning. More importantly, the interaction terms between 3D printing technology and institutional infrastructure are statistically significant.

The interaction between 3DPT and human infrastructure (M3DPT × HUI) is positive and significant (β = 0.36, p = 0.001), while the interaction between 3D printing technology and digital infrastructure (M3DPT × DII) is also positive and significant (β = 0.43, p = 0.014). These significant interaction effects provide evidence that institutional infrastructure moderates the relationship between 3D printing technology and STEMO. Specifically, the positive association between 3D printing technology and STEMO becomes stronger at higher levels of human and digital infrastructure. Thus, the findings indicate that the relationship between 3D printing technology and STEM educational outcomes is contingent, in part, on the availability of adequate human and digital infrastructure.

Table 7. Path and moderation analysis results.

	Hypothesis	Paths	β	*p*	Result
Direct effect	H1a	AVL = → MSTEMO	0.06	0.000	Accepted
	H1b	FUT = → MSTEMO	0.36	0.000	Accepted
	H1c	IIP = → MSTEMO	0.14	0.031	Accepted
	H1d	ASD = → MSTEMO	0.21	0.000	Accepted
	H2a	HUI = → MSTEMO	0.14	0.000	Accepted
	H2b	DII = → MSTEMO	0.22	0.000	Accepted
Moderating effect	H3a	M3DPT_X_MHUI = → MSTEMO	0.36	0.000	Accepted
	H3b	M3DPT_X_MDII = → MSTEMO	0.43	0.014	Accepted

β = standardized coefficients; p = significant value.

6. Discussion

This study provides empirical evidence of the positive association between 3DPT and STEMO, while indicating that these associations vary according to institutional conditions. Collectively, the findings extend the existing literature by offering a multidimensional perspective on 3DPT and by highlighting the moderating role of institutional infrastructure. Rather than viewing 3D printing as a standalone educational innovation, the findings suggest that its association with STEMO is related to how it is integrated into pedagogical practices and supported by institutional resources. The findings should also be interpreted within a bio-psycho-social perspective of the teaching–learning process. Teaching and learning involve interactions among learner, social, institutional and contextual dimensions. In the study, the psycho-social dimension is represented primarily through perceived STEM education outcomes and human infrastructure, including teacher-related capabilities and pedagogical support, while the technological-institutional dimension is represented by 3DPT and digital infrastructure. The biological dimension was not directly examined in the study. Thus the present study does not attempt to provide an assessment of the entire bio-psycho-social teaching–learning process; rather the present study focuses on the technological, psychological, pedagogical and social-institutional dimensions that are directly relevant to the integration of 3D printing in STEM education. This theoretical positioning is important when interpreting the findings and defining the scope of the conclusions.

Consistent with previous studies (Wang et al., 2024; Tejera et al., 2026), the findings indicate that 3DPT was positively associated with STEM education by enhancing students' engagement, motivation, and conceptual understanding. However, this study advances existing research by conceptualizing 3DPT as a multidimensional construct comprising technology availability, frequency of use, instructional integration, and access to complementary digital technologies. This approach provides a more detailed understanding of how different dimensions contribute to educational outcomes. Specifically, the results

indicated that availability of 3D printing technology alone has only a modest positive effect on STEM education outcomes, suggesting that access alone is insufficient to generate meaningful educational improvements. Although the availability effect was statistically significant ($\beta = 0.06$, $p = 0.001$), its relatively small coefficient indicates that its direct contribution is limited. Therefore, statistical significance should not be interpreted as evidence of a large educational effect. Instead, the educational value of 3D printing depends largely on its pedagogical integration and sustained use within teaching and learning activities. This finding provides a more cautious interpretation of the role of technology availability and suggests that simply providing 3D printing equipment may not be sufficient to produce substantial improvements in perceived STEM outcomes.

Among the factors examined, frequency of use emerged as the strongest predictor of STEM education outcomes. This finding lends empirical support to constructivist and experiential learning theories, which emphasize that knowledge is constructed through active engagement, repeated practice, and authentic learning experiences (Singh & Rao, 2024; Morris, 2020). Regular interaction with 3D printing technologies enables students to refine design ideas, test solutions, and learn through iterative problem-solving, thereby promoting deeper conceptual understanding. This finding is consistent with Tejera et al. (2026), who reported that sustained engagement with digital fabrication technologies significantly improved students' academic performance and participation in STEM learning. Nevertheless, because the present study is cross-sectional, the observed association does not establish that more frequent use of 3D printing necessarily causes better STEM outcomes.

Similarly, the significant effect of instructional integration underscores the importance of integrating 3D printing within curriculum design rather than treating it as an isolated technological resource. This finding aligns with previous research demonstrating that meaningful integration of digital fabrication into instructional activities enhances students' problem-solving abilities, creativity, and conceptual understanding (Tondeur et al., 2016/2017; Flowers, 2025). Furthermore, the positive contribution of complementary digital technologies, including computer-aided design software and digital modeling tools, reinforces constructionist learning theory by emphasizing learning through designing, creating, and refining digital artifacts (Jennifer, 2014). Together, these findings suggest that educational benefits arise from an integrated digital learning ecosystem in which technological tools complement one another throughout the learning process. However, these relationships should be interpreted cautiously because the STEM outcomes in this study were based on respondents' perceptions rather than objectively measured student achievement or observed classroom performance.

Similarly, beyond technology-related factors, institutional infrastructure plays a critical role in determining the effectiveness of 3D printing technology in STEM education. The significant positive effects of both human and digital infrastructure provide empirical support for socio-technical systems theory (Baxter & Sommerville, 2011), which argues that technological innovations produce optimal outcomes only when technological systems are aligned with organizational and human capabilities. In particular, the positive influence of human infrastructure supports the TPACK framework by demonstrating that teachers' ability to integrate technological, pedagogical, and disciplinary knowledge enhances the educational effectiveness of 3D printing. These findings are consistent with Bond et al. (2020) and Zawacki-Richter et al. (2022), who emphasized that teacher competencies and professional development are fundamental prerequisites for successful technology integration in education. Nevertheless, the present findings provide empirical support for these theoretical perspectives within the observed sample, rather than definitive confirmation of the theories, given the cross-sectional nature of the study.

Likewise, the significant contribution of digital infrastructure supports connectivism theory (Siemens, 2005), which emphasizes the importance of digital networks and technological environments in facilitating knowledge construction and collaborative learning. Reliable internet connectivity, digital platforms, and supporting software create conditions that enable students to access learning resources, collaborate effectively, and engage in technology-enhanced learning experiences. Consequently, the findings suggest that investments in digital infrastructure represent an essential institutional requirement for maximizing the educational benefits of 3D printing technologies. However, this interpretation should be considered in light of the fact that the measured outcomes were perceptual; therefore, the findings do not directly demonstrate corresponding improvements in objectively measured student achievement.

Furthermore, the results demonstrate that the association between 3D printing technology and perceived STEMO varies according to institutional infrastructure. The significant interactions between 3DPT and human infrastructure ($\beta = 0.36$, $p < 0.001$) and between 3DPT and digital infrastructure ($\beta = 0.43$, $p = 0.014$) provides direct statistical evidence of moderation. The positive interaction coefficients indicate that the association between 3DPT and perceived STEMO is stronger at higher levels of human and digital infrastructure. These findings extend the discussion beyond the direct associations of institutional infrastructure and suggest that technological and institutional conditions operate jointly within the observed educational context. This evidence reinforces socio-technical perspectives, which propose that technological innovations operate within complementary organizational capabilities and institutional resources (Mishra & Koehler, 2006; Bond et al., 2020). Accordingly, the educational impact of 3D printing should be understood as the outcome of interactions between technological, pedagogical, and institutional factors rather than the result of technological adoption alone. Importantly, the significant interaction effects indicate that the relationship between 3D printing technology and perceived STEM outcomes varies with institutional infrastructure, but they should not be interpreted as proof of a causal mechanism.

The findings also revealed that schools seeking to improve STEM education through 3D printing should move beyond simply acquiring technological equipment and instead prioritize frequent classroom use, meaningful curriculum integration, and sustained teacher professional development. Equally important is investment in robust digital infrastructure capable of supporting computer-aided design software, online collaboration platforms, and other complementary technologies required for effective digital fabrication. These findings indicate that successful implementation depends on a comprehensive institutional strategy that integrates technological investment with pedagogical capacity building and organizational support.

Similarly, the findings of this study illustrate that the integration of 3D printing technologies has considerable potential to enhance students' technical competencies, creativity, innovation, and problem-solving skills, thereby preparing graduates for participation in knowledge-based economies. However, disparities in infrastructure, technological resources, institutional capacity, and teacher preparedness may limit these benefits and potentially widen existing educational inequalities. Therefore, the successful implementation of 3D printing in education requires an enabling environment characterized by reliable infrastructure, supportive policy frameworks, sustained institutional investment, and continuous professional development for educators. Addressing these enabling conditions is essential for ensuring that the educational benefits of 3D printing are realized equitably across diverse educational contexts. At the same time, because STEM education outcomes were measured through self-reported perceptions, future research should combine survey measures with objective indicators such as student achievement, examination performance, classroom observations, or longitudinal measures to determine whether the observed relationships are also reflected in measurable educational outcomes.

Finally, the bio-psycho-social positioning adopted in this study highlights that the observed relationships represent selected dimensions of the teaching–learning process. The study primarily addresses psychological, pedagogical, technological, and social-institutional dimensions through perceived STEMO, HUI, 3DPT, and DII. The biological dimension was not directly measured and therefore should not be inferred from the findings. Future research could adopt longitudinal, experimental, or mixed-method designs incorporating objective student achievement measures, classroom observations, teacher practices, and learner-level characteristics. Such approaches would provide a more comprehensive assessment of how technological, psychological, social, institutional, and other relevant dimensions interact in technology-enhanced STEM education.

7. Implications and Contributions of the Study

7.1. Theoretical Contributions

This study makes several contributions to the theoretical literature on technology-enhanced STEM education. First, it develops an integrated conceptual framework that combines constructivism, constructionism, experiential learning, TAM, TPACK, socio-technical systems theory, and connectivism to explain the complex relationships among technological, pedagogical, and institutional factors influencing STEM education. By synthesizing these complementary perspectives, the study provides a broader theoretical lens for understanding technology integration in educational settings.

Second, the study advances the conceptualization of 3D printing technology by treating it as a multidimensional construct rather than a single technological resource. This perspective demonstrates that different dimensions of technology implementation represent distinct mechanisms through which educational outcomes may be achieved, thereby offering a more comprehensive framework for future research.

Third, the study extends the technology integration literature by positioning institutional infrastructure as both an enabling condition and a contextual factor that shapes the effectiveness of educational technologies. This contributes to the growing body of research emphasizing that technology adoption should be understood within broader organizational and institutional contexts rather than as an isolated intervention. The proposed framework also provides a foundation for future studies examining additional contextual factors that may influence the effectiveness of emerging educational technologies.

7.2. Practical Implications

The findings provide several practical implications for educators, school leaders, and policymakers seeking to strengthen STEM education through digital technologies. Educational institutions should adopt a strategic approach to technology implementation by aligning technological investments with curriculum design, instructional practices, and institutional capacity-building initiatives. Professional development programs should equip teachers with the pedagogical and technical competencies required to integrate digital fabrication technologies effectively into classroom instruction.

At the institutional level, investment strategies should extend beyond hardware acquisition to include sustainable digital ecosystems that support technology-enabled teaching and learning. This includes maintaining reliable ICT infrastructure, providing access to complementary digital tools, and establishing technical support systems that facilitate the long-term use of educational technologies. For policymakers, these findings highlight the importance of designing integrated educational policies that simultaneously address technological resources, teacher capacity, and institutional readiness to maximize the return on investments in educational innovation.

7.3. Social Implications

The findings have broader societal implications, particularly for countries seeking to strengthen human capital through STEM education. By supporting the development of technical, creative, and problem-solving competencies, the effective implementation of 3D printing technologies can contribute to preparing learners for participation in increasingly knowledge-based and technology-driven economies. As digital manufacturing technologies become more prominent across industries, educational systems have an important role in developing the competencies required for future workforce participation.

At the same time, the study highlights the importance of promoting equitable access to educational technologies. Differences in institutional capacity and digital infrastructure may limit opportunities for students in resource-constrained settings, potentially widening existing educational inequalities. Consequently, efforts to expand technology-enhanced STEM education should be accompanied by policies that promote inclusive access, strengthen institutional capacity, and reduce disparities in educational opportunities across schools and regions.

8. Conclusions

This study examined the relationship between 3D printing technology and STEM education outcomes, with particular emphasis on the moderating role of institutional infrastructure in Ethiopian secondary schools equipped with STEM centers and 3D printing laboratories. The findings confirm that 3D printing technology has a positive effect on STEM education outcomes; however, this effect varies across its dimensions, with frequency of use, instructional integration, and access to supporting digital tools demonstrating stronger influence than availability alone.

The study further demonstrates that institutional infrastructure plays a significant role in both directly influencing STEM education outcomes and strengthening the effectiveness of 3D printing technology. In particular, human infrastructure and digital infrastructure significantly enhance the relationship between 3D printing technology and STEM education outcomes, indicating that technology effectiveness depends on the readiness and capacity of the institutional environment.

From a theoretical perspective, the study contributes to the literature by integrating multiple theoretical lenses, including constructivism, constructionism, experiential learning theory, TPACK, socio-technical systems theory, and connectivism, to explain how technological and institutional factors jointly influence educational outcomes. The study also advances the literature by conceptualizing 3D printing technology as a multidimensional construct and empirically validating the moderating role of institutional infrastructure in technology-enhanced learning environments.

Practically, the findings suggest that successful implementation of 3D printing in education requires more than technology provision. Schools should prioritize frequent use of the technology, its integration into instructional practices, and continuous professional development for teachers. In addition, investment in digital infrastructure is essential to support effective implementation and sustainability of technology-enhanced learning.

Despite its contributions, this study has certain limitations. The cross-sectional design limits the ability to draw causal inferences, and the findings are based on data collected from selected secondary schools, which may limit generalizability to other educational contexts. Future research could employ longitudinal or experimental designs to examine causal relationships more robustly. Comparative studies across different educational levels or regions are also recommended. Additionally, future research may incorporate qualitative approaches to provide deeper insights into how 3D printing is implemented in classroom practice.

In conclusion, the study highlights that the educational value of 3DPT is not determined by access alone but by how effectively it is integrated into teaching and supported by institutional capacity. Strengthening both pedagogical practice and institutional infrastructure is therefore essential for maximizing the benefits of emerging educational technologies in STEM education.

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Institutional Review Board Statement: Prior to the study, formal written permission was obtained from the research ethical committee of Ambo University, school of Mechanical and industrial Engineering, Department of Industrial Engineering, and the permission letter was attached to the questionnaire and distributed to the participants. After all participants had been fully informed about the objectives of the study and how the collected data would be used, verbal informed consent was obtained from each study participant. Verbal rather than written consent was obtained because of the very low sensitivity of the information that needed to be collected. For the confidentiality of the participants, no personal identifiers were used in the data collection questionnaire, and the data obtained from the study participants were not accessed by anyone except the authors. In addition, participants' names and other personal identifiers were not used in any sections of the manuscript.

Data Availability Statement: The original contributions presented in the study are included in the article; further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

3D	Three-dimensional
3DPT	3D printing technology
ABO	Affective and behavioral learning outcomes
ASD	Access to digital resources
AVE	Average Variance Extracted
AVL	Availability
CFI	Comparative Fit Index
COA	Cognitive outcome
CR	Composite Reliability
DII	Digital infrastructure
FUT	Frequency of usage
GFI	Goodness-of-Fit Index
HUL	Human factor
IIP	Integration into instruction
KMO	Kaiser-Meyer-Olkin
RMR	Root Mean Square Error of Approximation
RMSEA	Root Mean Square Error of Approximation
SEM	Structural Equation Modeling
STEM	Science, Technology, Engineering and Mathematics
STEMO	STEM education outcomes
TAM	Technology Acceptance Model
TLI	Tucker–Lewis Index
TPACK	Technological Pedagogical Content Knowledge

Appendix A

Table A1. Survey questionnaire.

Items	Item Statement	Sources
AVL2	My school has access to functional 3D printing equipment for teaching STEM subjects.	Inoma et al. (2020); Anđic et al. (2023); To et al. (2024)
AVL3	3D printing facilities are available when needed for instructional purposes.	Anđic et al. (2023); To et al. (2024)
AVL4	The school has adequate physical resources to support 3D printing activities.	Inoma et al. (2020); To et al. (2024)
FUT3	I frequently use 3D printing technology in teaching STEM lessons.	Ford and Minshall (2019); Anđic et al. (2023); To et al. (2023)
FUT4	I often design learning activities that involve 3D printing.	Lin et al. (2018); Song and Wen (2018)
FUT5	Students frequently engage with 3D printing projects in my classes.	Lin et al. (2018); Song and Wen (2018); Omer et al. (2023)
IIP2	I use 3D printing to explain complex STEM concepts.	Lin et al. (2018); Pantazis et al. (2021)
IIP3	3D printing is aligned with my teaching methods and curriculum.	Mishra and Koehler (2006); Tondeur et al. (2016/2017)
IIP4	I design problem-solving activities using 3D printing tools.	Lin et al. (2018); Levin and Verner (2020); Song and Wen (2018)
IIP5	3D printing is effectively embedded in my instructional process.	Mishra and Koehler (2006); To et al. (2023)
ASD1	I have access to CAD software for 3D modeling.	Charles et al. (2018); Anđic et al. (2023)
ASD2	Digital tools and simulation software are available for STEM teaching.	Charles et al. (2018); Mishra and Koehler (2006)
ASD3	Students can access online resources for 3D design and learning.	Wisdom and Novak (2020); To et al. (2024)
HUI1	Teachers in my school are trained in using 3D printing technology.	Mishra and Koehler (2006); Tondeur et al. (2016/2017)
HUI2	Technical support is available for 3D printing activities.	Inoma et al. (2020); To et al. (2024)
HUI3	Professional development programs on educational technology are provided.	Endale et al. (2022); Tonkolu et al. (2026)
DII1	My school has reliable internet connectivity for digital learning.	Bond et al. (2020); Shahroom and Hussin (2018)
DII2	The school provides sufficient computer facilities for STEM education.	Shahroom and Hussin (2018); To et al. (2024)
DII3	Digital learning platforms are available for teaching and learning.	Bond et al. (2020); Kerimbayev et al. (2023)
DII4	Software required for STEM instruction is accessible.	Charles et al. (2018); Mishra and Koehler (2006)
DII5	The school supports digital collaboration tools for students and teachers.	Bond et al. (2020); Kerimbayev et al. (2023)
COA1	Students show improved understanding of STEM concepts.	Lin et al. (2018); Pantazis et al. (2021); Ferlyn et al. (2025)
COA2	Students demonstrate better problem-solving abilities.	Almulla (2023); Lin et al. (2018); Levin and Verner (2020)
COA3	Students perform better academically in STEM subjects.	Lin et al. (2018); Pantazis et al. (2021); Tamim et al. (2011)
COA4	Students show improved critical thinking skills.	Almulla (2023); Bou Saad et al. (2025); Wang et al. (2024)
ABO1	Students are more motivated in STEM learning activities.	Abu Khurma et al. (2023); Pantazis et al. (2021)
ABO2	Students show higher engagement in STEM classes.	Lin et al. (2018); Abu Khurma et al. (2023); Wang et al. (2024)
ABO3	Students demonstrate creativity in STEM projects.	Almulla (2023); Lin et al. (2018); Song and Wen (2018)
ABO4	Students collaborate effectively in STEM tasks.	Avinal and Aydın (2022); Xu and Ouyang (2022); Lin et al. (2018)

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