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Research article

Impact of 3D-printed models on elementary students' space science learning: Mixed methods and classroom action research study

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Abstract: Three-dimensional (3D) printing is recognized as a powerful tool for enhancing science education, creating tangible and interactive models that help students better understand complex scientific concepts and improve scientific literacy. This study investigated the impact of integrating 3D-printed science models as educational materials on elementary students' academic performance in space science. It also explored students' perceptions of the utilized models. The study employed an embedded mixed methods design and classroom action research. The quantitative phase used total enumeration and pre- and post-test assessments to gauge students' academic performance. The embedded qualitative phase consisted of semi-structured interviews with a few students to determine their perceptions of the 3D-printed science models used. Thirty-two Grade 6 students from an elementary school in Tinoc, Ifugao, Philippines, participated in the study. Quantitative results revealed a significant improvement in students' academic performance after integrating 3D-printed science models in their space science lessons. Qualitative findings disclosed five main themes: models' physical attributes, learning benefits, challenges experienced, personal preference, and suggestions for improving the models. Students found the models visually appealing, engaging, and interactive, with reasonable sizes that present concrete objects. The models, however, were viewed to be fragile, insufficient, and with unpleasant smells. The students suggested that more models with articulated parts should be printed in bigger sizes. Conclusively, this study demonstrates that integrating 3D-printed models as innovative science educational materials impacts elementary students' space science learning experience. Future studies should refine 3D-printed models to maximize their educational potential in science education.

Keywords: 3D printing, 3D-printed models, 3D-printed science models, elementary space science, science education, science educational materials, Philippines

1. Introduction

The world is changing fast, and technology is opening up new possibilities. Technology facilitates more effective teaching and learning processes than traditional instructional methods, enhancing teaching pedagogy and student engagement [11,14]. One of the emerging technologies is the three-dimensional (3D) printing technology that provides new learning opportunities [26]. Initially emerging as a tool for industrial purposes, 3D printing has found its place in classrooms, enabling teachers to create differentiated instruction. As it becomes increasingly accessible, integrating 3D-printed models into science education continues to expand, fostering innovation and enriching students' learning. The growing influence of 3D-printed models in reshaping the teaching and learning process highlights the importance of investigating how such models can be effectively utilized in science education.

3D printing, commonly known as additive manufacturing (AM), uses digital computer–aided design (CAD) modeling to construct 3D objects and 3D printers to assemble materials layer-by-layer [23,41]. This allows the creation of physical replicas that closely resemble the original objects. It captures precise dimensions and intricate features, making it possible to reproduce complex designs accurately. Further, 3D digital models are versatile assets that can be easily manipulated [29]. They can be scaled up or down to suit different applications, repurposed for various functions or educational needs, and customized with specific modifications to meet unique requirements. It has much potential and could be used in almost all scientific fields [2,4].

This versatility has fueled 3D printing's rise as a popular educational tool in recent years, as it can transform digital models into tangible objects, making it a valuable tool in classrooms. As 3D printers become increasingly accessible and commercially available, schools have begun adopting them as tools to enhance teaching and learning [10,21]. It allows educators to produce educational models, tools, spare parts, and even functional prototypes, offering a multifunctional approach to pedagogy [44]. By enabling students to engage with tangible objects [13], 3D printing supports hands-on learning, collaboration, and communication [2,13], hence making lessons more engaging across subjects. It can improve comprehension and retention, particularly for visual and kinesthetic learners, as students can manipulate physical objects tied to lesson content [1,19]. These benefits extend to younger learners, encouraging critical thinking, problem-solving skills [5], and self-guided inquiry, while deepening conceptual understanding of various theories [10].

Given this growing evidence, integrating 3D printing in science education is timely and strategic, particularly in science, technology, engineering, and mathematics (STEM), and the inclusion of artistry in the science, technology, engineering, arts, and mathematics (STEAM) curriculum. 3D printing can foster students' creativity, collaboration, problem-solving, and higher-order thinking skills (HOTS), and impact their interests, engagements, beliefs, and careers toward STEAM learning [24]. It could be an excellent tool for achieving the goals of STEAM [35] and help students develop competencies like inquiry and critical thinking [10]. It can accommodate diverse teaching and learning styles, such as the capacity to identify solutions, learn from mistakes, and solve challenges, enhanced by the design experience affected by 3D printing.

Globally, these trends are mirrored by the growing adoption of 3D printing in the Philippines. The current status of 3D printing in the country reflects increasing interest and steady growth. Although still an emerging technology, it demonstrates significant potential and is now applied across various sectors, including manufacturing, education, healthcare, and design. Despite this growing interest, public infrastructure supporting 3D printing remains limited, with notable facilities including the Advanced Manufacturing Center (AMCen) and the Additive Manufacturing Research Laboratory (AMREL). AMCen, the country's first AM hub, offers cutting-edge 3D-printing technologies and rapid prototyping capabilities [18,30]. Similarly, AMREL is a state-of-the-art research facility equipped with advanced AM machinery aiming to establish itself as the nation's leading institution for research in 3D-printing technologies, methodologies, and materials [40].

Clearly, the emergence of 3D-printed models offers innovative ways to engage students, enrich pedagogy, and create more meaningful learning experiences. These attributes make them a promising educational material for science education. However, despite the growing global and local 3D-printing infrastructure, 3D-printed models' integration in elementary science education remains in its infancy. Their adoption as structured instructional tools for space science lessons is largely unexplored. In response to these gaps, this study investigated the integration of 3D-printed models into elementary space science education and examined their effects on students' academic performance, perceptions, and overall experiences. By aligning with learning competencies, this research aimed to provide evidence-based insights on how 3D-printed science models can be utilized as teaching tools. Hopefully, findings from this study will inform educational stakeholders, offering practical guidance for technology-enhanced instruction. In doing so, this research contributes to advancing science education, improving space science literacy, and fostering a broader, more meaningful adoption of innovative technologies in elementary classrooms.

2. Literature review

2.1. 3D-printing technologies in education

3D printing is increasingly recognized as a transformative educational technology with significant potential to enhance teaching and learning. It enables educators to create tangible, customized models that make complex concepts more accessible and engaging. When integrated into classroom instruction, it promotes deeper conceptual understanding and supports the development of cognitive and practical skills. It allows students to associate directly with abstract concepts, making complex ideas more accessible and comprehensible. This technology has been shown to boost student motivation, creativity, and problem-solving abilities while strengthening knowledge retention.

For instance, Fokides and Lagopati [21] determined that integrating 3D printers in primary education has been shown to improve students' knowledge and skill development. Avinal and Aydin [6] found that students were thrilled with the activities created using 3D printing, increasing students' expectations of the lessons. They participated actively and remarkably assimilated these activities. They were not bored or distracted and showed great desire and high participation. Because of the intense focus and with the aid of 3D printing, the students did not face many challenges or issues during their classes.

In another study, Arslan and Erdogan [3] indicated that most students were optimistic about the impact of 3D-printed objects on their learning. They claimed that the objects transformed abstract concepts into concrete visual representations, facilitated learning, made lessons enjoyable, provided learning retention, encouraged them to learn more, increased their interest, and assisted them in developing creative thinking and design skills, allowing them to create various content-specific educational materials.

In relation to science education, Tanabashi [43] demonstrated that integrating 3D printing into a cross-disciplinary STEAM project positively impacted student learning and engagement. Students collaboratively created 3D-printed models that led to a deeper understanding of complex biological structures and functions. It fostered improved knowledge retention compared to traditional teaching methods. Student motivation and participation increased significantly due to the innovative and collaborative nature of the task, underscoring the effectiveness of 3D-printed science models as teaching tools for science education.

Likewise, Trujillo-Cayado et al. [45] found that incorporating 3D-printed models into science education significantly enhanced student learning and performance. Students who built models achieved better academic results than a control group. It increased student engagement and made learning more enjoyable. It facilitated a deeper understanding of complex chemical structures and concepts. Trujillo-Cayado et al. [45] concluded that 3D-printed models are a valuable tool for improving the effectiveness and engagement of STEM disciplines.

2.2. Elementary space science education in the Philippines

Elementary science education in the Philippines has undergone significant transformations in recent years, particularly with the implementation of the Kindergarten to Grade 12 (K-12) curriculum by the Department of Education (DepEd). This is especially due to the effect of the most recent coronavirus (COVID-19) pandemic, which significantly disrupted education in the country. The shift to remote and blended learning in the Philippines [15] had profound effects on its science education, impacting both the delivery of content and the engagement of students. This experience highlighted the need for long-term reforms in science education in the country. There is a greater push for integrating innovative tools, improving teacher training in technology, and developing more flexible curricula that can adapt to various learning environments [12,20]. The K-12 Science curriculum aims to equip students with the knowledge and skills needed to be informed citizens who can make responsible decisions about science-related issues impacting society, health, and the environment. It focuses on producing well-rounded individuals knowledgeable about science, technology, and the environment. These individuals should be able to solve problems creatively, care for the environment, make informed decisions, communicate effectively, and contribute positively to society [16,17].

In particular, space science is one of the primary topics for Grade 6 in the K-12 Science curriculum, covered during the last quarter of each academic year. It focuses on understanding the broader context of the Solar System, space exploration, celestial bodies, and the technological advancements that allow humanity to study the known universe. Students learn about the Earth's rotation and revolution motions, and relate these to the occurrence of day and night, the length of a day and a year, and the relative movement of the Sun, Moon, and stars [16]. Key topics include exploring the Solar System, emphasizing the different planets, their moons, their unique characteristics, and the Earth–Moon–Sun system. Students also learn about the Earth's Moon's phases, tides, and the concept of gravity affected by the Moon. The curriculum introduces basic principles of space exploration, such as the role of satellites and space missions, which help students appreciate how space science contributes to advancing human knowledge and technology. Hands-on activities and inquiry-based learning strategies encourage students to engage with these concepts through observations, models, and experiments [16].

In this study, the space science lessons that integrated 3D-printed models as educational materials focused on two key topics from the Grade 6 K-12 Science curriculum: 1) motions of the Earth and 2) the Solar System. The specific learning competencies addressed in these topics were as follows: a) "relates the rotation and revolution of Earth to the occurrence of day and night, the apparent movement of the Sun, Moon, and stars, and the lengths of a day and a year", and b) "compares the eight planets of our Solar System" [16].

The first lesson, Motions of the Earth, utilized 3D-printed models of several rockets, the Earth, Sun, and Moon to illustrate concepts such as rotation and revolution, their effects on day and night, and the changing positions of celestial bodies. For example, students physically manipulated the 3D-printed Earth model to simulate its rotation on its axis and revolution around the Sun, observing how these motions lead to day and night, as well as the apparent movement of the Sun and stars. Students were encouraged to predict the length of a day or a year based on the Earth's movement. This experiential use of the models reinforced the competency of relating Earth's motions to observable phenomena, ensuring that the models directly supported the instructional objectives.

For the Solar System lesson, the 3D-printed models represented the eight planets, designed to highlight their relative sizes, surface features, and orbital positions. Students engaged in activities where they compared the planets' characteristics while arranging the models in their correct order. The models complemented the lesson's content on planetary comparison, enabling students to develop a more accurate mental model of the planets of the Solar System. In addition, the rocket models were used to demonstrate space travel and the role of technology in studying the Solar System and other heavenly objects found in it, aside from the planets. This was complemented by activities where students simulated rocket launches concerning space exploration. Interacting with these models encouraged a deeper conceptual understanding of planetary relationships and characteristics.

2.3. Theoretical framework

Constructivism, a foundational theoretical lens of this study, emphasizes learners' active construction of knowledge through meaningful, real-world experiences [19,37]. It suggests that education should empower students to create knowledge, rather than passively receive it [7]. This empowerment was key to the study's focus, aligning with integrating 3D-printed science models as educational materials in science lessons. These models offer opportunities for students to visualize and manipulate abstract scientific concepts, encouraging them to link theoretical knowledge with practical, real-world applications. The constructivist emphasis on creativity, ownership of learning, and active participation parallels the aims of this study, which investigated the students' academic performances in space science and their perceptions of using 3D-printed models as educational tools.

By examining students' academic performances, the study sought to determine whether integrating the models led to measurable cognitive gains in space science. The quasi-experimental focus and use of pre- and post-test results directly corresponded to evaluating the extent of conceptual understanding that emerged when students actively engaged with the models designed to support visual and tactile exploration. The study's exploration of students' perceptions of the 3D-printed models aligned with the constructivist learner-centered orientation. Understanding how students interpret and respond to the learning experience provided critical insight into the success and authenticity of using the models. The depth of understanding achieved through this exploration is a testament to the study's thoroughness. Determining students' perceptions of the models enabled the study to uncover how they evaluated their learning experiences when exposed to constructivist-based instructional methods.

The mixed-methods embedded design and classroom action research approach adopted in this study reflected a constructivist lens. The embedded design, which integrates qualitative data within a predominantly quantitative framework, allowed for a richer and more nuanced understanding of how 3D-printed models influenced learning. Adopting classroom action research aligned with the constructivist principle of continuous improvement based on lived experiences in authentic learning contexts. The data analysis strategies employed in this study further reinforced the constructivist orientation. The pre- and post-tests provided empirical evidence of the learning gains. Complementing this, the manual thematic analysis of interviews offered insights into how students construct meaning and connect personally with the content. By triangulating these data sources, the study not only measured the impact of the intervention but also explored the dimensions of students' creativity, collaboration, and motivation, which are key hallmarks of constructivist learning.

Another theory supporting the use of 3D printing in science education is experiential learning. It involves a cyclical process of doing, reflecting, thinking, and applying, making learning more meaningful and engaging for students as they use their understanding in solving problems or making predictions [25]. It is a dynamic, student-driven approach to learning that emphasizes direct engagement with experiences, followed by analysis and reflection [22,27]. This theory aligns directly with the study's aims and research questions, providing a coherent and relevant framework for the research. Engaging with the models encourages students to hypothesize, test ideas, and reflect on their understanding, mirroring the experiential learning. By assessing students' pre- and post-test results, the study evaluated how this experiential engagement with the models translated into measurable improvements in learning outcomes. Moreover, exploring students' perceptions through qualitative data collection captured the reflective and analytical components of experiential learning, providing insights into how students processed and applied their experiences after using the models.

Experiential learning principles equally informed the study's research design and data analysis. The embedded mixed-methods design and classroom action research framework support the iterative nature of experiential learning, where direct experiences (i.e., integrating 3D-printed models as educational tools) were followed by reflection and evaluation to improve teaching pedagogies. The pre- and post-tests quantified how effectively experiential activities enhanced students' academic performance using the models. At the same time, interviews and observations uncovered how students engage with, reflect on, and internalize these experiences. Data analysis methods revealed evidence of academic gains, while thematic analysis highlighted patterns in students' reflective feedback. Together, these methods provided a comprehensive understanding of how integrating 3D-printed models, when framed through experiential learning, can enhance elementary students' space science conceptual understanding and support achievement of learning competencies.

3. Current study

3.1. Research gap

Although 3D printing has gained recognition as an innovative educational tool, much of the existing literature has primarily highlighted its benefits for student engagement, creativity, and motivation [6,21]. Studies have shown that 3D-printed models transform abstract concepts into concrete and tangible learning experiences, which enhance comprehension and retention [43,45]. However, despite these positive outcomes, there remains a lack of empirical studies examining how 3D-printing technology impacts academic performance in specific science domains, such as elementary space science. While existing studies often focus on general STEM applications or interdisciplinary STEAM projects [24,35,43], few have explored how 3D-printed models directly support learning competencies tied to curriculum standards, such as the Philippine K-12 Science curriculum. This gap limits an understanding of 3D printing's effectiveness as a structured educational material beyond its novelty and engagement value, especially in a local context. Moreover, while 3D printing is lauded for promoting hands-on and inquiry-based learning [5,10], there is a dearth of evidence on its potential to enhance students' conceptual understanding of elementary space science. In the Philippine setting, where the integration of advanced technologies like 3D printing in elementary science is still in its infancy [18], this research gap is particularly pronounced. The present study is designed to fill this void by investigating how 3D-printed models in space science influence students' academic performance and perceptions, thereby providing empirical evidence on their effectiveness as educational tools and in meeting curriculum-based learning competencies.

3.2. Research aims and questions

This study aimed to investigate the impact of integrating 3D-printed science models as educational materials in elementary space science education. The study also aimed to determine students' academic performance as affected by integrating 3D-printed science models and their perceptions of them. The following questions guided the study:

1. What are students' academic performances in space science before and after integrating the 3D-printed science models as educational materials?
2. Is there a significant difference in students' pre- and post-test results after integrating 3D-printed science models?
3. What are the students' perceptions regarding using 3D-printed science models in space science lessons?

3.3. Research significance

This study holds significant implications for both the field of education and the advancement of elementary space science education. The results and findings of this study contribute to a growing body of knowledge on the use of 3D printing as a pedagogical tool in elementary science education. By investigating the impact of 3D-printed science models on students' academic performance and perceptions, this study can provide valuable evidence to guide educators, students, and other stakeholders in enhancing science education. Educators may gain practical, evidence-based insights into the effectiveness of 3D-printed models in space science lessons, enabling them to make informed decisions in integrating such technologies into their curriculum. These insights can help teachers refine instructional strategies to create more engaging, hands-on learning experiences that foster deeper conceptual understanding and critical thinking. On the other hand, students may benefit directly from this approach by experiencing interactive and enjoyable learning environments, which can increase motivation, curiosity, and comprehension, especially for those who struggle with abstract concepts or traditional teaching methods.

Beyond teachers and students, this study may also inform school administrators, curriculum planners, and policymakers. Findings of this study can support curriculum designers in aligning 3D-printing technologies with national standards, such as the Philippine K-12 Science curriculum, while encouraging the inclusion of innovative, inquiry-based teaching tools. Policymakers may consider this evidence when allocating resources for educational technologies, ensuring equitable access to 3D printing in schools. Educational technology developers and 3D printing advocates may also benefit from the study's results by understanding how their tools are applied in real-world classrooms, allowing them to design models better suited to teachers' and students' needs. This study enhances space science teaching and supports broader goals of educational innovation, technological integration, and improved science literacy among elementary students.

4. Methodology

4.1. Research design

The study employed an embedded design, mixed methods, and classroom action research. Qualitative data were embedded within the quantitative framework to provide a richer understanding [46]. This design proved most suitable for focusing on quantitative data, while gaining a deeper understanding through qualitative data. A quasi-experimental design utilizing pre- and post-tests was employed for quantitative data gathering and analysis, offering an efficient and pragmatic approach to evaluate a group undergoing an intervention [42]. Thematic analysis was used to analyze, interpret, and determine patterns or themes to uncover the qualitative data's underlying meanings, ideas, and perceptions [31].

The study primarily focused on assessing the effectiveness of 3D-printed science models as educational materials in elementary space science. This involved gathering students' academic performance as quantitative data. Qualitative data were embedded in the study through interviews and observations of the students to gain a richer understanding of the quantitative results. This captured students' perceptions and experiences of the 3D-printed science models when used as educational materials during science lessons. While the pre- and post-tests were conducted at the beginning and end of the lessons, the interviews and observations were conducted during the lesson proper, when the 3D-printed science models were utilized in teaching space science.

Classroom action research is a reflective, systematic process where educators examine their teaching practices, assess the effectiveness of instructional strategies or interventions, and make data-informed decisions to improve classroom management and student learning outcomes [33]. Its goal is to enhance student engagement, understanding, and achievement within the classroom environment and, thus, refine teaching methods and strategies. By promoting critical reflection, it serves as a direct and empirical tool for addressing classroom challenges and adapting to diverse student needs. Specifically, this study utilized the cyclical four stages of action research by Mertler [34]: planning, acting, developing, and reflecting. Through an embedded design and classroom action research, the study yielded a rich dataset that informed whether the 3D-printed science models improved students' academic performance, and how students felt about using them in their science lessons. This provided a well-rounded view of the models' success and areas for improvement, offering a robust, flexible, and comprehensive approach to the study's conduct. This combination proved highly suited to the study's context, considering the curriculum's specified duration of science lessons and the need to prioritize quantitative data and analysis over qualitative data collection.

4.2. Participants

The participants comprised 32 Grade 6 students from a public elementary school in Tinoc, Ifugao, Philippines. The student population comprised 46.88% (N = 15) males and 53.13% (N = 17) females. The students were selected using total enumeration, as recommended by the School Head and the Class Adviser, based on the grade section where one of the researchers was teaching. The quantitative data involved a total enumeration of students’ academic performances. They were designated with pseudonyms from S1 to S32. The qualitative phase only involved 13 students who volunteered for the interviews. Their pseudonyms for the quantitative and qualitative phases remained the same. The study was conducted from February to April 2025, the last quarter of academic year 2024–2025.

4.3. Materials

The study utilized 3D-printed models of the Earth and its Moon, the Solar System, and various rockets (see Appendix A). Because of the 3D printer's restrictive specifications, the models were created in a monochrome color. The models were printed in several sets, but in smaller sizes due to the availability of filaments and time limitations. The models were edge-trimmed, sanded, and air-dried to eliminate possible risks and dangers. The researchers did not develop any of the models used. Instead, the models were carefully chosen and acquired from reputable online, open-access sources. This was due to time constraints, having only one available 3D printer, and the need for extensive printing times. The models were taken from several online designs shared by their makers or designers (see Appendix B). The researchers simply resized the models and printed them. The researchers make no claim to ownership or intellectual property for any of the 3D model designs used; their respective makers or designers own them. Although several identical model designs were available, the researchers chose the ones that were the easiest to print.

The materials for this study included the A1 Mini Desktop 3D printer, plastic filaments, and Bambu Studio slicing software. The A1 Mini Desktop 3D printer is a high-quality, user-friendly 3D printer, featuring a convenient interface for easy operation. It is a compact and feature-rich printer that can provide a compelling blend of sophistication and simplicity of use due to its automatic calibration, multi-color printing, and silent operation. This makes it an exceptional choice for both novice and expert users. It can print 3D models with a maximum build volume of 180 mm × 180 mm × 180 mm. It adopts an open-source technology, making it simple to link with a home network, and allows one to remotely monitor and control printing from a digital device [8]. These features made the A1 Mini well-suited for the scope of the study, supporting efficiency and versatility in printing space science models.

Bambu Studio is the compatible slicing software for the A1 Mini. A slicing software in 3D printing is a tool that converts a 3D model into a series of thin, horizontal layers, or slices, that the 3D printer can understand and print [32]. The Bambu Studio offers a range of advanced features tailored to optimize print quality and efficiency, such as automatic support generation, customizable print settings, and real-time print monitoring. The software supports various filament types and specialty materials, allowing users to fine-tune print parameters like layer height, infill density, print speed, and temperature. It allows seamless integration with the A1 mini hardware, providing a smooth user experience with print preview, queue management, and cloud-based functionality [9].

This study used polylactic acid (PLA) and acrylonitrile butadiene styrene (ABS) filaments. These two are the most common plastic filaments used in 3D printing. PLA filament is a biodegradable thermoplastic polymer known for its ease of use and durability [10]. PLA is unique because it is good for the environment [39]. It is made from plants and can break down naturally in special composting facilities. It is also safe because it does not release harmful chemicals while printing. It has a low printing temperature and adheres well to various print surfaces, reducing the likelihood of warping. PLA is known for its smooth finish and ability to produce detailed prints with sharp edges and vibrant colors. It is ideal for the creation of educational models [39].

Alternatively, ABS is a widely used thermoplastic in 3D printing known for its durability, strength, and heat resistance. It is commonly used for functional parts, mechanical components, and prototypes that require robustness and the ability to withstand higher temperatures. ABS has a higher printing temperature than PLA, often requiring a heated print bed to reduce warping and ensure good adhesion during printing [38]. It is more flexible and impact-resistant than PLA, making it ideal for producing items that need to endure stress or rough handling. However, ABS can emit fumes during printing, so printing in a well-ventilated area or with an enclosed 3D printer is recommended. While it offers strong performance, its tendency to warp and its sensitivity to environmental factors make it less beginner-friendly than PLA [38]. Despite these issues, ABS remains popular for producing tough, functional, high-quality 3D prints.

4.4. Instrument: validity and reliability

For quantitative data collection, the test items used in the pre- and post-test assessments were adopted from the teacher's science module for the Grade 6 level. The assessments comprised 10 multiple-choice questions to measure students' understanding of space science concepts. The test items were standardized and provided by DepEd, indicating that these underwent expert review and pilot testing to ensure appropriateness for the target grade level. Utilizing test items from the module ensured content validity and reliability, as the questions were directly aligned with the Grade 6 curriculum standards and learning competencies prescribed by the DepEd [16]. This alignment guaranteed that the test items accurately measured the intended learning outcomes, specifically the students' understanding of space science concepts. To further enhance reliability, the same set of 10 multiple-choice questions was used for both the pre-test and post-test, eliminating variability in test difficulty and allowing direct comparison of student performances.

Guide questions were used to gather qualitative data and were carefully reviewed to ensure construct validity and adherence to qualitative research standards. The initial set of questions underwent expert evaluation by three professional elementary science teachers from the same school, who assessed the relevance, clarity, and alignment of the questions with the research objectives and questions. Their feedback was incorporated into the final design of the guide questions to accurately capture students' experiences and perceptions of the 3D-printed science models used. In line with qualitative research philosophy, trustworthiness, transferability, dependability, and confirmability [28] were emphasized.

Trustworthiness was addressed by ensuring the questions were contextually grounded and could elicit authentic responses from volunteer student participants [36]. Credibility was reflected by sharing the interview transcriptions with the students to verify the accuracy and authenticity of their responses. Transferability was supported by aligning the questions with situations that could be meaningfully applied to similar educational settings. Dependability and confirmability were ensured through a transparent validation process, where expert feedback served as a form of peer review, enhancing the rigor and reliability of the qualitative data collection process.

To enhance trustworthiness, each researcher manually and independently coded subsets of the transcribed responses. Then, an agreement was established by comparing and discussing the coding outputs to reach consensus, refining the codes to ensure consistent application of themes across the dataset. This collaborative approach minimized individual bias and strengthened the credibility of the findings. Bracketing was also employed, particularly in terms of credibility and confirmability. The researchers consciously identified and set aside personal assumptions, biases, and preconceived notions about the effectiveness of 3D-printed models to ensure that the students' authentic experiences guided the findings. This process ensured that the emerging themes and interpretations were grounded in the students' perspectives, rather than the researcher's expectations. Moreover, to ensure the integrity of the translations, help from an English language expert, who was also fluent in the students' local language, was sought.

4.5. Procedures

The study utilized an embedded mixed-methods design in combination with Mertler's [34] cyclical four-step action research model, consisting of planning, acting, developing, and reflecting. Quantitative (pre- and post-test scores) and qualitative (interviews, observations, video recordings) data were collected at different stages and integrated during analysis to provide a comprehensive understanding of students' academic performance and perceptions. A concise procedural flow of the study is illustrated in Figure 1.

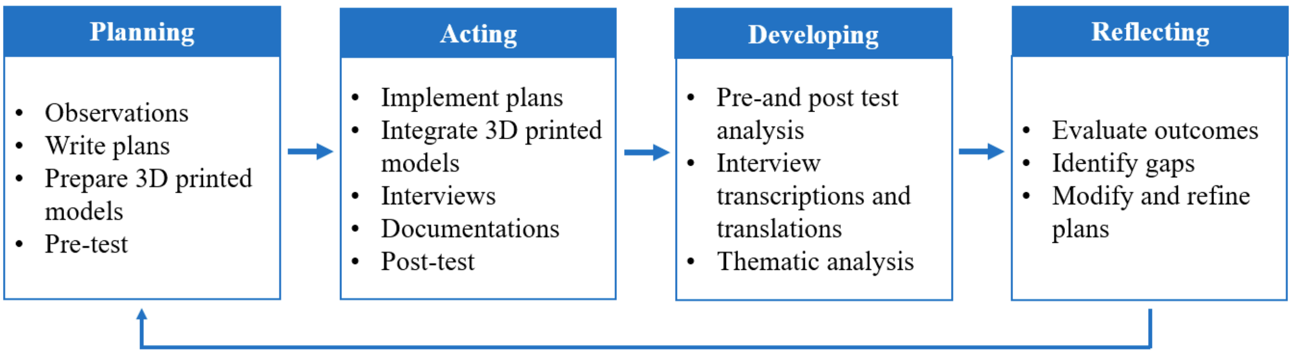

Figure 1. Procedural flow of the study.

First, classroom observations were conducted during the planning. Classroom observations were conducted to identify challenges in teaching space science concepts and to determine where 3D models could enhance instruction. Interventions were planned by designing lesson plans that integrated 3D-printed science models. The models were carefully selected, downloaded, sliced, and printed in at least four sets each. They were trimmed and cleaned to remove sharp edges and ensure students’ safety. A pre-test assessment among the students was also conducted at this stage, serving as the initial data for students' academic performance.

During the acting stage, the planned interventions were implemented over five consecutive science lessons, each lasting 45 minutes. In every lesson, at least two 3D-printed models were used as the primary teaching aids during activities, demonstrations, or supplementary tools to support content delivery. These interventions aimed to make space science's abstract concepts tangible. During the delivery of lessons, observations and documentation of any visible changes in students' perceptions and engagement before and after the integration of 3D-printed science models were undertaken. The students were asked open-ended questions regarding the models' utilization. The questions were incorporated while students were handling the models or at the end of the lessons, to avoid confusing the students with their learning process and study conduct. A video recording of the whole lesson was done to help the researchers document students' actions and responses when using models. The video recordings captured complex interactions that might be missed in real-time observations. After completing the week-long lessons incorporating 3D-printed models, a post-test assessment was conducted to measure changes in students' academic performance.

In the developing stage, quantitative data on students' performances were tallied on a spreadsheet, and statistically computed and analyzed. Students' papers were returned immediately after recording. The pre- and post-test scores were compared to determine if there was a significant improvement in students' academic performance after integrating the 3D-printed science models. Further, the students' interview responses were transcribed. Translations into English were done based on their responses, which were stated in their local language. Manual thematic analysis of student responses was done to identify key themes. Recurring themes were identified, which aided in understanding whether a change in students' scores was linked to their perception and experience of the models.

Finally, in the reflecting stage, the overall effectiveness of the intervention was evaluated in relation to the research aims and questions. The researchers critically examined how integrating 3D-printed science models influenced student learning gains and perceptions. This stage also involved identifying the intervention's strengths, weaknesses, and limitations, as well as the data collection process. Importantly, the lesson and action plans were refined and modified for future use, incorporating feedback from students' qualitative responses and suggestions. This process ensured that the refined instructional strategies and 3D-printed models would be better aligned with curriculum standards, space science learning competencies, and student needs in subsequent cycles of future action research. The reflection phase concluded with recommendations for broader implementation and avenues for further research.

Before conducting the study, the researchers obtained permission from the School Principal and the Grade 6 students' Class Adviser for data collection and video recording. Once approved, informed consent was solicited from students' parents or guardians. The consent reflected the study's objectives, scope, methodology, and possible student benefits. The informed consent also indicated the voluntary withdrawal of the child or ward's participation in the data collection process without penalty. The withdrawal only applied to data collection from the students. After obtaining consent, the students were also oriented toward the study's purpose, procedures, and potential hazards. The study encompassed all students, as it was conducted during science lessons.

4.6. Data analysis and management

The researchers were in charge of data gathering and analysis for embedded design and classroom action research, as well as integrating 3D-printed science models as educational materials.

For data tabulations and encoding, each student was assigned a pseudonym. Their personal information was removed for anonymity and confidentiality. Both quantitative and qualitative data were systematically analyzed to ensure accuracy, consistency, and rigor.

For the quantitative component, the conduct of pre- and post-tests was managed, checked, and appropriately recorded. Means (M), standard deviations (SD), and percentages were used for data computation on students' academic performance. A paired t-test determined significant differences in students' academic performances. Cohen's d was calculated to determine the effect size between the mean groups. The standardized test items, adopted from the DepEd science module, allowed for direct comparison of results while minimizing variability in test difficulty.

For qualitative data, researchers solely conducted the manual thematic analysis following a structured data management and coding analysis process. All interview responses were transcribed verbatim and reviewed multiple times to ensure accuracy and allow researchers to gain familiarity with the content. Afterward, the transcriptions were translated into English and were evaluated, modified, and approved by an English language expert. To enhance rigor, each researcher independently coded subsets of the transcripts, assigning initial labels to meaningful excerpts that reflected participants' perceptions and experiences with the 3D-printed science models. Coding agreement among the researchers was achieved through collaborative discussions, where researchers compared coding outputs, resolved discrepancies, and refined code definitions to ensure consistent application of codes and themes across the dataset.

After agreement on the coding framework, codes were grouped into categories and higher-order themes using inductive reasoning, which allowed themes to emerge naturally from the data, and deductive reasoning, which aligned findings with the research objective and questions. An audit trail documenting coding decisions, theme development, and revisions was maintained throughout the process, supporting dependability and transparency. The final themes were cross-checked with the raw data to verify alignment and accuracy. All the video recordings, transcriptions, translations, and spreadsheets were appropriately stored and used for the present undertaking only. Results and findings for quantitative and qualitative data were presented accordingly.

4.7. Ethical considerations

In conducting this study on integrating 3D-printed models into elementary space science learning, several ethical considerations were prioritized to ensure the protection and well-being of the Grade 6 students. Ethical approval for the study was obtained. Given that the participants were minors, informed consent was obtained from their parents or guardians, along with their students' assent. This was to ensure students' voluntary participation with a clear understanding of the study's objectives and procedures, as well as their right to withdraw their gathered data at any point without academic repercussions. The researchers provided clear step-by-step instructions to the students and established guidelines to ensure a safe and productive learning environment. The students were also offered guidance and support throughout the lessons and activities, helping them interact with the 3D-printed science models confidently and effectively. Strict measures were implemented to safeguard students' information and maintain confidentiality, ensuring anonymity throughout the study and presentation of its results and findings.

Safety protocols were followed throughout preparation to ensure that all materials met school safety standards. All the 3D-printed space science models were exposed to the sun, air-dried, and inspected for sharp edges or loose parts that could cause injuries. They were prepared and cleaned to eliminate potential contamination or dirt. Aside from sanding, trimming, and cleaning, first-aid kits and face masks were prepared and readily available. Regular quality checks were also conducted to verify that the printed models were durable and safe. The researchers observed energy conservation in printing the models and minimized waste and energy consumption, promoting environmental responsibility. Transparency was upheld by clearly communicating the study's findings to stakeholders, including students, parents, and the school.

5. Results and findings

5.1. Students' academic performances in space science and their significant difference

Table 1 presents students' overall academic performance in space science: S1 to S32, following the integration of 3D-printed models as educational materials. Results indicate an increase in the students' scores from the pre-test (M = 4.88, SD = 2.63) to the post-test (M = 7.75, SD = 2.52). The pre-test results reflected a low academic performance in space science among the Grade 6 students. On the other hand, the post-test results show improvement in the students' academic performance after integrating the models into their space science lessons.

Further, Table 1 also shows a significant difference [t(31) = -8.6534, p = .0001] in students' pre- and post-test results. This signifies significant progress in the academic performance of students in space science. Additional examination shows that Cohen's effect size (d = 1.11) indicates a large effect on the students' academic performance scores.

Table 1. Students' space science academic performances and their significant difference.

Tests	M	SD	N	df	t-value	p-value	Cohen's *d*
Pre-test	4.88	2.63	32	31	-8.6534*	0.0001	1.11
Post-test	7.75	2.52	32				

Note: * = significant ($p < 0.05$); ns = not significant ($p > 0.05$); Cohen's d = 0.20 means small effect; d = 0.50 means moderate effect; d = 0.80 means large effect.

5.2. Students' perception regarding the 3D-printed science models

The emerging themes based on the students' interview responses are summarized in Table 2. The study determined five main themes: 1) physical attributes of the 3D-printed models; 2) learning benefits from using the 3D-printed models; 3) challenges associated with using the 3D-printed models; 4) personal preferences in using the 3D-printed models; and 5) suggestions for improving the 3D-printed models.

Additionally, excerpts from interviews with the 13 volunteer students were purposefully selected, presented, and cited to exemplify key themes, representative responses, and notable variations from the manual thematic analysis. This approach was employed to ensure a balanced and credible interpretation of the findings by capturing recurring patterns and unique insights from participants. To maintain transparency, the same pseudonyms used in the quantitative data are consistently used, with identifiers assigned sequentially to safeguard anonymity while illustrating the diversity of perspectives. The purposeful selection of excerpts was guided by their relevance to the identified themes and their ability to provide depth, nuance, and context to the quantitative findings.

Table 2. Summary of themes emerged from the students' interview responses.

Main themes	Sub-themes
1. Physical attributes of the 3D-printed models	a. Reasonable sizes b. Subtle smells c. Appealing colors
2. Learning benefits from using the 3D-printed models	a. Enhanced learning b. Interactive learning c. Concrete representations and realism
3. Challenges associated with using the 3D-printed models	a. Fragility b. Insufficient quantity c. Unpleasant smells
4. Personal preferences in using the 3D-printed models	a. Individual vs. group use b. Mechanical articulation of the models
5. Suggestions for improving the 3D-printed models	a. Augmented quantity b. Increased size

5.2.1. Physical attributes of the 3D-printed models

5.2.1.1. Reasonable sizes

Students generally found the sizes of the models reasonable. While some preferred larger sizes for better visualization, most students felt that the sizes of the models were good enough. One student indicated that both the small and big sizes were fine, suggesting that the variety in size did not pose issues for them. They shared,

S5: *"The sizes of the models are good enough."*
S23: *"The small and big sizes of the models are okay."*
S21: *"The sizes of the model are just right."*

5.2.1.2. Subtle smell

While the smell of the models appeared to be a negative factor for some students, a few found the smell pleasant or acceptable. A student mentioned that they did not mind the smell and even noted that some models smelled good. Another reinforced this by stating that the models had a pleasant smell. They commented,

S7: *"I do not mind the smell. Some models even smell good."*
S15: *"The models have a pleasant smell."*

5.2.1.3. Appealing colors

Students generally found the colors of the models to be pleasing and appealing. They appreciated the models' colors, finding them good and pleasant to the eyes. Several students mentioned that the models' varying colors made them more appealing. They mentioned,

S31: *"The colors are good and are pleasant to the eyes."*
S5: *"The models are good since they have different colors."*

S23: *"I like the light and dark colors used in the models."*

5.2.2. Learning benefits from using the 3D-printed models

5.2.2.1. Enhanced learning

Students consistently felt that the models enhanced their understanding of the lessons. They emphasized that the models helped them understand science concepts deeply. They would not have understood the lesson better without the models to aid the discussion. They remarked,

S31: *"The models helped us understand our lesson deeply."*
S27: *"I understood the lessons because models were used to explain them further."*
S23: *"I understood the lessons well since models were involved during the discussions."*

5.2.2.2. Interactive learning

Students highlighted the interactive nature of the models, finding them engaging and contributing to their interest in the lessons. They particularly appreciated the models' articulated movements, manipulative nature, and the fact that they could touch them. Students expressed that they could visualize the objects' movement with the help of the models. A student added the realism of the models' movement. They conveyed,

S13: *"Some models have moving parts. We can hold them to learn more about their characteristics."*
S21: *"The models can sway and are manipulative."*
S20: *"Aside from the appearance, the models can move when I touch them."*
S23: *"The models' movement is good because it looks real."*

5.2.2.3. Concrete representations and realism

Students emphasized the importance of realism in the models, finding them valuable for their resemblance to real objects. A student mentioned that some models closely resembled real ones, particularly pertaining to the Earth and Moon models. This highlights the importance of authenticity. Another echoed this sentiment by noting that the models closely resembled what is seen in pictures. They indicated,

S27: *"Some models closely resemble the real ones."*
S20: *"The models closely looked like what I saw in pictures."*

5.2.3. Challenges associated with using the 3D-printed models

5.2.3.1. Fragility

Several students commented on the fragility of the models, highlighting their tendency to break or get damaged easily. They mentioned the models' thinness as a contributing factor to their fragility. A student noted that the Earth model was too thin and could break easily if dropped. Others echoed this concern with the other models, drawing attention to the model's susceptibility to damage when stepped on, since it was fragile. A student generalized these concerns, describing that some models were thin and small, and could easily be bent. They said,

S31: *"The Earth's model is too thin. If it is dropped, it will easily break."*
S30: *"It is easy to break since it is thin, and if we step on it, it will get damaged."*
S13: *"Some models are not durable because they are thin."*
S7: *"Some models are thin and small. It could easily be bent."*

5.2.3.2. Insufficient quantity

Students consistently expressed that the number of available models was insufficient. The limited individual interaction time, as students were forced to share models, created a sense of competition and frustration. A student expressed this frustration, mentioning the desire to hold the model longer but having to pass it to a seatmate. Others indicated that there were not enough models to share, as few models were available. They remarked,

S31: *"The models provided were insufficient. I wanted to hold them longer, but my seatmate took them immediately."*
S13: *"The models provided were not enough."*
S20: *"I had to share the models with other groups because the number of models was insufficient."*
S30: *"The models given were not enough for individual use. I had to share them with my classmates."*

5.2.3.3. Unpleasant smells

Although some students were not troubled by the models' odor, some associated the models' odor with an unpleasant plastic smell. The model's smell was similar to that of a cellophane or trash bag, as described by a student. Another indicated their negative sensory experience with the models' smell. They observed,

S6: *"The models are smelly. It smells like plastic, and I do not like it."*
S3: *"Some models smell like cellophane or trash bags."*

5.2.4. Personal preferences in using the 3D-printed models

5.2.4.1. Individual vs. group use

Students overwhelmingly preferred receiving models individually, primarily to avoid conflict, and to have more time to explore the models without pressure. They believed individual access would allow them to focus on learning without competition or time constraints. They wanted to avoid fighting over the models and emphasized the importance of individual access to prevent conflicts. A student proposed a system where models are initially given individually before being shared with the group, suggesting a balance between individual and group exploration. Another highlighted the benefit of individual access, where they could hold the models longer, emphasizing the increased time for exploration and interaction. The students shared,

S27: *"It is better to receive models individually so we will not fight over them."*
S23: *"I prefer to hold the models on my own."*
S21: *"The models can be given individually, then shared with the group later."*
S15: *"I wanted to hold the models on my own so I can touch them for a longer time."*

5.2.4.2. Mechanical articulation of the models

Although students generally enjoyed the models, some preferred the models with moving parts compared to the stationary ones. They shared that the mechanical articulating parts made the models more attractive. They mentioned,

S7: *"I like the models with moving parts better than those that do not move."*

S30: *"The models are more attractive with moving parts."*

5.2.5. Suggestions for improving the 3D-printed models

5.2.5.1. Augmented quantity

Students strongly advocated printing more models to ensure that everyone has the opportunity to interact with the models longer. They mentioned the need for more models to prevent students from fighting over it, underscoring the issue of limited access. One suggested that the availability of more 3D-printed models allows for a deeper understanding of the lessons. Another noted that more models will make the class less boring. They suggested,

S13: *"More models should be produced so we will not fight over them."*

S27: *"We need more models to be available for future lessons to help us understand them fully."*

S3: *"We want more models because the class will be less boring when we have models to see and touch."*

5.2.5.2. Increased size

Some students emphasized the need for larger-sized models to improve the visibility of details and enhance their overall learning experience. A student agreed that larger models would be more motivating. Another highlighted the importance of size to further appreciate the models' characteristics. They recommended,

S31: *"Some models are small. I want bigger sizes."*

S20: *"I need bigger models so that I can enjoy holding them."*

S7: *"The small models need to be available in bigger sizes so I can be motivated further."*

S13: *"It would be better to make the models bigger so their physical features will be seen clearly."*

6. Discussion

The results demonstrate a significant improvement in the Grade 6 students' academic performance in space science after integrating 3D-printed models as educational materials. Before using the models, the students' pre-test scores indicated a weak foundation in space science concepts. However, after incorporating 3D-printed models, their post-test scores improved significantly. This was further conveyed by the large effect size between the pre- and post-test scores, emphasizing the substantial impact that the integration of models had on students' space science learning. This may suggest that the tangible, interactive nature of the models enabled students to grasp complex space science concepts better, leading to a deeper understanding and retention of knowledge. From a constructivist perspective, this improvement reflects how students actively built knowledge through interaction with authentic learning materials rather than passively receiving information, supporting the observations of Avinal and Aydin [6], Arslan and Erdogan [3], Fokides and Lagopati [21], Tanabashi [43], and Trujillo-Cayado et al. [45]. It may also suggest that using the models was not just a minor improvement but an innovative tool in this study, facilitating learning at a much more effective and engaging level. The interactive and manipulative qualities of the models provided concrete, real-world representations of abstract space science concepts, allowing students to build a deeper understanding through active exploration and personal discovery. This also aligns with hands-on engagement and opportunities in the experiential learning theory divulged by Kong [25]. This resonates with the growing adoption of 3D-printing technologies in the classroom, as Arvanitidi et al. [4] and Fokides and Lagopati [21] posited. Improving students' academic performance implies that 3D-printed models could be invaluable in addressing common learning difficulties associated with abstract scientific concepts, potentially bridging gaps in students' comprehension, and enhancing overall academic achievement in science education. Using models supports STEAM learning, as Kit Ng et al. [24], Nazha and Szabolcs [35], and Tanabashi [43] pointed out.

The physical attributes of the 3D-printed models used affected students' responses. The students' positive perceptions of the models' size, smell, and color were not merely for aesthetic elements, but also denoted their engagement, perception, and learning experiences. This reinforces the constructivist and experiential learning emphasis on accommodating diverse students' needs. Most students reported that the sizes of the models were appropriate. Their acceptance across various sizes suggests adaptability to learning styles, underscoring the importance of varied formats to meet diverse needs. The colors of the models emerged as a distinctly positive attribute, with many students commenting on their visual appeal. The appreciation for light and dark color schemes indicates that contrast and variation in color can contribute to model effectiveness by making individual components easier to distinguish and reducing visual fatigue. The models' sizes and colors underscore the importance of visual accessibility of educational materials. This reflects constructivist pedagogy, which values design features that support learners in actively making sense of content. This extends the observations of Avinal and Aydin [6], Arslan and Erdogan [3], Tanabashi [43], and Trujillo-Cayado et al. [45] on the positive outlook of students toward 3D-printed technologies as educational tools. Indeed, educators should continue leveraging size variations and color theory in developing 3D-printed models.

Interestingly, the olfactory aspect of the models elicited mixed responses. While some students found the smell unpleasant, others described it as neutral and even pleasant. Although olfactory perception is rarely a focal point in educational materials design, these responses suggest that the models used can subtly affect students' attention. Noticeable smells warrant attention, particularly in enclosed or prolonged learning environments. As Polygenis [38,39] recommended, filament properties must be considered when 3D-printing models. Educators might consider using low-odor or scent-neutral filaments. Such sensory elements, while subtle, align with experiential learning theory, emphasizing the role of multisensory experiences in deepening engagement and retention.

The students' responses provide clear evidence that the interactivity and realism of the 3D-printed models significantly contribute to enhancing their conceptual understanding and engagement in space science. The students acknowledged that the models contributed to deeper learning and comprehension of space science concepts. This suggests that the models used were effective visual and tactile aids, enabling students to grasp abstract or complex ideas more concretely. Students remarked that they understood the lessons well due to the use of models, highlighting the cognitive support these educational materials offer. This illustrates the core constructivist belief that meaningful learning occurs when students actively construct understanding through tools that make abstract concepts accessible. This is in a similar vein to Akyol et al. [2], Aslan and Çelik [5], Budinski et al. [10], Chen and Cheng [13], Eldebeky [19], Fokides and Lagopati [21], Tanabashi [43], and Trujillo-Cayado et al. [45], who asserted that 3D-printing technologies benefit students' learning.

Regarding the interactive and manipulative quality of the models, students associated them with greater engagement and interest in the lessons. The articulated, movable parts of the models allow for a hands-on learning experience. The students' responses suggest that physical interaction with the models transforms passive observation into manipulative experiential exploration, which may increase conceptual clarity. This perfectly aligns with experiential learning, as students cycle through doing, reflecting, and applying knowledge in authentic contexts. This echoes students' haptic learning experience, allowing them to physically explore and manipulate the models, as Abu Khurma et al. [1], Arslan and Erdogan [3], Chen and Cheng [13], and Trujillo-Cayado et al. [45] presented.

The students' appreciation of the realistic appearance and motion of the models reveals the importance of the authenticity of the models. Realism helps bridge the gap between theoretical knowledge and real-world application. The students indicated that the models' resemblance to actual objects or images enhanced their learning experience. This is comparable to the result obtained by Arslan and Erdogan, in which students claimed that 3D model objects concretize visual representations [3]. Authentic educational materials foster contextual understanding, making abstract science concepts more relatable and understandable. This reflects that perceived authenticity enhances relevance and knowledge transfer, vital for meaningful learning. Constructivism also emphasizes such authentic tasks, where learners engage with realistic problems that strengthen knowledge transfer. The students' positive feedback highlights how 3D-printed models acted as authentic, hands-on learning tools, bridging theoretical concepts with practical, real-world applications. These benefits are central to both constructivist pedagogy and experiential learning approaches.

While the 3D-printed models used benefit students' learning and engagement in space science, this study highlights several practical limitations that impact their effectiveness in the classroom. Students expressed significant concern regarding the fragility of the models, particularly pointing to their thinness and susceptibility to damage when dropped or stepped on. This issue suggests a potential mismatch between the models' intended purpose as manipulative tools and the required material durability. The lack of physical robustness compromises the longevity of the models. If models are easily damaged, students may become hesitant to interact fully, undermining the experiential learning process central to constructivist pedagogy. Most models with PLA filaments were more fragile than those printed with ABS. This corresponds to Polygenis' [38,39] clarification that ABS filaments are more durable than PLA. Educators should prioritize material quality and structural reinforcement in future model iterations, especially for thin, movable, or regularly handled parts.

The limited number of available models significantly impacted students' interaction time and created a sense of competition and frustration during lessons. Students reported needing to share models with seatmates or entire groups, reducing the depth and duration of engagement with the models. This scarcity issue is a direct barrier to equitable learning, as not all students receive the same tactile or visual access. This issue highlights resource availability as an overlooked aspect of instructional planning in this study. This scarcity did not likely mirror the use of more models for students' interactive learning, as indicated in DepEd's K-12 space science curricula [16]. Effective implementation of models requires not just the presence of the materials but sufficient quantities to ensure meaningful, individual, or small-group use. Suggested solutions include investing in cost-effective 3D-printing methods to produce more models or designing modular models that allow multiple students to engage simultaneously with different components.

Another challenge noted by students was the unpleasant smell emitted by some models, often described as similar to plastic. This was mostly observed among the models printed with ABS filaments. While this may seem minor, it can negatively affect students' sensory experience, particularly in close or prolonged interaction scenarios. This sensory aversion may be relevant for students with heightened sensory sensitivity, who may find it challenging to ignore strong or unpleasant odors. Although only a subset of students raised this concern, it is a non-trivial design flaw due to the type of filaments used. However, to ensure the students' safety during the lessons, they were immediately provided with face masks every time they manipulated the models to mitigate smell issues and discomfort without compromising the models' visual or tactile features. The model's unpleasant smell is intrinsic to the filaments used. As Polygenis [38,39] mentioned, ABS filaments release more irritating smells when printing compared to PLA. Educators are highly encouraged to seek low-odor, non-toxic filaments to produce 3D models, or air them out before classroom use to reduce chemical smells. Further research could explore sensory-friendly materials that minimize discomfort without compromising visual or tactile features.

The students' personal preferences also influence the 3D-printed models' effectiveness. Students preferred individual access to the models rather than in a group, which aligns with constructivist and experiential learning principles emphasizing learner autonomy. This appears to be affected by avoiding interpersonal conflict and the desire for uninterrupted exploration. The concern that group sharing may lead to disagreements or competition reflects how resource scarcity can negatively impact classroom dynamics and learning equity. Students noted that having individual access to the models enabled more sustained interaction, which is essential for deep learning. This issue contrasts with the students' collaboration and communication when using the models, as Akyol et al. [2] and Chen and Cheng [13] emphasized. Individual access to learning tools grants students a sense of ownership and agency, fostering a more personal connection to the learning material and minimizing social stressors that might impede focus. Students who can manipulate models without time pressure or social negotiation are more likely to internalize scientific concepts. Educators should provide enough models for individual or pair-based use, particularly during a lesson's early or exploratory phases. Alternatively, structured model rotation systems where students work individually, then share within groups, can strike a balance between autonomy and collaborative learning.

Students also showed a distinct preference for models with moving parts, noting that such features made the models more attractive and engaging. The ability to interact with dynamic elements of the models likely contributed to students' conceptual clarity and interest, reflecting constructivist and experiential learning principles underpinning learning through active manipulation and exploration. This preference points to the importance of aesthetics and interactivity in educational tools. This is relevant to hands-on learning highlighted by Abu Khurma et al. [1] and

Chen and Cheng [13]. Movable models make learning materials more appealing and support exploratory behavior and curiosity-driven learning. Educators should consider including articulated or movable features in models wherever appropriate, especially when movement is conceptually relevant. However, attention should also be given to durability, as added mobility may increase the risk of breakage, as noted in related findings about models' fragility.

The students' feedback provides valuable insights into the future practical and pedagogical refinement of 3D-printed models. Their suggestions for augmented quantity and increased size of the models used highlight not only logistical concerns but also the affective and cognitive factors that influence the effectiveness of models as educational materials. Students' repeated calls for an increased quantity of models reflect a critical concern about limited access, which they linked to reduced learning opportunities and even classroom tensions. This suggestion points to resource scarcity as a barrier to equitable learning experiences in this study. Students noted that more models would support a more profound understanding and reduce boredom, which are significant for sustaining attention and interest in science learning. Although Fokides and Lagopati [21] indicated that schools are starting to adopt 3D-printing technologies, their educational integration in the Philippines is underexplored and yet to be realized. This is reflected in the country's limited 3D-printing infrastructure, as reported by DOST [18]. When 3D printers and models are readily available, students have more time and space for exploratory and autonomous learning, leading to greater conceptual clarity and confidence. Educators should prioritize scaling the production of models, ensuring that each student has adequate access to these educational materials.

The students' desire for larger-sized models emphasizes the importance of visual accessibility and physical ergonomics of educational materials. Their feedback suggests that smaller models obscure physical features, limiting their ability to observe and understand key details. This is particularly critical in science education, where spatial relationships and structural features are essential for understanding systems and functions. Small, intricate models may demand more visual effort, especially in group settings. Conversely, larger models can better support observational learning, as they make structural details more discernible and physically easier to manipulate. The students' participation and expectations mentioned by Avinal and Aydin [6], Arslan and Erdogan [3], Tanabashi [43], and Trujillo-Cayado et al. [45] may be further enhanced using larger models. Educators should aim to increase the physical dimensions of models, particularly when presenting complex or detail-oriented concepts. These students’ suggestions regarding augmented quantity and increased model size reinforce the value of constructivist and experiential learning approaches, where interaction and accessibility to well-designed 3D-printed science models support deeper conceptual understanding. Ensuring adequate quantities and appropriately sized models empowers students to explore, manipulate, and internalize scientific concepts more effectively, fostering equitable and engaging learning experiences.

The study's results and findings offer valuable direction for educators seeking to enrich space science education through innovative, student-centered tools. The potential and integration of 3D-printed models in space science reinforces the premises of Budinski et al. [10] and Thyssen and Meir [44], presenting 3D-printing technologies as a dynamic approach to the teaching and learning process. By considering students' experiences and preferences, future implementations of 3D-printed models in the classroom can be more effective, equitable, and engaging. As the integration of educational technologies continues to evolve, 3D printing stands out as a promising avenue to bridge conceptual gaps and make science more accessible and meaningful for young learners. Embracing this innovation enriches classroom experiences and empowers students to participate in their learning actively. As a final point, thoughtful and inclusive application of 3D printing can contribute to a more dynamic, responsive, and future-ready science education.

7. Conclusions and implications

3D printing is increasingly recognized as a powerful tool for enhancing science education. It improves students' academic performance and offers them interactive learning experiences. The study aimed to explore the impact of 3D-printed models on students' academic performance and perceptions. The study investigated whether the 3D-printed models could improve students' understanding of space science concepts and provide a more interactive learning experience. The quantitative results provide strong evidence that integrating 3D-printed models significantly enhances students' academic performance. The marked improvement in post-test scores compared to pre-test results, coupled with the large effect size, underscores the substantial impact of these models on students' understanding of space science concepts. The qualitative findings enrich these quantitative results by providing detailed insights into the students' experiences, perceptions, and interactions with the 3D-printed models. Students consistently reported that the models' physical attributes contributed to their engagement, enjoyment, and comprehension of the lessons. The manipulative and interactive qualities of the models encouraged active participation. Students valued the authenticity of the models, noting that their realistic representations of space objects made abstract concepts more concrete and relatable. However, challenges such as the fragility of the models, limited availability for individual use, and the unpleasant smell of certain filaments were identified as barriers to maximizing the learning experience. These concerns reveal the importance of both the functional design and sensory considerations in developing educational materials. Overall, the results and findings suggest that 3D-printed models enhanced students' cognitive understanding and positively influenced their attitudes, motivation, and curiosity toward space science, reinforcing the transformative role of innovative, student-centered tools in modern science education.

The results and findings of this study have substantial implications for the advancement of science education, particularly in promoting constructivist and experiential learning in elementary classrooms. The demonstrated improvement in students' academic performance and their positive perceptions highlight the potential of 3D-printed models as powerful pedagogical tools for simplifying abstract scientific concepts like those in space science. This implies that incorporating 3D-printing technologies into science education can lead to more meaningful learning experiences, particularly in complex subjects where visualization and manipulation of concepts are critical. For students, 3D-printed models create interactive, motivating learning experiences that make complex topics more accessible, particularly for those who struggle with traditional teaching methods. Beyond classroom practice, the results provide guidance for curriculum designers, administrators, and policymakers in integrating 3D printing in the classroom, ensuring equitable access to innovative tools and supporting science education. Overall, the study underscores that 3D printing can enrich STEM or STEAM-based education by encouraging creativity, hands-on experience, and interdisciplinary connections, conclusively supporting deeper conceptual understanding and a more student-centered approach to science learning.

8. Limitations and recommendations

While the study's findings suggest that 3D-printed models can enhance space science education in elementary schools, it is important to acknowledge the limitations of this study and consider its implications for future studies. First, the small sample size limits the generalizability of the results. The study involved a small student population from a particular grade level. It only included elementary students from a single, local school, limiting the generalizability of the findings to a broader population. Second, the findings are context-specific, as the absence of cross-cultural or multi-school comparisons hinders their applicability to a broader range of educational settings. This is due to the study's limited resources and logistical issues. Third, the models' integration into the science lessons was bound by time constraints. Short-term engagement of students with the models was apparent. This limited the extent to which the models were incorporated. Fourth, only one model and unit of a 3D printer with its corresponding slicing software were used, including only two filament types. This limited access to other 3D-printing technology resources. Fifth, in the broader science curriculum context, the 3D-printed models used were limited and only aligned with space science lessons, with a few learning competencies based on the Philippine K-12 Science curriculum. Sixth, the study's non-experimental design and lack of a control group weaken the ability to draw causal inferences. Other intervening variables that may have influenced student performance and perceptions were not considered. Lastly, on the qualitative side, the data relied heavily on voluntary interviews with a subset of students, which could introduce selection bias. This may have affected the depth and diversity of the qualitative insights, potentially affecting the comprehensiveness of the findings. Nonetheless, the researchers still advocate integrating 3D-printed models as educational materials in science education.

Based on the study's results, findings, and limitations, several recommendations can be made to improve the implementation and further exploration of 3D-printed models in science education. Future research should involve larger and more diverse student samples across multiple schools or cultural contexts to enhance the generalizability of the findings. Qualitative data collection should include broader participation, such as enumerative reflections or structured focus groups, to capture a wider range of student perspectives. This approach would reduce potential selection bias and provide richer insights into the experiences of students who may not voluntarily share feedback. Incorporating an experimental design with control and experimental groups is recommended to strengthen causal inferences regarding the impact of 3D-printed models on student academic performance and engagement. Longitudinal studies spanning various learning competencies, multiple academic quarters, or academic years could also provide a clearer understanding of the sustained effects of these models on students' conceptual science understanding. The production of 3D-printed models should be scaled up and maintained at a high quality to ensure sufficient availability for individual or pair-based use, minimizing competition and maximizing hands-on learning opportunities. Educators and schools should also consider investing in 3D printers and filaments, and durable, sensory-friendly, and ergonomically designed models to address issues related to fragility, odor, and accessibility. Finally, collaboration with local industries, government agencies, or technology hubs could further support cost-effective production and innovation in 3D-printing model design.

Author contributions

All authors contributed to the review, editing, literature review writing, planning, and implementing the study. All authors contributed to the data collection and analysis. All authors have read and approved the revised and published version of the article.

Use of Generative-AI tools declaration

The authors declare that no generative artificial intelligence (Gen-AI) tools were used in creating this article. Also, no Gen-AI tools were used to slice and print the 3D models used in the study. However, Grammarly was used for the initial language editing of the paper.

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Conflict of interest

All authors declare no conflicts of interest in this paper.

Ethics declaration

This study was reviewed and granted ethical clearance approval by the research ethics committee of Ifugao State University (IFSU) - Tinoc Campus.

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Appendix

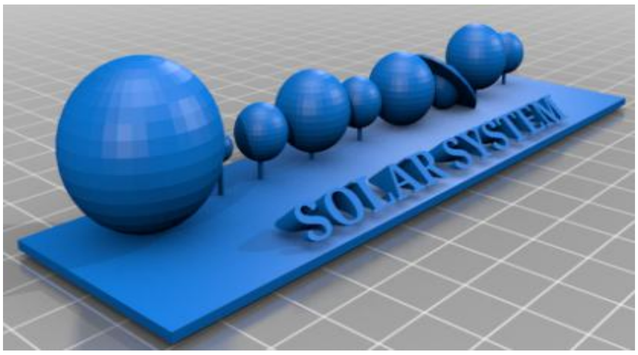
Appendix A. Examples of the 3D-printed space science models used in the study.

a. Earth model

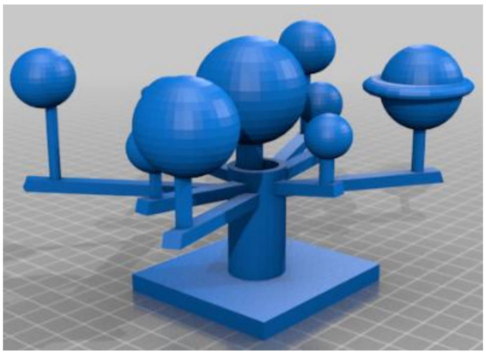
b. Rocket model 1

c. Rocket model 2

d. Rocket model 3



e. Digital 3D model of Solar System 1



f. Digital 3D model of Solar System 2

Appendix B. Makers/designers of the 3D-printed models used in the study.

3D printing models	Makers/designers	Sources/links
1. Solar system	yliu1581 Yingtao Liu July 01, 2021	https://www.thingiverse.com/thing:4898013
2. Solar System, Sistema Solar	edBlue75 Eduardo Feijoo Madrid November 27, 2019	https://www.thingiverse.com/thing:4003014
3. Earth Globe Lamp	DoctorWh0 Doctor Who March 08, 2019	https://www.thingiverse.com/thing:3475736
4. Textured Earth	bld Ben Diedrich Alabama February 10, 2012	https://www.thingiverse.com/thing:17336
5. gCreate Official Rocket Ship	gCreate gCreate Brooklyn, NY August 14, 2014	https://www.thingiverse.com/thing:427789

6.	An old retro rocket	vandragon_de vd print Germany November 10, 2017	https://www.thingiverse.com/thing:2636131
7.	Fusée Tintin / Tintin Rocket	ZeKazz Nico Kazz France March 13, 2018	https://www.thingiverse.com/thing:2823726
8.	Modelling the Solar System with OnShape	SpoonUnit Spoon Unit UK August 28, 2016	https://www.thingiverse.com/thing:1739983
9.	Our Solar System	rweaving Ryan Weaving Atwater, CA May 18, 2012	https://www.thingiverse.com/thing:23324
10.	High Detailed Moon Lamp	moononournation Leung CHAN June 11, 2018	https://www.thingiverse.com/thing:2955930

Note: 3D model designs with their corresponding URLs may not be available due to updates, upgrades, and/or removal by their makers/designers.