Supporting Inquiry-Based Learning of Density Using a 3D-Printed Instructional Kit

Loh Su Ling, Nurul Faizah binti Fauzi, Asmah binti Bohari

Institute of Teachers Education, Technical Education Campus, Malaysia

DOI: https://doi.org/10.47772/IJRISS.2026.100600106

Received: 27 May 2026; Accepted: 01 June 2026; Published: 18 June 2026

ABSTRACT

Teaching density and buoyancy through inquiry-based science learning is often constrained by the lack of instructional materials that enable controlled comparison of mass and volume. This study examined the use of a 3D-printed instructional kit, the Density Discovery Kit (DD-Kit), designed to support inquiry-based learning of density by stabilising experimental conditions and enabling systematic comparison of mass and volume. By reducing extraneous variation in object properties, the kit foregrounds proportional reasoning and evidence-based explanation rather than perceptual or intuitive judgement. The kit comprises a set of cubes and spheres that create contrasting density scenarios, including several cubes and spheres of identical volume but different mass and an additional cube and spheres with a different volume and mass. These configurations were used to elicit predictions and challenge the common misconception that heavier objects necessarily sink. A mixed-methods approach was employed with 68 students, using pre- and post-tests and classroom observations. Results from a Wilcoxon Signed-Rank Test showed a statistically significant improvement in students' post-test scores ($Z = -4.451$, $p < .001$) with a large effect size. Observational data indicated active engagement in inquiry practices such as prediction, measurement, reasoning, and explanation-building. The findings suggest that purposefully designed hands-on manipulatives can enhance understanding of density through structured inquiry.

Keywords: 3D-priting; density; inquiry-based science education; hands-on learning; secondary science

INTRODUCTION

Inquiry-Based Science Education (IBSE) has been widely promoted as an effective pedagogical approach for enhancing students' conceptual understanding, scientific reasoning, and engagement in science classrooms (Iksan et al., 2018; Kaliampos et al., 2025; Mao, 2023; Marshall & Smart, 2013). Grounded in constructivist learning principles, IBSE emphasises students' active involvement in asking questions, conducting investigations, analysing data, and constructing explanations based on evidence (Sahin, 2013; van Uum et al., 2016). Through these processes, learners are expected to develop not only scientific knowledge but also an understanding of how scientific knowledge is generated and validated.

Studies have shown that inquiry-based approaches can support deeper understanding of scientific concepts when students are meaningfully engaged in hands-on investigation and reasoning(Iksan et al., 2018; Kaliampos et al., 2025; Marshall & Smart, 2013; Meier & Hendel, 2019; van Uum et al., 2016). However, the effectiveness of IBSE depends strongly on how inquiry activities are enacted in classrooms(Opara & Etukudo, 2014; Parker et al., 2018; Quansah et al., 2019; Sun et al., 2014). Poorly structured inquiry tasks or insufficient instructional support can result in superficial engagement, where students follow procedures without developing coherent explanations or conceptual insight (Mao, 2023; Sun et al., 2014). As such, the quality of inquiry implementation, rather than inquiry pedagogy alone, is critical to student learning outcomes.

One factor influencing the enactment of IBSE is the availability and suitability of instructional materials (Dorsah et al., 2024; Kaptan & Timurlenk, 2012; Quansah et al., 2019). Inquiry activities depend on resources that allow students to manipulate variables, collect reliable data, and compare outcomes systematically. When such resources are unavailable or inconsistent, inquiry-based instruction is often reduced to teacher-led

demonstrations or loosely guided activities that do not support evidence-based reasoning (Dorsah et al., 2024). This challenges are especially evident in science topics that involve proportional reasoning and quantitative relationships, where uncontrolled materials can obscure rather than clarify conceptual understanding.

The teaching of density and buoyancy exemplifies these challenges. Understanding density requires learners to coordinate mass and volume as a ratio and to relate this abstract relationship to observable phenomena such as floating and sinking. Previous studies have documented persistent student misconceptions in this area, including the belief that heavier objects necessarily sink or that object size alone determines buoyancy (Harrell et al., 2014; Hashweh, 2016; Xu & Clarke, 2012; Zvoch et al., 2021). Addressing such misconceptions through inquiry requires instructional conditions that enable controlled comparison and systematic investigation—conditions that may be difficult to achieve using everyday classroom objects with varying physical properties.

From an epistemic perspective, learning density poses particular challenges because it requires students to coordinate two measurable quantities—mass and volume—into a proportional relationship, while simultaneously suppressing intuitive heuristics based on size, weight, or visual appearance. When instructional materials vary simultaneously across multiple dimensions, students may struggle to isolate relevant variables and are more likely to rely on perceptual reasoning rather than evidence-based inference (Xu & Clarke, 2012). Consequently, inquiry activities that lack controlled comparison may inadvertently reinforce misconceptions rather than support conceptual change. In this study, the instructional materials were therefore designed to create structured contrasts, including sets of objects with controlled volume and systematically varied mass, alongside objects with different volumes and masses. These configurations function as epistemic scaffolds that stabilise inquiry conditions and enable learners to attribute observed outcomes to specific relationships between mass, volume, density, and buoyancy.

Research Problem

In the lower secondary science context of the present study, implementing inquiry-based learning for the topic of density and buoyancy presents persistent practical challenges. Although inquiry-oriented activities are encouraged, classroom investigations are typically conducted using readily available objects such as stones, plastic items, or classroom materials that vary simultaneously in size, mass, and material composition. These uncontrolled variations make it difficult for students to systematically compare variables or interpret empirical evidence meaningfully. Consequently, students often rely on intuitive reasoning—most commonly the assumption that heavier objects will sink—rather than constructing explanations grounded in measurements and proportional reasoning. This challenge is further compounded by limited access to standardised laboratory apparatus or purpose-designed instructional materials at the lower secondary level. Without resources that allow controlled manipulation of mass and volume, inquiry activities tend to become observational or teacher-directed rather than genuinely investigative. As a result, opportunities for students to engage in structured inquiry—where predictions are tested against evidence and misconceptions are confronted—are constrained. Addressing this instructional gap is essential for supporting support students' understanding of density and buoyancy and for realising the intended goals of inquiry-based science education in everyday classroom practice.

Research Focus

In response to this challenge, the study investigates the use of a 3D-printed instructional kit, the Density Discovery Kit (DD-Kit), designed to create contrasting density scenarios for inquiry. The kit comprises a set of cubes, including several cubes of identical volume but differing mass and an additional cube with a different volume and mass. These configurations are intentionally designed to elicit predictions, challenge the common misconception that heavier objects necessarily sink, and support systematic investigation of the relationship between mass, volume, density, and buoyancy. The research focuses on how the use of such materials within a structured inquiry sequence supports students' understanding of density and their engagement in inquiry processes, including prediction, measurement, reasoning, and explanation-building. By examining learning outcomes and classroom inquiry practices, the study seeks to provide empirical evidence on the role of carefully designed instructional materials in supporting meaningful inquiry-based science learning.

Research Aim and Research Questions

The aim of this study is to investigate the extent to which the use of a purposefully designed instructional kit supports lower secondary students' understanding of density and their engagement in inquiry-based learning processes. Based on this aim, the following research questions are formulated:

- To what extent does the use of the Density Discovery Kit improve students' understanding of density and buoyancy?

- How do students engage in inquiry-based learning processes when using the Density Discovery Kit during classroom investigations?

LITERATURE REVIEW

Although Inquiry-Based Science Education (IBSE) is widely associated with improved conceptual understanding and scientific reasoning, research indicates that its effectiveness depends less on the presence of inquiry activities per se and more on the epistemic quality of those activities(Marshall & Smart, 2013; Pedaste et al., 2015; van Uum et al., 2016). Specifically, inquiry learning is most productive when students are provided with instructional conditions that allow for systematic manipulation of variables, reliable measurement, and the generation of evidence that can be meaningfully interpreted and discussed (Pedaste et al., 2015; Sun et al., 2014). Meta-analyses and design-oriented syntheses of inquiry learning highlight that poorly supported inquiry—where learners are unable to distinguish relevant variables or evaluate competing explanations—often leads to procedural compliance rather than conceptual understanding (Pedaste et al., 2015). Thus, the success of IBSE hinges on the extent to which classroom tasks are designed to support genuine evidence-based reasoning.

Beyond issues of availability, the quality of inquiry enactment can be understood as being shaped by how instructional materials structure students' opportunities to reason with evidence. Inquiry tasks require resources that stabilise experimental conditions and function as epistemic tools—artefacts that delimit what can be observed, compared, and inferred—thereby enabling learners to attribute outcomes to specific variables through systematic comparison and quantitative reasoning (Hardie, 2015; Pedaste et al., 2015). When such conditions are not met, students' investigations are more likely to rely on intuitive judgments rather than on evidence-based inference, particularly in contexts involving proportional relationships (Xu & Clarke, 2012). This limitation is particularly consequential in science topics involving proportional relationships, where uncontrolled variation in physical objects can obscure underlying concepts and reinforce naïve explanations. As a result, material constraints may undermine the epistemic aims of inquiry-based learning by restricting students' opportunities to test predictions, reconcile data with theory, and construct coherent explanations.

Educational technologies can address such challenges when they are purposefully designed to support inquiry processes rather than merely enhance presentation (Pearson & Dube, 2022). While digital simulations and virtual laboratories have been widely adopted to visualise abstract concepts, they often lack opportunities for embodied, hands-on interaction that supports measurement, comparison, and physical reasoning. From object-based and embodied learning perspectives, tangible artefacts are understood to support learning by allowing learners to handle objects, perform measurements, and coordinate perceptual experience with symbolic representations such as formulas and numerical data (Chatterjee & Hannan, 2016; Hardie, 2015; Valdespino & Larson, 2019). Their educational value can further be understood in terms of technological affordances, namely the actions they enable and constrain for learners, such as controlled comparison, systematic measurement, and isolation of variables, within inquiry-based investigations.

Within this pedagogical context, three-dimensional (3D) printing has emerged as an educational technology with particular relevance for inquiry-based science learning(Ford & Minshall, 2019; Tejera et al., 2025). As an additive manufacturing process, 3D printing enables the production of physical objects with precise, repeatable, and customisable properties. In science classrooms, this precision allows teachers to design manipulatives that control specific variables—such as volume—while systematically varying others, such as mass (Ford & Minshall, 2019). Prior studies have shown that 3D-printed models can support understanding and engagement by making abstract scientific relationships tangible and measurable (Ford & Minshall, 2019; Hansen, 2014;

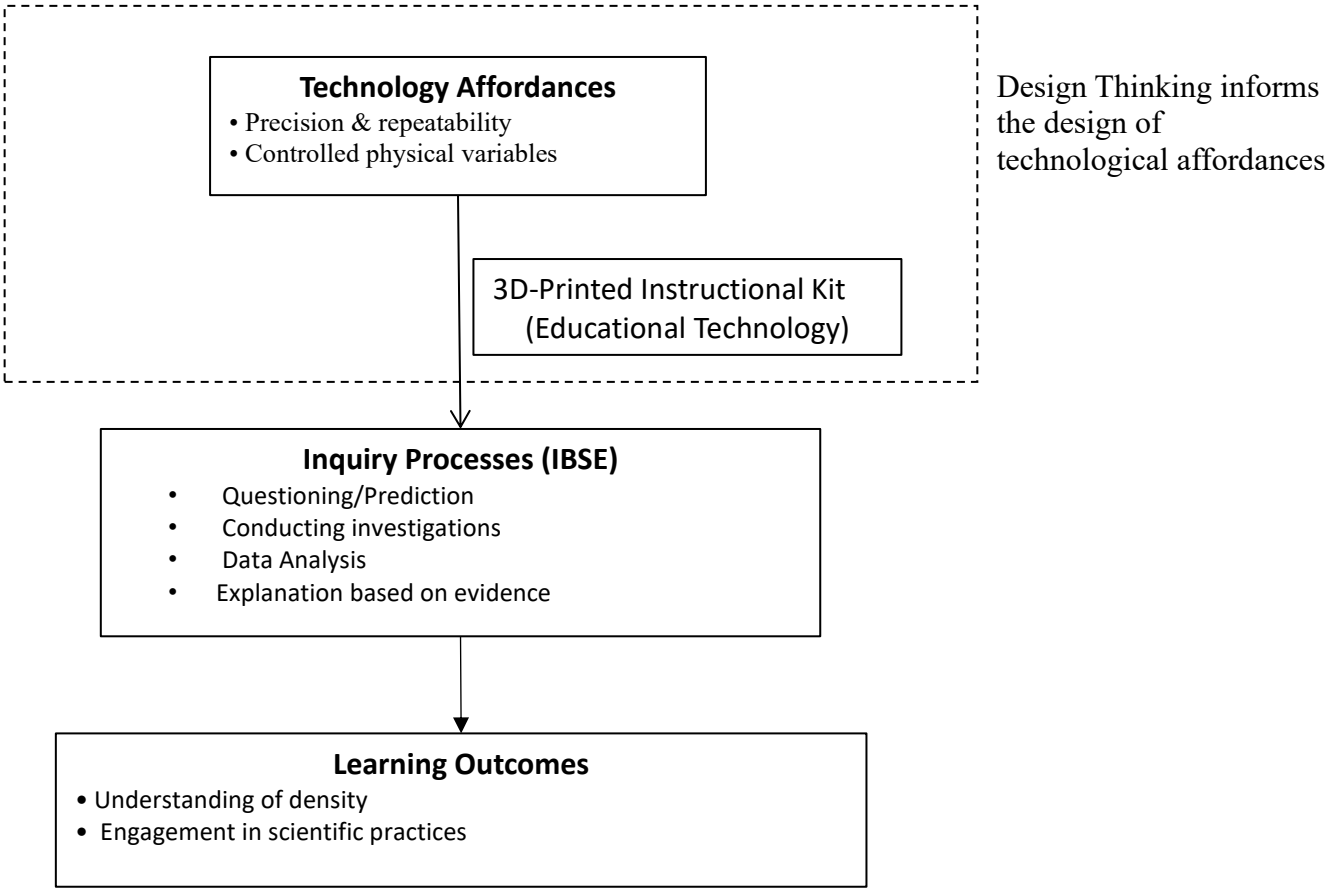
Hsiao et al., 2019) Importantly, the pedagogical value of 3D printing can be understood not in the act of printing itself, but in its capacity to function as an enabling infrastructure for technology-supported inquiry (Pearson & Dube, 2022).

To ensure that technological affordances translate into meaningful learning, instructional artefacts must be intentionally aligned with pedagogical goals and classroom realities. Design Thinking has been described as a human-centred, iterative design logic that supports the development of context-responsive educational innovations(Liedtka, 2013; Razzouk & Shute, 2012). In the context of educational innovation, Design Thinking has been widely used to support teacher-led development of tangible learning resources, particularly in situations where conventional materials are insufficient or misaligned with the epistemic demands of inquiry-based instruction(Abdullah, 2022; Goldman & Zielezinski, 2016). Its emphasis on empathy with users, iterative refinement, and alignment between design intent and classroom practice makes it especially relevant for the design of manipulatives intended to support inquiry-based learning.

In educational technology research, Design Thinking is most productive when employed as a methodological lens to justify design decisions, guide iterative prototyping through classroom testing, and align technological features with inquiry tasks rather than as a theory of learning(Liedtka, 2013; Razzouk & Shute, 2012). Studies adopting Design Thinking in educational contexts highlight its value in producing pedagogically purposeful artefacts that stabilise learning conditions, reduce extraneous variability, and foreground students' reasoning with evidence(Greenhalgh, 2016; Myllymäki et al., 2024). In this study, Design Thinking informs the development of a 3D-printed instructional kit designed to support structured inquiry into density, while the design process itself is not positioned as the primary object of investigation. Instead, the analytical focus remains on how technology-supported inquiry processes shape students' conceptual understanding and engagement with scientific practices.

CONCEPTUAL FRAMEWORK

Figure 1 Conceptual framework linking technological affordances, inquiry processes, and learning outcomes



Drawing on the literature, this study adopts a conceptual framework that links educational technology affordances, inquiry processes, and learning outcomes (Figure 1). As illustrated in Figure 1, the 3D-printed instructional kit is positioned as a mediating educational technology whose design affordances—enabled by 3D printing—include precision, repeatability, including controlled volume in selected object sets and systematically varied mass across contrasting configurations. These affordances stabilise experimental conditions and reduce extraneous variability, allowing students to engage in structured inquiry processes central to Inquiry-Based Science Education (IBSE), such as prediction, measurement, calculation, observation, and explanation. By minimising material ambiguity, the instructional kit directs students' attention toward reasoning about relationships between mass, volume, density, and buoyancy, thereby supporting collaborative discussion, evidence-based argumentation, and explanation-building. As represented in Figure 1, sustained engagement in these structured inquiry processes is theorised to contribute to improved understanding of density, reduction of common misconceptions, and increased engagement with scientific practices. Within this framework, Design Thinking operates as a background design logic that informs the alignment of technological affordances with inquiry tasks and learning goals, while the primary analytical focus of the study remains on how technology-supported inquiry processes influence students' learning outcomes.

RESEARCH METHODOLOGY

This study employed a mixed-methods approach to examine the extent to which a 3D-printed instructional kit facilitates students' understanding of density through structured inquiry activities. Consistent with the conceptual framework (Figure 1), the design focused on examining learning outcomes and inquiry processes enabled by technology-supported inquiry, rather than evaluating the design process itself. Quantitative data were used to assess changes in students' understanding, while qualitative data provided insight into students' inquiry behaviours during classroom enactment. The integration of both data sources allowed for a more comprehensive examination of learning effects associated with the instructional intervention(Creswell, 2012; Tashakkori & Creswell, 2007).

The participants were 13 year-old students from a lower secondary science classroom in a local public school. The study was conducted during regular science lessons as part of the curriculum unit on density. Students had previously been introduced to basic concepts of mass and volume but had limited experience engaging in structured inquiry activities involving controlled manipulation of physical variables. The instructional intervention was implemented by the classroom teacher, who was also a member of the research team, during regular science lessons, ensuring that the learning activities were conducted under authentic classroom conditions. Informed consent was secured from the school administration and students' identities were anonymised, and all data were used solely for research purposes.

The study followed a sequential procedure consisting of a pre-test, implementation of the structured inquiry activity using the 3D printed instructional kit, classroom observation during enactment, and a post-test administered immediately after the intervention. The instructional intervention involved the use of a 3D-printed instructional kit named Density Discovery Kit (DD-Kit) designed to support structured inquiry into density and buoyancy. The kit comprises a set of cubes and spheres that create contrasting density scenarios, including several cubes and spheres of identical volume but different mass and an additional cube and spheres with a different volume and mass. These configurations were used to elicit predictions and challenge the common misconception that heavier objects necessarily sink. It also enabled students to conduct controlled comparisons that are difficult to achieve using conventional classroom materials. Students engaged in a structured inquiry activity aligned with the phases of Inquiry-Based Science Education (IBSE), including prediction, measurement, calculation, observation, and explanation. The inquiry tasks were guided by a worksheet that scaffolded students' reasoning while allowing opportunities for peer discussion and collaborative sense-making.

To examine changes in students' understanding, a pre-test and post-test design was employed. The test items focused on key concepts related to density and buoyancy, including the relationship between mass, volume, density, and floating or sinking behaviour. The same test was administered before and after the instructional intervention to allow for direct comparison of learning gains. Qualitative data were collected through classroom observations during the inquiry activities. Observation focused on students' engagement in inquiry processes, including prediction making, measurement practices, collaborative discussion, and explanation building. Field

notes were recorded to capture observable inquiry behaviours that reflected students' engagement with scientific practices, consistent with the process level of the conceptual framework.

Data Analysis

Pre- and post-test scores were analysed to determine whether there was a statistically significant improvement in students' understanding following the intervention. Given the non-normal distribution of the data, a Wilcoxon Signed-Rank Test was employed to compare pre-test and post-test scores. Effect size was calculated to estimate the magnitude of the observed learning gains. Observation data were analysed using thematic analysis to identify recurring patterns in students' inquiry behaviours. Initial coding focused on behaviours aligned with IBSE phases, such as prediction, measurement, calculation, observation, and explanation. These codes were then grouped into broader themes reflecting students' engagement with inquiry practices and evidence-based reasoning. The qualitative findings were used to complement the quantitative results by providing process-level insight into how learning occurred during the inquiry activities.

RESULTS

A Wilcoxon Signed-Rank Test was conducted to examine differences between students' pre-test and post-test scores following the instructional intervention. This non-parametric test was selected due to the non-normal distribution of the difference scores. A total of 68 matched pairs were included in the analysis. As shown in Table 1, 40 students demonstrated higher post-test scores than pre-test scores, 8 students showed lower post-test scores, and 20 students showed no change.

The analysis revealed a statistically significant increase in post-test scores compared to pre-test scores, $Z = -4.451$, $p < .001$ (Table 2), indicating improved performance following the intervention. To estimate the magnitude of this change, an effect size (r) was calculated using the formula $r = Z/\sqrt{N}$. With $Z = -4.451$ and $N = 68$, the resulting effect size was $r \approx 0.54$, which represents a large effect according to conventional benchmarks (Cohen, 1988). These results suggest that the instructional intervention was associated with a substantial improvement in students' understanding of density.

Table 1 Summary of Wilcoxon Signed-Rank Test Results

Comparison	N	Mean Rank	Sum of Ranks
Negative ranks (Post < Pre)	8	20.00	160.00
Positive ranks (Post > Pre)	40	25.40	1016.00
Ties	20	–	–
Total	68		

Table 2 Wilcoxon Signed-Rank Test statistics

Statistic	Value
Z	−4.451
Asymp. Sig. (2-tailed)	< .001

To further interpret these quantitative gains, the following section presents qualitative findings from classroom observations that provide insight into students' engagement in inquiry processes during the instructional activities. Classroom observations indicate that the DD-Kit supported key inquiry processes, including prediction, measurement, calculation, and explanation, providing process-level evidence to complement the quantitative findings as summarised in Table 3.

Table 3 Summary of Observed Inquiry Behaviours

Theme	**Observation Description**
Collaborative Measurement and Data Generation	Students worked in small groups to measure object dimensions and mass, compare results, and agree on recorded values, indicating shared engagement in evidence generation and verification.

Prediction and Hypothesis Formation	Prior to immersion, students articulated predictions about floating and sinking based on object characteristics and prior beliefs, revising these predictions when comparing objects with contrasting density scenarios.
Linking Calculations to Observable Outcomes	Students calculated density values and referred explicitly to these calculations when explaining observed buoyant behaviour during group discussions.
Sustained Engagement in Inquiry Processes	Students remained engaged across multiple inquiry phases, including measurement, calculation, observation, and discussion, supported by the manipulability and clarity of the 3D-printed objects.

Classroom observations indicate that students' engagement with the Density Discovery Kit (DD-Kit) supported key inquiry processes central to Inquiry-Based Science Education (IBSE) (Table 3). Students consistently engaged in collaborative measurement and data generation, working in small groups to measure object dimensions and mass, compare values, and reach agreement on recorded data. This shared engagement in evidence generation provided a foundation for subsequent inquiry activities. Prior to immersion of the objects in water, students articulated predictions regarding floating and sinking behaviour, frequently drawing on prior conceptions related to mass or visual appearance. The inclusion of contrasting density scenarios prompted students to compare objects systematically and revise their predictions, indicating active hypothesis formation. During the investigation, students calculated density values and explicitly linked these calculations to observed buoyant behaviour, using quantitative evidence to justify their explanations. Observation data further suggest that students sustained engagement across multiple inquiry phases—including measurement, calculation, observation, and discussion—supported by the manipulability and clarity of the 3D-printed objects. Together, these observations provide process-level evidence that the DD-Kit facilitated structured inquiry practices, complementing the quantitative findings on students' understanding.

DISCUSSION

This study examined the extent to which a 3D-printed instructional kit supported students' understanding of density through structured inquiry activities. Guided by the conceptual framework, the findings indicate that students demonstrated statistically significant learning gains alongside observable engagement in key inquiry processes. The convergence of quantitative and qualitative evidence suggests that the instructional intervention supported meaningful engagement with the relationships among mass, volume, density, and buoyancy, which are widely recognised as conceptually challenging for learners.

The significant improvement in post-test scores, accompanied by a large effect size, indicates that students' understanding of density improved following the inquiry activity. Although the single-group design does not permit causal attribution, the magnitude of the observed gains is notable in light of persistent difficulties documented in the teaching and learning of density (Harrell et al., 2014; Hashweh, 2016). Prior research has shown that students often rely on intuitive reasoning based on size, weight, or visual appearance, which can interfere with understanding density as a relational concept(Xu & Clarke, 2012; Zvoch et al., 2021). The present findings suggest that providing instructional conditions that foreground systematic comparison and quantitative reasoning may support students in moving beyond such intuitive explanations.

Qualitative observations provide insight into the inquiry processes through which these learning gains may have emerged. Students were observed engaging in collaborative measurement and data generation, articulating and revising predictions, and explicitly linking calculated density values to observed buoyant behaviour. These practices correspond closely with established phases of Inquiry-Based Science Education, indicating that students were actively engaged in reasoning with evidence rather than merely following procedural steps (Pedaste et al., 2015; van Uum et al., 2016). Such engagement with prediction, measurement, and explanation is widely regarded as central to supporting conceptual understanding in inquiry-oriented science classrooms(Marshall & Smart, 2013; Pedaste et al., 2015).

The configuration of the instructional materials appeared to play an important mediating role in supporting inquiry enactment(Chatterjee & Hannan, 2016). The inclusion of objects with identical volume but different mass, alongside objects with different volumes and masses, created contrasting density scenarios that prompted

students to compare outcomes systematically. Observation data suggest that these contrasts encouraged students to confront discrepancies between expectations and observations, leading to revision of predictions and refinement of explanations. This pattern aligns with research emphasising the role of carefully designed material conditions in supporting conceptual change, particularly for abstract or relational scientific concepts(Hashweh, 2016; Zvoch et al., 2021).

The findings also resonate with broader literature on the use of physical artefacts and object-based learning in science education. Research has suggested that tangible, manipulable objects can support learners' engagement by anchoring abstract ideas in observable phenomena and by facilitating collaborative sense-making (Chatterjee & Hannan, 2016; Hardie, 2015). In the present study, students' sustained engagement across multiple inquiry phases suggests that the physical properties and manipulability of the 3D-printed objects supported continued focus on the investigative task, even when students encountered procedural challenges such as calculating the volume of spheres. While the instructional intervention employed controlled artefacts, this does not imply that authentic, irregular objects are pedagogically unnecessary. Rather, structured inquiry with stabilised variables can serve as a foundation for subsequent transfer to more complex contexts, where learners are better equipped to coordinate mass and volume across varied shapes and materials. Such progression aligns with research on conceptual change, which suggests that reducing cognitive and perceptual load during initial learning can support deeper understanding before reintroducing real-world complexity.

Within this study, Design Thinking informed the development of the instructional kit by guiding alignment between technological affordances, inquiry tasks, and classroom realities (Brown, 2008; Razzouk & Shute, 2012). However, Design Thinking was not examined as an instructional mechanism, and no claims are made regarding its direct influence on learning outcomes. Rather, its role was confined to shaping the design of the educational artefact, which in turn supported inquiry processes during classroom enactment. This distinction is important for interpreting the findings, as it reinforces that observed learning gains are associated with structured inquiry supported by material affordances rather than with the design approach itself.

The absence of a comparison group limits causal interpretation, and the study was conducted within a single classroom context, which may constrain generalisability. In addition, the instructional intervention was implemented by the classroom teacher, who was also a member of the research team. While this practitioner-researcher role supported authentic classroom enactment, it may have introduced potential bias in instructional delivery or observation. Future research may address these limitations by incorporating comparison groups, independent observers, or implementation across multiple classrooms.

CONCLUSIONS AND IMPLICATIONS

The findings of this study have several implications for science education practice, instructional design, and future research. First, the results suggest that carefully designed physical instructional artefacts can play an important role in supporting the enactment of Inquiry-Based Science Education (IBSE), particularly when teaching abstract and relational concepts such as density. By stabilising experimental conditions and enabling systematic comparison of variables, the Density Discovery Kit (DD-Kit) supported students' engagement in prediction, measurement, calculation, and explanation—core processes associated with meaningful inquiry learning. These findings highlight the value of purposefully designed manipulatives in contexts where conventional classroom materials may limit opportunities for controlled scientific investigation.

Second, the study underscores the importance of aligning technological affordances with pedagogical goals. The use of 3D printing in this study did not function as an end in itself but as a means of supporting structured inquiry processes. The educational value of emerging technologies therefore lies not in their novelty, but in how their design features are leveraged to foreground students' reasoning with evidence. For educators and curriculum designers, this emphasises the need to prioritise pedagogical alignment when integrating technologies into inquiry-based science instruction. While much of the literature on 3D printing in education focuses on makerspace-based pedagogies that involve student-led design and fabrication, the present findings suggest that carefully designed teacher-developed artefacts may provide an alternative pathway for supporting inquiry learning, particularly in contexts where open-ended making presents practical or pedagogical constraints (Bower et al., 2020).

Third, the findings contribute to research on technology-supported inquiry learning by demonstrating how physical instructional technologies can mediate the relationship between inquiry processes and conceptual understanding. The integration of quantitative learning outcomes with qualitative evidence of inquiry practices provides a more comprehensive account of how learning occurs during inquiry activities. Future research should examine the implementation of similar instructional artefacts across larger and more diverse student populations to establish the transferability of the findings across educational contexts. Longitudinal studies employing delayed post-tests would also be valuable in determining whether the conceptual gains associated with the DD-Kit are retained over time and transferred to related scientific concepts beyond density and buoyancy.

This study examined the extent to which a 3D-printed instructional kit supported students' understanding of density through structured inquiry activities. The findings revealed statistically significant improvements in students' conceptual understanding, accompanied by observable engagement in key inquiry processes including prediction, measurement, calculation, and explanation. Guided by a conceptual framework linking technological affordances, inquiry processes, and learning outcomes, the study highlights the role of purposefully designed instructional artefacts in supporting inquiry enactment. The DD-Kit functioned as a mediating educational technology that reduced extraneous variability and foregrounded systematic reasoning, enabling students to engage meaningfully with the relationships among mass, volume, density, and buoyancy. While these findings provide encouraging evidence for the educational value of the DD-Kit, they should be interpreted within the context of a single cohort and immediate post-intervention outcomes. Further multi-site and longitudinal investigations are needed to establish the generalisability and long-term durability of the observed learning gains. Collectively, these findings provide evidence that well-designed, pedagogically aligned physical learning resources can enhance inquiry-based science learning and demonstrate how 3D printing can be leveraged not merely as a technological innovation, but as a practical means of strengthening conceptual understanding in science classrooms.

REFERENCES

1. Abdullah, R. A. (2022). The use of 3d printing on design thinking in the design process: A literature review. Journal of Industrial Product Design Research and Studies,1 (1), 9-22. 10.17509/jipdrs.v1i1.47469
2. Bower, M., Stevenson, M., Forbes, A., Falloon, G., & Hatzigianni, M. (2020). Makerspaces pedagogy–supports and constraints during 3D design and 3D printing activities in primary schools. Educational Media International, 57(1), 1–28. https://doi.org/10.1080/09523987.2020.1744845
3. Brown, T. (2008). Design thinking. Harvard Business Review, 86, 84–92.
4. Chatterjee, H. J., & Hannan, L. (2016). Engaging the senses: Object-based learning in higher education. Routledge. https://doi.org/10.4324/9781315579641
5. Creswell, J. W. (2012). Educational research: planning, conducting, and evaluating quantitative and qualitative research. (4th edition). Pearson.
6. Dorsah, P., Awini, G., Okyer, M., Alhassan, A.-G., Shahadu, I., & Kpemuonye, A. K. N. (2024). Challenges in Teaching Integrated Science in Junior High Schools. OALib, 11(02), 1–13. https://doi.org/10.4236/oalib.1111101
7. Ford, S., & Minshall, T. (2019). Invited review article: Where and how 3D printing is used in teaching and education. Additive Manufacturing, 25, 131–150. https://doi.org/10.1016/j.addma.2018.10.028
8. Goldman, S., & Zielezinski, M. B. (2016). Teaching with design thinking: Developing new vision and approaches to twenty-first century learning. In L. A. Annetta & J. Minogue (Eds.), Connecting Science and Engineering Education Practices in Meaningful Ways (Vol. 44, pp. 237–262). Springer International Publishing. https://doi.org/10.1007/978-3-319-16399-4
9. Greenhalgh, S. (2016). The effects of 3D printing in design thinking and design education. Journal of Engineering, Design and Technology, 14(4), 752–769. https://doi.org/10.1108/JEDT-02-2014-0005
10. Iksan, Z., Abu Bakar, N., Amirullah, A. H., & Mohd Salehudin, S. N. (2018). Understanding the concept of life process in animals based on 7E inquiry model through lesson study approach. Creative Education, 09(11), 1763–1774. https://doi.org/10.4236/ce.2018.911128

11. Hansen, M. (2014). Characteristics of schools successful in STEM: Evidence from two states' longitudinal data. Journal of Educational Research, 107(5), 374–391. https://doi.org/10.1080/00220671.2013.823364
12. Hardie, K. (2015). Innovative pedagogies series: Wow: The power of objects in object-based learning and teaching. Higher Education Academy. .
13. Harrell, P. E., Subramaniam, K., & Harrell, P. E. (2014). Teachers need to be smarter than a 5 th grader: What elementary pre-service teachers know about density. Electronic Journal of Science Education, 18 (6).
14. Hashweh, M. Z. (2016). The complexity of teaching density in middle school. Research in Science & Technological Education, 34(1), 1–24. https://doi.org/10.1080/02635143.2015.1042854
15. Hsiao, H. S., Chen, J. C., Lin, C. Y., Zhuo, P. W., & Lin, K. Y. (2019). Using 3D printing technology with experiential learning strategies to improve preengineering students' comprehension of abstract scientific concepts and hands-on ability. Journal of Computer Assisted Learning, 35(2), 178–187. https://doi.org/10.1111/jcal.12319
16. Kaliampos, G., Saregar, A., Fadillah, M. A., & Ravanis, K. (2025). An exploration of physics teachers' lesson plans within the IBSE framework: The case of teaching mechanics in autistic students. Education Sciences, 15(11), 1535. https://doi.org/10.3390/educsci15111535
17. Kaptan, K., & Timurlenk, O. (2012). Challenges for Science Education. Procedia - Social and Behavioral Sciences, 51, 763–771. https://doi.org/10.1016/j.sbspro.2012.08.237
18. Liedtka, J. (2013). Design at darden working paper series design thinking: What it is and why it work. Design@darden.org
19. Mao, Y. (2023). Issues and strategies in inquiry-based learning evaluation. Open Journal of Social Sciences, 11(04), 422–440. https://doi.org/10.4236/jss.2023.114030
20. Marshall, J. C., & Smart, J. B. (2013). Teachers' transformation to inquiry-based instructional practice. Creative Education, 4(2), 132–142. https://doi.org/10.4236/ce.2013.42019
21. Meier, R. M., & Hendel, S. A. (2019). A project-based learning unit plan: An inquiry into frogs. Open Journal of Social Sciences, 7(11), 70–78. https://doi.org/10.4236/jss.2019.711006
22. Myllymäki, S., Hannila, E., Kokkonen, M., Jantunen, H., & Fabritius, T. (2024). Design thinking-driven development of a modular X-Band antenna using multi-material 3D printing. International Journal on Interactive Design and Manufacturing, 18(2), 901–910. https://doi.org/10.1007/s12008-023-01504-4
23. Opara, P. N., & Etukudo, D. U. (2014). Factors affecting teaching and learning of basic science and technology in primary schools. Journal of Educational Policy and Entrepreneurial Research, 1(1), 46-58.
24. Parker, J., Osei-Himah, V., Asare, I., & Ackah, J. K. (2018). Challenges faced by teachers in teaching integrated science in junior high schools in Aowin Municipality-Ghana. Journal of Education and Practice, 9(12), 65 – 68.
25. Pearson, H., & Dube, A. (2022). 3D printing as an educational technology: theoretical perspectives, learning outcomes, and recommendations for practice. Education and Information Technologies, 27. https://doi.org/10.1007/s10639-021-10733-7
26. Pedaste, M., Mäeots, M., Siiman, L. A., de Jong, T., van Riesen, S. A. N., Kamp, E. T., Manoli, C. C., Zacharia, Z. C., & Tsourlidaki, E. (2015). Phases of inquiry-based learning: Definitions and the inquiry cycle. Educational Research Review, 14(February), 47–61. https://doi.org/10.1016/j.edurev.2015.02.003
27. Quansah, R. E., Sakyi-Hagan, N. A., & Essiam, C. (2019). Challenges affecting the teaching and learning of integrated science in rural junior high schools in Ghana. Science Education International, 30(4), 329–333. https://doi.org/10.33828/sei.v30.i4.10
28. Razzouk, R., & Shute, V. (2012). What is design thinking and why is it important? Review of Educational Research, 82(3), 330–348. https://doi.org/10.3102/0034654312457429
29. Sahin, A. (2013). STEM Project-Based Learning: Specialized form of Inquiry-Based Learning. In R. M. Capraro & W.W. Slough (Eds.), Project-Based Learning: An integrated science, technology, engineering, and technology (STEM) approach (pp. 59-64). Rotterdam: Sense Publishers.

30. Sun, D., Wang, Z. H., Xie, W. T., & Boon, C. C. (2014). Status of Integrated Science Instruction in Junior Secondary Schools of China: An exploratory study. International Journal of Science Education, 36(5), 808–838. https://doi.org/10.1080/09500693.2013.829254
31. Tashakkori, A. & Creswell, J. (2007). Exploring the nature of research questions in mixed methods research. Journal of Mixed Methods Research, 1(3), 207–211. https://doi.org/10.1177/1558689807302814
32. Tejera, M., Galiç, S., & Lavicza, Z. (2025). 3D modelling and printing in teacher education: A systematic literature review. Journal for STEM Education Research. Springer Nature. https://doi.org/10.1007/s41979-025-00147-2
33. Valdespino, A., & Larson, C. (2019). Object-based learning. Academic Technologies.
34. van Uum, M. S. J., Verhoeff, R. P., & Peeters, M. (2016). Inquiry-based science education: towards a pedagogical framework for primary school teachers. International Journal of Science Education, 38(3), 450–469. https://doi.org/10.1080/09500693.2016.1147660
35. Xu, L., & Clarke, D. (2012). Student difficulties in learning density: A distributed cognition perspective. Research in Science Education, 42(4), 769–789. https://doi.org/10.1007/s11165-011-9232-7
36. Zvoch, K., Holveck, S., & Porter, L. (2021). Teaching for conceptual change in a density unit provided to seventh graders: A comparison of teacher- and student-centered approaches. Research in Science Education, 51(5), 1395–1421. https://doi.org/10.1007/s11165-019-09907-8