Enhancing Primary Students' Conceptual Understanding of Density Using a 3D-Printed Teaching Aid

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ABSTRACT

Teaching and learning in primary science often involve abstract ideas that are challenging for young learners to visualise and understand. One such challenge is explaining why objects float or sink, as students frequently rely on intuitive reasoning based on size or weight. This study examined the effectiveness of a 3D-printed teaching aid, Density Puzzle, in supporting Year Three students' understanding of floating and sinking phenomena. A quasi-experimental pre-test–post-test non-equivalent control group design was employed. One group received prevailing instruction, while the experimental group engaged in inquiry-based learning activities using Density Puzzle. Pre-tests and post-tests were administered to both groups, and the data were analysed using non-parametric statistical tests. The results showed significant improvements in students' understanding within both groups. Although no statistically significant difference was found between groups in post-test scores, the experimental group demonstrated a larger median learning gain (25.00%) compared to the control group (12.50%). These findings suggest that while prevailing instructional approaches can effectively support learning, the integration of 3D-printed teaching aids may further enhance students' understanding through hands-on exploration and inquiry. The study highlights the potential of practical and accessible teaching aids to support more effective teaching and learning of this topic in primary science classrooms.

Keywords:
3D printing; Density; Inquiry-based Science education; Teaching aids; Primary Science education

Introduction

Teaching and learning in primary science often involve abstract concepts that are difficult for young learners to visualise and understand (Kaptan & Timurlenk, 2012). At the primary level, students are not expected to formalise scientific relationships using equations or ratios; instead, learning focuses on explaining observable phenomena based on object properties (KPM, 2017). Teaching aids therefore play an important role in supporting students' understanding by providing concrete and hands-on learning experiences that make abstract ideas more accessible. Previous studies have shown that the use of hands-on and inquiry-oriented teaching aids can enhance students' engagement and learning outcomes in science classrooms (Maulana et al., 2023; Opara & Etukudo, 2014). Despite these benefits, science teachers frequently encounter challenges in selecting or developing appropriate teaching aids due to limitations in resources, instructional time, and pedagogical support (Dorsah et al., 2024; Quansah et al., 2019). These challenges are particularly evident in primary science classrooms, where effective learning often depends on students' opportunities to interact directly with physical materials.

One science concept that continues to pose significant challenges in primary education is density. To make sense of floating and sinking phenomena, students must reason about observable object properties rather than rely solely on intuitive judgments (Hashweh, 2016; Xu & Clarke, 2012). Research has shown that young learners frequently use perceptual cues such as size or weight when explaining these phenomena, leading to misconceptions such as the belief that heavier or larger objects always sink (Dorji, 2021; Seah et al., 2015). These misconceptions are not limited to primary students. Similar difficulties have been identified among secondary students, pre-service teachers, and university students, suggesting that misconceptions about density are persistent and resistant to change when instruction does not explicitly address conceptual understanding (Dawkins et al., 2008; Harrell et al., 2014; Panagou et al., 2024). Such findings suggest that difficulties in explaining floating and sinking are not easily resolved through

verbal explanations alone and require instructional approaches that allow students to compare objects systematically and reflect on observable outcomes.

In the Malaysian primary science curriculum, the topic of floating and sinking is introduced at Year Three (KPM, 2017). At this level, students are expected to explain observable outcomes, such as why certain objects float while others sink, based on comparisons of object properties. Although the curriculum encourages inquiry-based learning, classroom practice often relies on everyday objects that vary simultaneously in size, shape, and material. This variation makes it difficult for students to focus on relevant features and may reinforce intuitive explanations rather than promote conceptual understanding (Xu & Clarke, 2012). Furthermore, the limited availability of purpose-designed teaching aids that allow controlled comparison of object properties constrains teachers' ability to implement effective inquiry-based activities. Without suitable teaching aids, inquiry lessons may be reduced to teacher-led demonstrations, limiting opportunities for students to actively explore, predict, and explain floating and sinking phenomena.

To address the identified problem, this study introduces Density Puzzle, a 3D-printed teaching aid designed to support inquiry-based learning of floating and sinking phenomena among Year Three students (9-year-old). The teaching aid consists of identically sized cubes produced with different infill percentages, allowing students to visually compare hollow and more solid designs and observe how objects of the same size behave differently when placed in water. Through hands-on activities involving prediction, observation, and explanation, students are guided to reflect on observable outcomes and object properties.

The objectives of this study are to:

1. examine the change in Year Three students' understanding of floating and sinking phenomena following instruction using prevailing teaching methods.
2. examine the change in Year Three students' understanding of floating and sinking phenomena following inquiry-based instruction using the 3D-printed teaching aid Density Puzzle.
3. compare the learning gains between students taught using prevailing instructional methods and those taught using the 3D-printed teaching aid.

Literature Review

Inquiry-Based Science Education (IBSE) provides the pedagogical foundation for this study. IBSE emphasises learning through active engagement with phenomena, where students construct understanding by making predictions, conducting investigations, analysing observations, and developing explanations grounded in evidence (Pedaste et al., 2015; van Uum et al., 2016). At the primary level, inquiry-based learning is particularly important because it supports students' sense-making through guided engagement with phenomena and teacher-supported reasoning, rather than through formal abstraction (Qablan et al., 2024). However, the literature consistently indicates that the effectiveness of IBSE depends not only on pedagogical intent but also on the availability and quality of instructional materials that support inquiry processes (Dorsah et al., 2024; Kaptan & Timurlenk, 2012).

A few studies reported persistent challenges in students' explanations of floating and sinking phenomena. Learners frequently rely on intuitive reasoning based on perceptual cues such as size, weight, or material appearance, leading to misconceptions that are resistant to change (Dorji, 2021; Seah et al., 2015). These reasoning patterns have been observed across educational levels, suggesting the robustness of everyday explanatory frameworks (Dawkins et al., 2008; Harrell et al., 2014; Panagou et al., 2024). Importantly, instructional research indicates that such difficulties are exacerbated when learning materials introduce uncontrolled variation, making it difficult for learners to isolate relevant factors and generate coherent explanations (Hashweh, 2016).

In the Malaysian primary science curriculum, instructional goals emphasise supporting students in explaining observable outcomes in consistent and reasoned ways, rather than formalising the mathematical relationships underlying density, as specified in the curriculum documents (KPM, 2017). This curricular emphasis highlights the importance of instructional materials in mediating students' engagement with observable phenomena during inquiry activities. From a learning sciences perspective, instructional materials are understood as epistemic resources rather than passive supports. Designed artefacts shape students' opportunities to reason with evidence by structuring

attention, reducing extraneous variability, and enabling meaningful comparison across cases (Hansen & Richland, 2020). Within inquiry-based learning, such artefacts support the core processes of prediction, observation, and explanation by making critical features salient and observations interpretable. Conversely, when instructional artefacts are poorly designed or improvised, inquiry tasks may fail to adequately challenge intuitive reasoning, resulting in procedural engagement rather than conceptual change (Hashweh, 2016).

Synthesising this body of research points to several design principles for effective teaching aids in primary science. First, artefacts should enable controlled comparison by holding constant irrelevant features while varying properties that are pedagogically meaningful. Second, artefacts should remain developmentally appropriate, supporting observation and explanation without requiring formal measurement or abstract calculation. Third, teaching aids should align closely with curriculum expectations to ensure coherence between learning activities and assessment goals. These principles are particularly salient for topics such as floating and sinking, where everyday classroom objects often obscure underlying patterns due to uncontrolled variation.

Recent research in science education and educational technology further emphasises that the effectiveness of inquiry-based learning is shaped not only by pedagogical approach but also by the design of instructional artefacts that mediate learners' engagement with phenomena (Hansen & Richland, 2020). From this perspective, 3D printing is increasingly conceptualised as enabling infrastructure that allows teachers to design and produce curriculum-aligned artefacts with controlled features, rather than as an instructional innovation in itself (Ford & Minshall, 2019; Turakhia et al., 2024). This framing aligns with calls for technology use in primary science education to prioritise pedagogical intent and developmental appropriateness over novelty.

Three-dimensional (3D) printing is understood not as an instructional goal in itself, but as an enabling means for producing purpose-designed teaching aids that embody these design principles. 3D printing allows teachers to create consistent artefacts with controlled internal structures while maintaining identical external features, thereby supporting systematic comparison during inquiry activities (Ford & Minshall, 2019; Ng et al., 2022). Research on makerspaces further cautions that effective implementation in primary settings requires careful pedagogical planning, as time constraints, cognitive load, and technical complexity can undermine learning when making activities are poorly aligned with instructional goals (Bower et al., 2020). Recent studies indicate that educators frequently use makerspaces as sites for designing and refining instructional tools aligned with curriculum goals, rather than focusing exclusively on student-driven fabrication (Turakhia et al., 2024), underscoring the importance of teacher guidance and pedagogical intent (Oliver, 2016).

Synthesising the reviewed literature, this study adopts a conceptual framework (see Figure 1) in which inquiry-based learning is mediated by purpose-designed instructional artefacts that support students' engagement with scientific phenomena. Within this framework, teaching aids function as epistemic supports that enable controlled comparison and interpretation of observations, thereby strengthening inquiry enactment and conceptual understanding. Three-dimensional printing is conceptualised as enabling infrastructure that allows teachers to produce such artefacts in a feasible and curriculum-aligned manner. Guided by this framework, the present study examines the use of a 3D-printed teaching aid to support primary students' inquiry-based learning about floating and sinking phenomena.

Figure 1
Conceptual Framework

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          │         3D printing             │
          │   (Enabling infrastructure)     │
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                        │ produce
                        ▼
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          │   Curriculum-aligned Teaching   │
          │     aids (Artefacts / objects)  │
          └─────────────────────────────────┘
                        │ mediates
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          │  Inquiry-based Learning Process │
          │   (predict - observe - explain) │
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          │ Conceptual understanding of     │
          │ scientific phenomena            │
          │ (Floating & Sinking)            │
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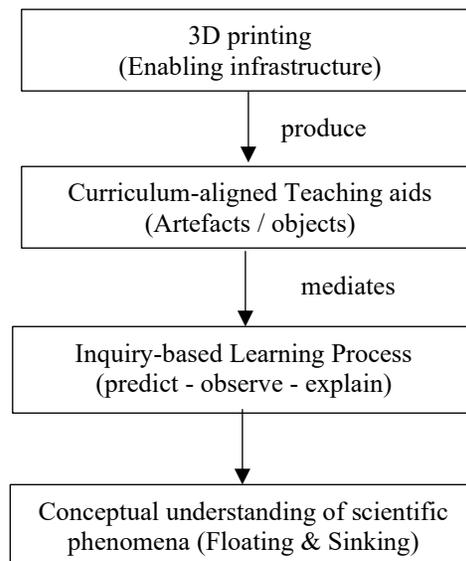
Methods

Research Design

This study employed a quasi-experimental pre-test–post-test non-equivalent control group design to examine the effectiveness of a 3D-printed teaching aid in supporting Year Three (nine-year old) students' understanding of floating and sinking phenomena. This design was chosen because intact classes were used, and random assignment of students was not feasible within the school context. Such designs are commonly adopted in classroom-based educational research to examine the impact of instructional interventions under authentic teaching conditions.

Samples and Population

Two Year Three classes from a public primary school participated in the study. One class with 35 students was assigned as the experimental group, while the other class with 30 students served as the control group. The participants were nine-year-old students following the Malaysian primary science curriculum (see Table 1). Both classes were taught the same curriculum topic related to floating and sinking within the same instructional period and were comparable in terms of age, curriculum exposure, and learning objectives. The study was conducted as part of regular classroom instruction. Ethical considerations were observed, and students' identities were anonymised during data analysis. Permission to conduct the study was obtained from the Ministry of Education and the school administration. The instructional intervention was implemented by one of the researchers during her teaching practicum at the participating school.

Table 1
Profile of Participants

Group	Gender	Number	Total
Control	Male	15	30
	Female	15	
Experimental	Male	19	35
	Female	16	

Research Instruments

The instructional material used in this study was Density Puzzle, a 3D-printed teaching aid adapted and pedagogically modified from an openly shared infill test cube design by Roman (2024). The original design was modified to align with primary science curriculum requirements, including internal structure visibility, size consistency, and suitability for classroom-based inquiry activities. The teaching aid consists of identically sized cubes produced with different internal structures, ranging from hollow to more densely printed designs, with one face left open to allow visual examination of internal structure as presented in Figure 2. Learning activities focused on visual comparison and observation of the cubes' behaviour in water. This design enabled visualisation of density through controlled comparison. By holding external size constant while varying infill percentage, young students could observe that objects of the same size can differ in mass and behave differently in water. This supported visual reasoning and conceptual understanding without requiring abstract calculation, which is developmentally inappropriate at the Year Three level. Everyday classroom objects were intentionally not used in the experimental condition because such materials typically vary simultaneously in size, material, and structure, encouraging reliance on perceptual cues such as size or weight. However, everyday objects may be incorporated as extension activities in the next lesson to support the application of density concepts to real-life contexts.

Students' understanding of floating and sinking phenomena was assessed using a researcher-developed achievement test consisting of eight multiple-choice items. The items were aligned with the Year Three science learning standards and focused on students' ability to explain observable outcomes rather than on formal scientific definitions or calculations. Content validity of the instrument was established through expert review by two experienced primary science teachers, who evaluated the items for clarity, curriculum alignment, and age appropriateness. Scores were converted into percentages for analysis.

Figure 2
Density Puzzle

Research Procedures

The experimental and control groups were taught by two different Year Three science teachers, reflecting the use of intact classrooms under normal school conditions. Both classes were taught the same science topic related to floating and sinking over the same instructional duration. The experimental group engaged in inquiry-based learning activities using the 3D-printed teaching aid (see Figure 3). Students worked in small groups and were guided through the following steps:

1. Prediction – Students predicted whether each cube would float or sink based on its appearance and internal structure.
2. Observation – Students placed the cubes in water and observed their behaviour.
3. Explanation – Students discussed and explained the observed outcomes by referring to the visible internal structure of the cubes and their observations.

The teacher facilitated discussion by prompting students to compare cubes of the same size and reflect on why their behaviour in water differed. The control group received prevailing instruction, which included teacher explanation using PowerPoint presentation and guided discussion. Both teachers followed the same curriculum topic, learning objectives, and instructional duration, and lesson implementation was aligned in advance to ensure comparability. While the involvement of different teachers introduced instructional variability, this design enhanced the ecological validity of the study by reflecting authentic classroom practice.

Figure 3
Students Engaged in Inquiry-Based Learning Activities

Data Analysis

Data were analysed using IBM SPSS Statistics. Descriptive statistics, including median scores and median gain percentages, were calculated to examine learning trends within and between groups. Given the small sample size and the bounded nature of the assessment scores, assumptions of normality required for parametric tests could not be confidently met. Therefore, non-parametric statistical analyses were employed. The Wilcoxon Signed-Rank Test was used to examine within-group differences between pre-test and post-test scores, while the Mann–Whitney U Test was used to compare gain scores between the control and experimental groups.

Results

Descriptive analysis was conducted to examine students' performance before and after instruction. As shown in Table 2, both the control and experimental groups demonstrated improvement from pre-test to post-test.

Table 2
Descriptive Statistics for Pre-test and Post-test Scores

Group	Pre-test Median (%)	Post-test Median (%)	Median Gain (%)
Control Group	62.50	75.00	12.50
Experimental Group	50.00	75.00	25.00

Note. Scores are presented as percentages to reflect students' achievement levels in explaining floating and sinking phenomena.

The control group recorded a median increase of 12.50%, indicating improved understanding of floating and sinking phenomena following prevailing instruction. The experimental group demonstrated a larger median increase of 25.00%, suggesting greater learning gains among students who participated in inquiry-based activities using the 3D-printed teaching aid.

The Wilcoxon Signed-Rank Test was used to examine changes in students' understanding within each group. The results are summarised in Table 3.

Table 3

Wilcoxon Signed-Rank Test Results for Within-Group Comparisons

Group	Z value	p value
Control Group	–2.958	.003
Experimental Group	–3.132	.002

For the control group, the analysis revealed a statistically significant improvement between pre-test and post-test scores (z = –2.958, p = .003). This finding indicates that prevailing instructional methods were effective in supporting students' understanding of floating and sinking phenomena. Similarly, the experimental group showed a statistically significant improvement following instruction using the 3D-printed teaching aid (z = –3.132, p = .002). This result suggests that inquiry-based learning activities supported by Density Puzzle contributed positively to students' learning.

To compare learning gains between the two groups, gain scores were analysed using the Mann–Whitney U Test. As presented in Table 4, the analysis indicated that there was no statistically significant difference in gain scores between the control and experimental groups (z = –0.766, p = .444).

Table 4

Mann–Whitney U Test Results for Comparison of Gain Scores

Comparison	Z value	p value
Control vs Experimental	–0.766	.444

Although the difference was not statistically significant, the descriptive results in Table 1 show that the experimental group achieved a larger median gain compared to the control group. This suggests that while both instructional approaches were effective, the use of the 3D-printed teaching aid may have provided additional support for students' learning through hands-on exploration. These findings provide evidence that both prevailing instruction and inquiry-based learning supported by a 3D-printed teaching aid can effectively enhance primary students' understanding of floating and sinking phenomena.

Discussion

The findings indicate that prevailing instruction was effective in supporting Year Three students' understanding of floating and sinking phenomena. Students in the control group demonstrated a statistically significant improvement in their understanding of floating and sinking phenomena following prevailing instruction that relied on teacher explanation with PowerPoint and guided discussion. This finding indicates that well-structured teacher-led instruction can effectively support learning when aligned with curriculum expectations and learning objectives (van Uum et al., 2016). Consistent with prior research, clear explanations and opportunities for discussion can help young learners move beyond intuitive explanations based on surface features and develop more appropriate reasoning about observable outcomes (Dorji, 2021; Seah et al., 2015 & Zvoch et al., 2021). However, the smaller median learning gain observed in the control group suggests potential limitations of prevailing instruction when students have limited opportunities to interact directly with the teaching aids.

Students in the experimental group also showed a statistically significant improvement in their understanding of floating and sinking phenomena, with a larger median learning gain compared to the control group. This finding suggests that inquiry-based learning activities supported by Density Puzzle were effective in enhancing students' learning. Importantly, the teaching aid was designed to align with primary curriculum expectations. Students were not required to measure mass or engage in abstract calculations; instead, they visually examined the internal structure of identically sized cubes printed with different infill percentages and observed their behaviour in water. This design enabled controlled comparison, allowing students to focus on observable differences while holding external size constant. Such comparison supports visual reasoning and reduces reliance on intuitive explanations based solely on size or appearance (Hansen & Richland, 2020). The larger median gain suggests that the artefact's design helped students revise intuitive ideas by making otherwise hidden properties conceptually accessible during inquiry activities.

A potential question arising from this study concerns why everyday classroom objects were not used as the primary teaching aid in the experimental condition, given their frequent use in teaching floating and sinking phenomena. While everyday objects are familiar and readily available, they typically vary simultaneously in size, material, shape, and internal structure. For primary students, such uncontrolled variation can obscure the relationship between object properties and observed outcomes, encouraging reliance on perceptual cues such as size or apparent weight rather than supporting conceptual understanding of density (Xu & Clarke, 2012). The use of Density Puzzle was therefore a deliberate pedagogical choice. By holding external size constant and varying internal structure through different infill percentages, the teaching aid enabled students to visualise that objects of the same size can differ in mass and behave differently in water. This controlled comparison supported students' visual reasoning during inquiry activities and reduced cognitive demands associated with isolating relevant variables. Importantly, everyday objects were not rejected as pedagogically unimportant; rather, they are more appropriately introduced as extension materials after students have developed a coherent conceptual framework, allowing them to apply their understanding of density to more complex, real-life situations.

Although the experimental group demonstrated a larger median learning gain, the difference in learning gains between the control and experimental groups was not statistically significant. This finding should not be interpreted as evidence that the 3D-printed teaching aid was ineffective, but rather as an indication that both instructional approaches may be developmentally appropriate and pedagogically effective for supporting Year Three students' understanding within the limited duration of the intervention. Several factors may have contributed to the absence of a statistically significant difference. The instructional intervention was conducted over a short period, which may have limited the extent to which differences between groups could emerge. Additionally, students' prior knowledge and variability in classroom interaction may have influenced learning outcomes. In primary classrooms, conceptual change often requires repeated exposure and sustained opportunities for exploration and reflection (Hashweh, 2016; Xu & Clarke, 2012). Nevertheless, the larger median gain observed in the experimental group suggests that the use of the 3D-printed teaching aid may provide additional learning support beyond prevailing instruction. Rather than replacing existing teaching practices, such teaching aids can be viewed as complementary tools that enhance inquiry-based learning by making key object properties more visible and comparable (Maulana et al., 2023). At the primary level, where learning emphasises explanation of observable phenomena rather than formal abstraction, well-structured teacher-led instruction can yield learning outcomes comparable to inquiry-based approaches, particularly in short-term implementations.

Implications for Teaching and Learning in Primary Science

The findings of this study have several implications for teaching and learning in primary science classrooms. First, they underscore the importance of aligning instructional resources with curriculum expectations and developmental readiness. While PowerPoint-based visual representations can effectively support explanation and discussion, teaching aids that allow students to coordinate visualisation with physical observation may further support inquiry-based learning. Teaching aids do not need to introduce formal scientific concepts beyond the syllabus; instead, they should support students in explaining observable phenomena through comparison and observation (Hansen & Richland, 2020; van Uum et al., 2016). Second, the study demonstrates the potential of low-cost, 3D-printed teaching aids to support inquiry-based learning (Ford & Minshall, 2019; Ng et al., 2022). By allowing teachers to design materials with controlled features, such teaching aids can help address common misconceptions while remaining accessible and practical for classroom use. Finally, the results suggest that effective teaching of floating and sinking phenomena benefits from a combination of clear instruction, guided discussion, and hands-on exploration. Teachers may consider integrating simple, purpose-designed teaching aids into existing lessons to provide students with more opportunities to observe, predict, and explain scientific phenomena.

Beyond its immediate classroom application, the use of Density Puzzle also has implications for makerspace-informed pedagogy in primary education. Makerspaces have been shown to support hands-on, inquiry-oriented learning by enabling teachers and students to engage with designed artefacts that make abstract ideas more tangible (Turakhia et al., 2024). However, research has also highlighted that effective makerspace implementation depends on clear pedagogical intentions, curriculum alignment, and manageable levels of technical complexity (Bower et al., 2020). In this study, 3D printing was not positioned as a student-driven design activity, but as a teacher-facilitated means of producing purpose-designed teaching aids. Similarly, research on makerspace pedagogy has emphasised the

importance of clear pedagogical intent and teacher guidance when integrating making technologies into formal classroom contexts (Oliver, 2016). By using 3D printing to create controlled, curriculum-aligned teaching aids instead of focusing on the design process itself, teachers can leverage the affordances of makerspaces to enhance inquiry-based learning while remaining within primary-level learning expectations.

Conclusion

This study examined the use of Density Puzzle, a 3D-printed teaching aid, to support Year Three students' understanding of floating and sinking phenomena. The findings showed that both prevailing instruction and inquiry-based learning supported by the teaching aid led to significant improvements in students' understanding, with the experimental group demonstrating a larger median learning gain, although no statistically significant difference was found between groups. The study highlights that 3D printing in primary science can be effectively used by teachers to create controlled, curriculum-aligned teaching aids without requiring students to engage in complex design or formal scientific measurement. By focusing on observable object properties and guided inquiry, such teaching aids can enhance learning while remaining appropriate to primary-level expectations. Overall, the findings suggest that teacher-facilitated use of 3D printing, including within makerspace contexts, has potential to support effective and accessible science learning in primary classrooms.

Limitations and Future Studies

This study has several limitations that should be acknowledged. First, the use of a quasi-experimental design and a relatively small sample size limit the generalisability of the findings. Second, the instructional intervention was implemented over a short period, which may have constrained the extent of learning gains observed and reduced the likelihood of detecting statistically significant differences between groups. In addition, the experimental and control groups were taught by two different Year Three science teachers, reflecting authentic classroom conditions. While this introduced instructional variability, lesson objectives, content coverage, and instructional duration were aligned in advance to ensure comparability between groups. The involvement of different teachers may have influenced classroom interactions and instructional emphasis; however, the fact that both groups demonstrated statistically significant learning gains suggests that the findings are robust across variations in teacher implementation. At the same time, this variability enhances the ecological validity of the study by reflecting realistic school-based teaching contexts rather than tightly controlled experimental conditions. Finally, the instructional intervention was conducted by one of the researchers during her teaching practicum at the participating school. Although this ensured consistency in lesson delivery and alignment with curriculum expectations, the dual role may have introduced researcher-related bias.

Future studies could extend the present work by examining instructional sequencing approaches in which purpose-designed teaching aids are used during initial inquiry to support controlled comparison, followed by the introduction of everyday classroom objects as extension activities. Such studies would allow researchers to investigate how students transfer their conceptual understanding of density from controlled instructional contexts to more complex, real-life situations involving objects that vary simultaneously in size, material, and structure. Examining this progression may provide deeper insights into conceptual transfer, application, and durability of learning in primary science classrooms. Lastly, future research may involve longer implementation periods, larger samples, repeated inquiry cycles, and the involvement of independent teachers or multiple instructors across different schools. These extensions would enable a more comprehensive examination of the effectiveness, scalability, and classroom feasibility of 3D-printed teaching aids for supporting primary students' understanding of floating and sinking phenomena.

Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Acknowledgment

teachers of SJK (C) Kuo Min Nilai, namely Ms Law Pey Yu and Ms Sam Sirn Hooi, for their valuable assistance in validating the pre-test and post-test instruments. In particular, we would like to thank Ms Janice Ching Nian En for her support and cooperation in facilitating the implementation of the study.

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