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Exploring pre-service primary teachers' understanding of surface-to-volume ratio in nanoscience: Effects of an inquiry-based teaching intervention

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ABSTRACT

Comprehending the surface-to-volume ratio (S/V) is essential for elucidating several nanoscale and macroscopic phenomena; nonetheless, studies repeatedly indicate that learners, especially pre-service teachers, find it challenging to associate geometric relationships with physical behavior. This study examines the conceptual evolution of twenty pre-service primary educators who engaged in a three-and-a-half-hour inquiry-based educational sequence centered on the fundamental principles of nanoscale science and engineering. A pre-post-post strategy was employed to assess textual explanations and classroom video data, aiming to define reasoning patterns and shifts in comprehension. Pre-test replies were primarily characterized by intuitive, phenomenological explanations that did not consider S/V, indicating a limited understanding of how particle size and surface exposure affect dissolution. Subsequent to the intervention, numerous participants articulated scientifically coherent reasons, directly associating fragmentation with enhanced surface area and accelerated disintegration, while misconceptions remained prevalent among many. Post-test results, received later than expected, revealed partial retention and consolidation, with a group of students either sustaining or enhancing their comprehension. Video analysis indicated that tactile manipulation, representational tasks, and guided inquiry fostered constructive cognitive conflict and peer negotiation, promoting conceptual reconstruction. The results highlight the necessity of explicitly teaching scaling relationships in teacher education programs and suggest that even short, well-organized inquiry-based interventions can support noticeable conceptual development in pre-service primary teachers' reasoning about S/V relationships. The implications of incorporating nanoscale concepts into elementary science curricula and teacher training programs are examined.

Keywords: nanoscience education, surface-to-volume ratio, pre-service teachers, inquiry-based learning, conceptual understanding

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INTRODUCTION

Nanoscience and nanotechnology are fundamental components of modern scientific and technological advancement, impacting areas such as energy, medicine, environmental science, and materials engineering (Nasrollahzadeh et al., 2019). As nanoscale concepts rapidly infiltrate daily life, science education scholars contend that essential principles of nanoscience should be incorporated at all educational levels and integrated into teacher training programs (Pnevmatikos et al., 2024; Schmid et al., 2023). In this context, the promotion of nano literacy has been increasingly recognized as a key dimension of contemporary scientific literacy. As nanoscience and nanotechnology permeate everyday life, several studies have proposed and implemented instructional approaches to introduce core nano-related concepts across

The authors dedicate this article to the memory of Prof. Anna Spyrtou, who passed away before the preparation of this study, and whose work and commitment to science education continue to inspire.

◊ Deceased

educational levels, from primary through higher education. These efforts aim to support coherent learning progressions that connect familiar macroscopic experiences with nanoscale reasoning. Within this broader educational agenda, the present study focuses on pre-service primary teachers, a group that plays a crucial role in establishing early conceptual foundations yet remains underrepresented in nanoscience education research (Peikos et al., 2022). This disparity is particularly evident in contexts where educators are often generalists with limited formal preparation in the physical sciences yet are expected to foster core scientific literacy in students (Dulta et al., 2022).

Within this broader effort to promote nano literacy and to systematize nanoscience education across educational levels, two major frameworks have played a pivotal role in defining the core concepts that should underpin teaching and learning in the field. The "big ideas of nanoscale science and engineering" proposed by Stevens et al. (2009) offered an early, comprehensive conceptual structure to guide curriculum development and instructional design in nanoscience education. Building on this foundational work, Sakhnini and Blonder (2015), drawing on a Delphi study with the expert community, articulated a set of essential concepts of nanoscale science and technology for school education. Together, these two contributions have substantially informed subsequent research, curriculum design, and the development of learning progressions in nanoscience and nanotechnology education.

Among the core ideas identified in these frameworks, concepts related to size, scale, and size-dependent properties occupy a central position, as they provide learners with explanatory tools to make sense of the distinctive behavior of matter at the nanoscale (Swarat et al., 2011). In particular, big idea 1 (size and scale) and big idea 5 (size-dependent properties) have been widely recognized as especially productive for educational design, as they support conceptual continuity between everyday macroscopic experiences and nanoscale reasoning. These ideas offer a coherent conceptual pathway for introducing learners to nanoscale phenomena through familiar contexts, thereby creating fertile ground for addressing key explanatory concepts such as the surface-to-volume ratio (S/V). In this context, the notions of size and scale, along with size-dependent properties, are crucial for comprehending the distinct behavior of matter at the nanoscale and for creating conceptual continuity between commonplace phenomena and advanced applications in nanomedicine, electronics, and materials science. Initiatives to implement these big ideas have produced guidebooks and instructional materials that furnish educators with organized learning objectives and teaching methodologies consistent with nanoscale thinking (Stevens et al., 2009). Nonetheless, considerable obstacles persist in converting these theoretical concepts into tangible learning experiences that are accessible to both learners and the pre-service educators responsible for designing them, necessitating deliberate content transformation and experimentally grounded instructional design (Manou et al., 2018). Although the S/V is not formulated as a standalone "big idea" in the framework of Stevens et al. (2009), it constitutes a core explanatory mechanism that is conceptually embedded in big idea 1 (size and scale) and underpins big idea 5 (size-dependent properties), as it provides a geometric basis for understanding why material behavior changes with size.

As characteristic dimensions diminish, the S/V increases non-linearly, affecting processes such as dissolution, chemical reactivity, diffusion, heat transfer, and many biological structure-function interactions (Taylor & Jones, 2009). The markedly increased S/V of nanoparticles accounts for many of their distinctive properties, including higher catalytic activity, enhanced chemical reactivity, and improved solubility. Recent advancements in pharmaceutical nanotechnology illustrate that minimizing drug particle size substantially enhances the available surface area, consequently boosting dissolving rates and bioavailability of poorly soluble medications (Zhuo et al., 2024). In educational contexts, this notion has served as an accessible introduction to nanoscience, with research indicating that macroscopic experiments, such as dissolving sugar, effervescent tablets, or model medication capsules, can effectively support nanoscale thinking (Adadan et al., 2017).

Despite its conceptual significance, a substantial body of research indicates that students at all educational levels encounter persistent difficulties in understanding surface-area-to-volume relationships and their implications for physical and biological phenomena (Andreou & Kotsis, 2005; Enochs & Gabel, 1984). Research in biology and chemistry education indicates that students frequently struggle to coordinate surface area and volume as related quantities, confuse the two measures, or rely on intuitive heuristics such as "larger objects act faster" when predicting phenomena influenced by S/V relationships (Taylor & Jones, 2009).

Investigations involving educators indicate comparable difficulties: even seasoned teachers may struggle to comprehend or implement S/V connections in real scientific contexts or to create instructional activities that effectively link mathematical proportionality with physical behavior (Romesburg, 2011). These challenges indicate that S/V, despite its mathematical simplicity, necessitates meticulously structured training to cultivate scientifically coherent reasoning.

To tackle these issues, numerous scholars have investigated experiential, representational, and inquiry-based methodologies for teaching S/V relationships and size-dependent properties. Cohen et al. (1999) developed manipulatives that enable students to explore surface area-to-volume ratios across variously shaped or subdivided solids, thus rendering differences in dissolution and reaction rates observable. Romesburg (2011) identified S/V as an exemplary context for inquiry-based learning due to its capacity to connect mathematical proportionality with real-world biological and physical systems, allowing students to construct explanations grounded in quantitative reasoning. Interventions situated in nanoscience contexts have further demonstrated that incorporating macroscopic experiments within meaningful narratives (e.g., drug administration, diffusion, and materials engineering) can enhance students' understanding of size-dependent properties and S/V relationships (Adadan et al., 2017; Metaxas et al., 2021, 2025). Similarly, multimedia-rich and project-based modules in secondary education have been shown to support students' understanding of size and scale concepts fundamental to nanoscale phenomena (Blonder & Sakhnini, 2012).

Recent literature reviews highlight that research on nanoscience and nanotechnology education has predominantly focused on secondary education, while substantially fewer studies have addressed pre-service primary teachers' understanding of nanoscale concepts, such as the S/V, and how this understanding develops through focused instructional interventions (Schmid et al., 2023). At the same time, research indicates that both in-service and pre-service teachers frequently perceive themselves as inadequately prepared to teach nanoscale science, due to limited subject-matter preparation, scarcity of instructional resources, and restricted opportunities to engage in inquiry-based learning in emerging scientific domains (Blonder & Sakhnini, 2012; Manou et al., 2022). Recent research indicates that pre-service primary teachers often enter teacher education programs with limited scientific literacy and relatively low confidence in teaching physics-related concepts, factors that can constrain their engagement with emerging scientific domains such as nanoscience. Empirical studies in the Greek context have shown that pre-service teachers' overall scientific literacy remains uneven and, in some cases, comparable to that of primary school students, underscoring the need for targeted conceptual and pedagogical support in teacher education (Stylos et al., 2023; Tsoumanis et al., 2023). At the same time, pre-service primary teachers frequently report low self-efficacy in physics teaching, a dimension closely associated with their willingness to engage with conceptually demanding topics and inquiry-based instructional practices (Stylos et al., 2022). These challenges are compounded by well-documented learner difficulties in understanding fundamental geometric quantities such as length, surface area, and volume, which form the conceptual foundation for S/V reasoning and size-dependent phenomena (Andreou & Kotsis, 2005). Taken together, these findings highlight a structural gap in pre-service teacher preparation: prospective primary educators are expected to mediate advanced explanatory ideas—such as scaling relations and nanoscale properties—despite limited conceptual grounding and confidence in core scientific constructs. This gap provides a strong rationale for the design and investigation of inquiry-based instructional interventions that explicitly support the development of S/V reasoning within teacher education programs. Taken together, these findings underscore a pressing need for systematically designed and empirically evaluated instructional interventions that explicitly target S/V reasoning and size-dependent properties in pre-service teacher education. Examining how prospective primary teachers conceptualize S/V, how their reasoning develops through structured inquiry-based learning experiences, and which misconceptions persist over time is therefore essential for informing curriculum design and strengthening the foundations for confident and effective nanoscience teaching in elementary classrooms.

This study addresses this need by examining pre-service primary teachers' reasoning regarding the relationship between S/V and dissolution rate before, shortly after, and several weeks after their participation in an inquiry-based nanoscience teaching sequence. Based on the big ideas of nanoscale science and engineering (Stevens et al., 2009), the intervention aimed to support conceptual development through macroscopic experiments, representational tools, tactile models, and guided inquiry tasks. Dissolution was selected as the central phenomenon because it is familiar from everyday life, clearly observable at the macroscopic level, and strongly related to changes in surface exposure. It therefore provides an appropriate context for eliciting and developing S/V reasoning without requiring advanced chemical knowledge.

More specifically, the study was guided by the following research questions:

1. What levels of conceptual understanding do pre-service primary teachers demonstrate regarding the relationship between S/V and dissolution rate before, immediately after, and several weeks after an inquiry-based nanoscience intervention?
2. How do participants' explanations change across the three measurement points in terms of intuitive, partially informed, and scientifically coherent reasoning?
3. What persistent misconceptions or reasoning difficulties remain after the intervention?
4. How do classroom interactions and video-recorded episodes illustrate processes of cognitive conflict, peer negotiation, and conceptual reconstruction during the inquiry-based activities?

THEORETICAL FRAMEWORK

The big ideas introduced by Stevens et al. (2009) has been crucial in influencing research and curricular development in nanoscience education. The framework delineates nine fundamental ideas that encapsulate the essential intellectual architecture of nanoscale science and engineering and has informed recent efforts to promote nano-literacy across educational levels, emphasizing conceptual continuity from primary education to advanced applications (Pnevmatikos et al., 2024). Big idea 1 (size and scale) and big idea 5 (size-dependent properties) are particularly relevant to pedagogy as they elucidate the relational characteristics of nanoscale phenomena and facilitate the creation of learning progressions that link macroscopic experiences to nanoscale reasoning. Big idea 1 underscores that scientific explanations frequently rely on comprehending relative scale, dimensionality, and proportional relationships, as well as acknowledging that alterations in size can result in non-linear variations in geometric and physical attributes. Big idea 5 elaborates on this rationale by delineating how the properties of materials, optical, thermal, chemical, or mechanical, systematically alter as characteristic dimensions diminish, particularly in areas where surface phenomena or quantum effects prevail. By emphasizing how scale influences interactions inside and across materials, these Big ideas offer a conceptual framework for learners to comprehend, elucidate, and anticipate nanoscale behavior. They function as structural anchors for learning progressions that transition students from qualitative assessments of size to more advanced elucidations of size-governed features fundamental to modern nanoscience (Stevens et al., 2009).

A concept that holds a fundamental role in the convergence of these significant ideas is the S/V. S/V quantitatively represents the relationship between an object's surface area and its volume as its dimensions vary. In geometrically identical objects, volume escalates with the cube of linear dimensions, whereas surface area climbs with the square, leading to disproportionately greater S/Vs as size diminishes. This geometric relationship is simple; however its implications are significant for physical, chemical, and biological systems. In chemical kinetics, a greater surface area to volume ratio enhances the availability of reactive sites, hence accelerating reaction rates and dissolution processes (Taylor & Jones, 2009). In diffusion and transport phenomena, a high S/V facilitates the efficient movement of substances across borders, a principle essential to cellular physiology and respiratory systems (Cohen et al., 1999). In materials research, a high S/V supports improved catalytic activity, greater solubility, and modified mechanical properties of nanoparticles. Pharmaceutical research indicates that decreasing particle size significantly enhances dissolving rates and bioavailability, becoming surface area to volume ratio a crucial design parameter in nanomedicine formulation (Zhuo et al., 2024). Thus, S/V offers a cohesive framework for learners to comprehend the distinct behaviors of nanoscale materials compared to their macroscale equivalents.

Despite its conceptual importance, extensive research indicates that both students and teachers frequently grapple with enduring misconceptions regarding S/V and related nanoscale phenomena, while simultaneously recognizing the educational value and relevance of nanoscience-nanotechnology when supported by targeted professional development (Manou et al., 2022; Spyrtou et al., 2021). Research in biology education indicates that students frequently confuse surface area with volume, do not comprehend the scaling relationship between the two, or cannot explain the benefits of a high S/V for cells, tissues, or organisms (Cohen et al., 1999). Studies in chemistry and physics education also reveal challenges with proportional reasoning, misconceptions on geometric scaling, and dependence on intuitive heuristics such as "larger objects act faster" or "dissolution is solely contingent on the type of material" (Taylor & Jones, 2009). These simplistic models are also present in nanoscience contexts, where learners may recognize that nanoparticles exhibit distinct behaviors but find it challenging to relate these behaviors to fundamental geometric or physical concepts (Blonder & Sakhnini, 2012). These findings suggest that misconceptions regarding S/V are entrenched and necessitate educational settings that directly connect geometric reasoning to physical results across various representational levels.

Inquiry-based and constructivist educational methods provide effective avenues for enhancing learners' engagement with abstract nanoscale concepts, including S/V. Inquiry frameworks prioritize active exploration, model construction, prediction, and explanation enabling students to harmonize intuitive concepts with actual data (McNew-Birren & van den Kieboom, 2017; Peikos et al., 2022). Previous research indicates that tactile exercises involving students in the manipulation, subdivision, or comparison of items of varying sizes can enhance the visibility and significance of S/V interactions (Cohen et al., 1999). Inquiry activities grounded in real-world situations, such as medication administration, diffusion processes, or material performance, have demonstrated the ability to enhance comprehension of size-dependent features by linking macroscopic experiences with nanoscale interpretations (Adadan et al., 2017). Multimodal and project-based methodologies employed in nanoscience teaching, encompassing digital simulations, physical models, movies, and narrative scenarios, have similarly exhibited beneficial impacts on students' conceptual understanding (Blonder & Sakhnini, 2012). This body of study indicates that inquiry-rich contexts facilitate the progressive development of nanoscale reasoning by offering the necessary representational, experiential, and cognitive resources to integrate geometric, physical, and chemical concepts.

METHODOLOGY

The research utilized a pre-post-post design within a higher education framework, concentrating on enhancing pre-service teachers' conceptual knowledge via a systematic instructional intervention. While the study primarily employed a qualitative approach, aligned with research focused on elucidating reasoning patterns and conceptual transformations in science education (Creswell & Poth, 2018), descriptive quantitative data were additionally integrated to delineate the distribution of comprehension levels across measurement intervals. This hybrid approach accords with suggestions in scientific education research for integrating qualitative depth with quantitative tracking of learning patterns, particularly in intervention studies addressing complex topics such as nanoscale phenomena (Johnson & Onwuegbuzie, 2004). The study employed three sequential measurements, administered prior to instruction, immediately post-instruction, and several weeks later, to document both short-term changes and the retention and potential restructuring of ideas over time, adhering to established methodologies for assessing conceptual stability in science education (Sinatra et al., 2014).

Twenty pre-service primary teachers participated in an elective course on science and emerging technologies as part of a teacher education program in Department of Primary Education. The participants were in the advanced stages of their undergraduate education, possessing considerable familiarity with fundamental scientific principles but minimal knowledge of nanoscience. In alignment with standard characteristics of generalist primary educators, their formal education in physics and chemistry was inconsistent, and few indicated previous involvement in nanoscale science outside of popular scientific contexts. Participation was optional, and the intervention was included in standard course activities. The emphasis on pre-service primary teachers underscores the necessity to investigate how prospective educators develop fundamental comprehensions of nanoscale concepts, especially in light of findings indicating that teachers frequently perceive themselves as inadequately prepared to instruct in nascent scientific domains (Blonder & Sakhnini, 2012).

Data were gathered using several instruments aimed at capturing both textual reasoning and real-time learning processes. The principal instrument was a written questionnaire administered at three intervals (Pre, Post, and Post-Post). The questionnaire had open-ended questions that examined participants' explanations of dissolution phenomena, their interpretations of S/V correlations, and their capacity to relate scaling to observable behavior. Open-ended formats were selected to provoke comprehensive explanatory reasoning instead than recognition-based replies, consistent with best practices in conceptual understanding research (Treagust, 2006). All teaching sessions were recorded on video to document discourse, student interactions, and instances of conceptual negotiation. These recordings provided additional data for corroborating trends observed in written responses. A rubric was created to classify levels of conceptual comprehension, differentiating between naïve, somewhat informed, and scientifically accurate interpretations. The rubric was based on previous frameworks utilized in research investigating learning progressions and proportional reasoning in nanoscale contexts (Taylor & Jones, 2009) and comprised four sequential levels (level 0-level 3). The levels reflected qualitative distinctions in participants' explanations of dissolution phenomena, especially for their use of S/V reasoning.

At level 0, responses were either irrelevant or failed to provide an interpretable explanation of the phenomenon in question.

At level 1, explanations were primarily intuitive or phenomenological, depending on common reasoning (e.g., body absorption, ease of swallowing, or generalized chemical effects) without consideration of surface area, volume, or particle size.

At level 2, explanations incorporated partial or nascent scientific aspects, such as mentions of size reduction or fragmentation, yet failed to establish a clear or cohesive link to S/Vs or to elucidate how enhanced surface exposure influences the dissolution rate.

At level 3, explanations were scientifically coherent and explicitly connected fragmentation or size reduction to an increased surface area-to-volume ratio, utilizing this relationship to elucidate accelerated breakdown.

The instructional intervention lasted roughly three hours and thirty minutes, conducted across two sessions structured around constructivist and inquiry-based methodologies (Martínez-Borreguero et al., 2018). The intervention was designed as an introductory instructional sequence rather than a thorough explanation of S/V, with the goal of initiating mental engagement with scaling relationships and size-dependent features within a constrained instructional timeframe. The educational objectives focused on enabling participants to express the relationship between surface area-to-volume ratio and size, elucidate their implications for disintegration processes, and relate these concepts to nanoscale applications, prioritizing conceptual clarity and pedagogical significance for prospective primary educators.

Activities were organized to progress from tangible experiences to more abstract reasoning. Participants interacted with tactile models that demonstrated the scaling of surface area and volume across various forms and fragmented solids. They performed studies comparing the dissolving rates of intact and crushed materials. This task was selected to offer a comprehensible macroscopic reference for comprehending how enhanced surface exposure hastens interactions with surrounding medium, while also facilitating application to nanoscale contexts where dissolution, reactivity, and diffusion are dictated by S/Vs. They examined actual nano-applications through guided conversation, focusing on adhesion phenomena, diffusion processes, and medicinal formulations, linking macroscopic patterns to nanoscale explanations.

Representational challenges necessitated that students illustrate, annotate, or model the variations in surface area and volume relative to size, hence facilitating the amalgamation of geometric and scientific thinking (Dolonen & Ludvigsen, 2012). The learning activities aligned with research demonstrating that multimodal representations and inquiry-based methods can promote conceptual development in nanoscience subjects (Adadan et al., 2017; Cohen et al., 1999; Ünlü et al., 2023). The main learning activities are presented in **Figure 1**.

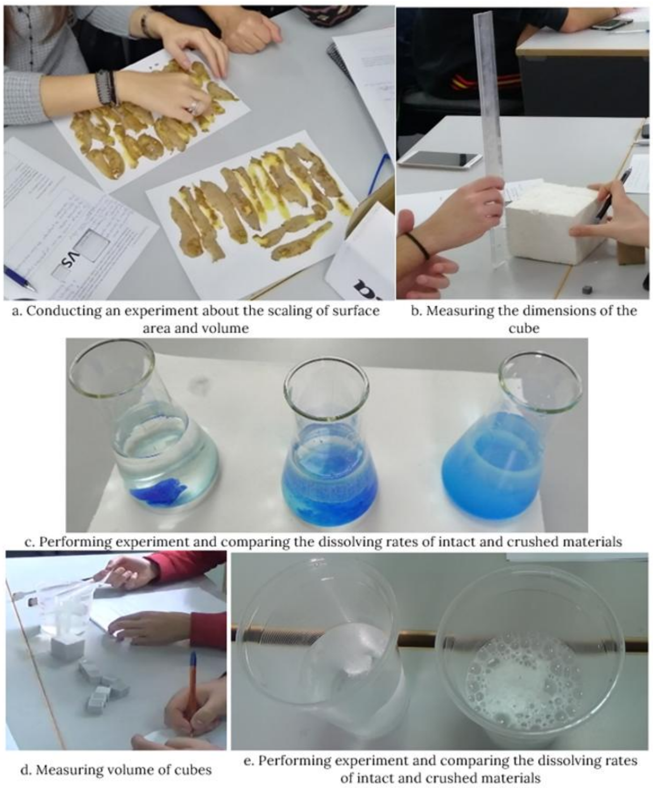

Figure 1. Photos from the five learning activities included in the inquiry-based nanoscience intervention (the authors' own elaboration)

The data analysis followed a multi-step, iterative analytic process. Written responses were transcribed and analyzed using the conceptual rubric described above. The coding process utilized an iterative, constant-comparative approach, enabling the refinement of categories as new patterns surfaced (Strauss & Corbin, 1998). To guarantee reliability, two researchers independently coded a subset of the written replies, including roughly 30% of the whole dataset, across all three measurement points. The initial interrater agreement attained 85%. Discrepancies regarding the coding rubric were deliberated until consensus was reached, leading to the refinement of the rubric definitions. The first author subsequently applied the established rubric to the entire dataset. Video data were analyzed as a complementary qualitative source in order to contextualize and triangulate the patterns identified in the written responses. The analysis focused on selected classroom episodes in which participants explicitly discussed surface area, volume, particle size, fragmentation, dissolution rate, or nanoscale applications. Episodes were first identified through repeated viewing of the recordings and then coded according to three interactional categories: cognitive conflict, peer negotiation, and conceptual reconstruction. Cognitive conflict referred to moments in which participants expressed uncertainty, contradiction, or surprise when their initial explanations did not fit the observed dissolution results. Peer negotiation referred to exchanges in which students compared, challenged, or refined one another's explanations.

Table 1. Distribution of coded analysis units across conceptual understanding levels

Level	Pre	Post	Post-post
L0	0	0	0
L1	18	14	9
L2	3	2	6
L3	5	5	4

Conceptual reconstruction referred to moments in which participants reformulated their reasoning by connecting fragmentation or size reduction with increased exposed surface area and faster dissolution. These video-based categories were not treated as separate quantitative variables, but as qualitative evidence used to support and interpret the written-response findings. Quantitative comparisons across the three measurement points were based on descriptive frequency distributions of coded analysis units across the four conceptual understanding levels.

RESULTS

The analysis of pre-test replies indicated that participants primarily utilized intuitive or phenomenological explanations, with minimal reference to geometric or mechanistic reasoning regarding dissolution. Each written response was segmented into smaller meaning-based units of analysis. Therefore, the unit of analysis was not the individual participant as a whole, but the distinct explanatory idea or reasoning element expressed within each participant's response. As a result, a single participant could contribute more than one analysis unit when his or her answer included more than one identifiable explanatory element. This procedure explains why the total number of coded analysis units at each measurement point could exceed the number of participants. The number of participants remained at 20, whereas the number of analysis units varied according to the complexity and multiplicity of the explanations provided. The bulk of analysis units were classified at lower levels of comprehension, predominantly at level 1, which is defined by intuitive, phenomenological explanations devoid of S/V reasoning. **Table 1** indicates that, at the pre-test stage, 18 coded analysis units were classified at level 1, three at level 2, and five at level 3, respectively. No occurrences of level 0 reasoning were detected. The data reveal that participants commenced the intervention with a restricted understanding of how surface exposure or particle size affects dissolving, frequently ascribing variations to physiological requirements, absorption, or generic chemical properties.

It should be noted that the frequencies presented in **Table 1** refer to coded analysis units rather than to individual participants. Since participants' open-ended responses sometimes contained more than one explanatory idea, the total number of analysis units may exceed the number of participants.

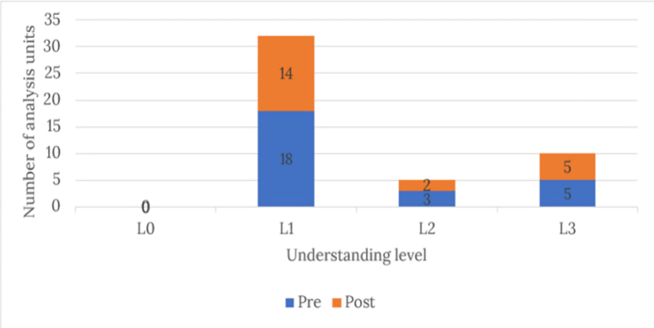

Figure 2. Comparison of conceptual understanding levels from pre to post (the authors' own elaboration)

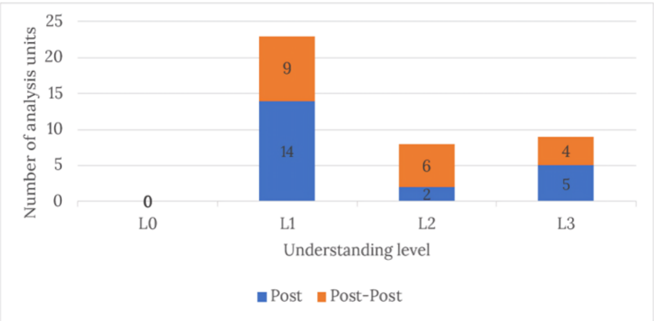

Figure 3. Comparison of conceptual understanding levels from post to post-post (the authors' own elaboration)

Subsequent to the intervention, a little alteration in the allocation of analysis units towards more scientifically substantiated explanations was noted.

Figure 2 demonstrates a decline in level 1 coded analysis units from eighteen to fourteen, whereas level 3 coded analysis units remained stable and level 2 coded analysis units showed a minor reduction. Notably, multiple participants provided level 3 explanations that clearly cited S/V ratios, linking fragmentation and enhanced surface exposure to accelerated dissolution. Nonetheless, many continued to provide reasons related to density, ease of ingestion, or general chemical characteristics, indicating a persistent dependence on common intuitions.

The postponed post-test provided insight into the stability and preservation of conceptual transformation.

Figure 3 illustrates a further reduction in the number of level 1 coded analysis units to nine, while level 2 coded analysis units increased to six, suggesting a shift toward partially informed reasoning within participants' explanations.

Level 3 analysis units diminished little from five to four; nevertheless, three of these contained entirely accurate explanations that expressly referenced S/V. Misconceptions from earlier phases, such as difficulties in swallowing or material-specific interpretations, were predominantly missing in delayed answers, suggesting partial long-term refinement.

The qualitative analysis of the video recordings provided complementary evidence about how participants negotiated the meaning of S/V reasoning during the inquiry activities. Three types of episodes were identified: cognitive conflict, peer negotiation, and conceptual reconstruction. Episodes of cognitive conflict occurred mainly during the fragmentation and dissolution activities, when participants observed that crushed material dissolved faster than intact material and attempted to reconcile this observation with their initial explanations. Several participants initially attributed the difference to material type, density, or ease of absorption, rather than to increased exposed surface area.

Episodes of peer negotiation were observed when students compared their explanations and attempted to decide whether the faster dissolution was related to smaller size, larger exposed surface, or a different physical property. In these exchanges, students often moved from everyday explanations toward more explicitly geometric reasoning. Episodes of conceptual reconstruction were identified when participants reformulated their explanations by linking fragmentation to increased surface area relative to volume and, consequently, to faster interaction with the surrounding liquid. These video-based observations support the written-response findings by showing that the intervention created opportunities for students to question their initial ideas and gradually develop more coherent explanations. However, the recordings also showed that transferring S/V reasoning to less familiar nanoscale applications, such as adhesion or diffusion, remained difficult for several participants.

DISCUSSION

The findings indicate a pattern of partial conceptual development in pre-service primary teachers' reasoning about S/V relationships. Across the three measurement points, participants' explanations showed a movement away from mainly intuitive or phenomenological accounts and toward more explicit references to size reduction, exposed surface area, and dissolution rate. However, this development was uneven. Some participants produced scientifically coherent explanations after the intervention, whereas others continued to rely on every day or material-based explanations, such as density, ease of absorption, or general chemical properties.

This pattern suggests that the inquiry-based sequence created opportunities for conceptual change but did not fully resolve the difficulties associated with S/V reasoning. The practical fragmentation and dissolution activities appeared to help participants connect a visible macroscopic phenomenon with an underlying geometric explanation. At the same time, the persistence of partially informed and non-mechanistic explanations shows that the concept remained challenging. This is not surprising, because S/V reasoning requires learners to coordinate surface area, volume, proportional change, and physical effect at the same time. Therefore, the findings should be interpreted as evidence of promising but incomplete conceptual development rather than as evidence of full conceptual mastery.

The persistence of misconceptions observed in this study is consistent with previous research showing that learners often struggle to coordinate surface area and volume as related quantities and to apply proportional reasoning to physical phenomena (Stavy & Tirosh, 1996; Taylor & Jones, 2009). The present findings add to this literature by showing how these difficulties appear among pre-service primary teachers in a nanoscience education context. Before the intervention, many explanations remained close to everyday experience and did not use geometric reasoning. After the intervention, several responses became more scientifically informed, but the continued presence of level 1 and level 2 explanations indicates that S/V reasoning cannot be assumed to develop fully through a single short instructional sequence.

This result is important for teacher education. Pre-service primary teachers may be expected to introduce young learners to emerging scientific ideas, but they themselves may not yet possess stable conceptual resources for explaining size-dependent phenomena. Therefore, teacher education programs should provide repeated opportunities to use S/V reasoning across different contexts, such as dissolution, diffusion, biological exchange, adhesion, and nanoparticle reactivity.

For pre-service primary teacher education, the findings point to the need for more explicit and repeated instruction on scaling relationships. S/V should not be presented only as a mathematical ratio, but as an explanatory tool that helps learners understand why changes in size can produce changes in physical and chemical behavior. Teacher education courses should therefore combine physical models, drawings, guided inquiry questions, and macroscopic experiments with explicit discussion of the underlying mechanism. Such activities can help prospective teachers move beyond everyday explanations and develop explanations that connect observable phenomena with geometric and nanoscale reasoning.

The results also suggest that nanoscience can be meaningfully introduced in primary teacher education when it is connected to familiar phenomena, such as dissolution. However, the persistence of misconceptions indicates that a single short intervention is not sufficient for stable understanding across all participants. Future instructional designs should therefore include repeated applications of S/V reasoning in different contexts and should explicitly prepare pre-service teachers to recognize and address similar misconceptions in their future pupils.

Limitations

Several constraints of this study must be recognized when evaluating the results. The limited sample size constrains the generalizability of the findings. The identified conceptual patterns align with previous research on learners' comprehension of S/V connections and nanoscale phenomena; nonetheless, the small participant pool necessitates that conclusions be regarded as indicative rather than representative. More extensive cohorts may uncover a wider array of reasoning tendencies or diverse pathways of conceptual growth.

A second constraint pertains to the course-specific setting in which the intervention was executed. The participants were enrolled in a specific elective course characterized by its distinct curricular framework, pedagogical culture, and expectations. These contextual factors may have affected the nature of student engagement, the types of explanations generated, and the methods by which inquiry activities facilitated conceptual transformation. The instructional sequence, while based on inquiry and constructivist ideas, may not yield uniform outcomes across varying institutional or curricular contexts.

A third restriction pertains to the lack of long-term classroom implementation with children. The study focused on the conceptual growth of pre-service teachers rather than their future instruction of nanoscale concepts in genuine primary classrooms. The findings fail to elucidate how these prospective educators may implement S/V reasoning in their teaching, how students may react to such instruction, or how educators' perceptions may further develop through actual teaching experiences. Subsequent research that tracks educators in their professional practice would facilitate the closure of this gap.

The dependence on open-ended textual explanations and qualitative categorization increases intrinsic interpretive complexity. Despite the implementation of several steps to guarantee the trustworthiness of the coding process, including iterative category refining and independent coder concordance, qualitative interpretation inherently entails a certain level of subjectivity. Students' written responses may inadequately reflect their underlying logic, especially if they encounter difficulties in articulating ideas graphically or verbally. Integrating open-ended questions with supplementary diagnostic formats or more frequent real-time inquiries may yield a more thorough understanding of student cognition.

CONCLUSIONS

This study examined pre-service primary teachers' reasoning about S/V and its role in explaining dissolution and other size-dependent phenomena. The findings suggest that the inquiry-based intervention supported some development in participants' explanations. Several participants moved from intuitive or everyday explanations toward more mechanistic accounts that referred to size reduction, exposed surface area, and dissolution rate. However, the results also show that this development was partial and uneven. Some misconceptions and non-mechanistic explanations remained present after the intervention, indicating that S/V reasoning is conceptually demanding and requires more sustained instructional attention.

The delayed post-test results suggest that some aspects of participants' improved reasoning were retained over time. However, given the small sample size, the descriptive character of the analysis, and the use of coded analysis units rather than participant-level statistical comparisons, these findings should be interpreted cautiously. They provide evidence of partial conceptual retention, but not definitive proof of lasting conceptual change.

The study highlights the educational value of explicitly addressing S/V in pre-service primary teacher education. S/V can function as an important explanatory bridge between familiar macroscopic phenomena, such as dissolution, and more abstract nanoscale processes. When supported through tactile models, inquiry activities, drawings, and guided discussion, the concept can become more accessible to prospective primary teachers. At the same time, the persistence of difficulties in participants' explanations indicates that short interventions should be followed by repeated opportunities to apply S/V reasoning in different contexts.

Future research should examine similar interventions with larger samples, clearer participant-level tracking, and longer-term follow-up. It would also be useful to investigate how pre-service teachers transfer their own understanding of S/V into instructional designs for primary pupils. Further curriculum development should focus on age-appropriate models, representations, and inquiry sequences that help young learners understand scaling relationships and size-dependent properties in scientifically meaningful ways.

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