Part 11 / Strand 11

Informal, Non-formal And Out-Of-School Science Education

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Part 11 / Strand 11 Informal, Non-formal And Out-of-school Science Education

Teaching and learning theories and practices in informal, non-formal, and out-of-school settings such as museums, science centres, outdoor settings, community programs (including indigenous communities), communications media, after-school programs and clubs. Includes design, adoption, exchange, and evaluation of informal, non-formal, and out-of-school learning environments, especially those organised by institutions other than schools, as well as informal and non-formal approaches to the teaching/learning of science.

Sub-themes:

1) Science Learning in Museums and Science Centers
2) Community-based Science Education Programs
3) Outdoor and Field-based Science Learning
4) Evaluation of Informal Science Learning Experiences

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Strand 11: Informal, Non-Formal And Out-Of-School Science Education

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Informal And Non-Formal Science Education: Learning In Vastly Different Settings

Strand 11 encompasses the design, evaluation, exchange, and implementation of informal and non-formal learning environments and recognizes diverse approaches to science teaching and learning across after-school initiatives, clubs, communication media, community programs, digital spaces, homes, Indigenous contexts, museums, outdoor environments, and science centers. These settings provide opportunities for science engagement, identity development, and inquiry. Science learning taking place outside the classroom complements formal schooling and broadens access to scientific learning (Braund & Reiss, 2006; Falk & Dierking, 2010; Rennie, 2014). Aligned with the ESERA 2025 conference theme, Transitions in Science Education: Sustainability and Digital Advances, *Strand 11 Informal, Non-formal and Out-of-school Science Education* highlights how science learning evolves across interconnected environments and educational landscapes, spanning a wide range of life domains, it creates new points of connection for science learning and thereby fosters sustainability. The Strand 11 papers illustrate how science learning occurs during interactions among educators, institutions, families, learners, and communities across informal settings. We grouped the articles based on their locations: school-linked, museum and science centers, home-based and remote, and game-based and designed learning. The paper subsets reflect distinct educational settings and illustrate the breadth of informal and non-formal science learning represented within the strand.

School-Linked Non-Formal Programs

School-linked non-formal programs connect student out-of-classroom science engagement with curriculum and educational goals. Science clubs, competitions, laboratories, and research experiences extend science connections and provide contexts where learners engage in experimentation, inquiry, and authentic scientific practices. These environments are important complements to formal schooling because they connect science to real contexts and experiences (Braund & Reiss, 2006; Dillon et al., 2006; Hofstein & Rosenfeld, 1996; Pfeiffer & Bradbury, 2023). School-linked non-formal programs extend learning across educational landscapes beyond classroom boundaries.

Museum And Science Center Partnerships

Museums and science centers are active learning spaces where visitors engage with collections, objects, educators, and scientific practices (Falk & Dierking, 2010; Patrick, 2023). Partnerships among citizen science initiatives, communities, museums, researchers, and schools encourage participation in science (Kampschulte & Hatcher, 2021). Museums and science centers promote public inquiry and engagement and direct interactions with objects that stimulate meaning making (Preston et al., 2026; Moussouri, 2002; Patrick & Moorman, 2021; Yeh, 2023), yet at the same time allow to broaden perspectives (Knabe et al, 2025). Citizen science initiatives further strengthen connections among museums, schools, and scientific communities (Bonney et al., 2016).

Home-Based And Remote Learning

Researchers recognize home as important sites for science learning because families connect science to everyday life. Family experiences influence science engagement and shape how learners encounter science during conversations, exploration, shared activities, and tinkering (Archer et al., 2015). Family contexts contribute to developing science interest (Tenenbaum et al., 2004). At-home science activities, family support, and virtual experiences support exploration and embed science in daily experiences. Moreover, the COVID driven push in technological developments dramatically extends the possibilities of science learning at home. Virtual experiences broaden access to informal settings and provide alternatives when face to face connections are limited (Radianti et al., 2020). The authors of the study highlight the growing relationships among families, technology, and science learning.

Game-Based And Designed Learning Environments

Designed learning environments boost science engagement and inquiry. Educational design, games, and differentiated learning experiences create structured opportunities for experimentation, problem solving, and interaction with scientific ideas. Game-based learning supports motivation and conceptual understanding (Arnab et al., 2015). Game-based approaches and structured laboratory experiences shape the design of learning aids and influence opportunities for participation and learning. Games provide spaces where learners negotiate ideas, collaborate, and interact with scientific concepts. Differentiated environments promote participation during intentional design choices. Out-of-school laboratories are adaptive learning environments that reinforce authentic learning experiences and structured inquiry (Scharfenberg & Bogner, 2010).

The papers in Strand 11 demonstrate the breadth, adaptability, and continued importance of informal, non-formal, and out-of-school science education across diverse educational landscapes. Spanning school-linked programs, museums and science centers, home-based and remote learning environments, and game-based and designed experiences, the studies illustrate how science learning occurs through interactions among learners, families, educators, communities, institutions, and technologies. The contributions highlight the capacity of informal science learning environments to foster engagement, inquiry, identity development, and participation while responding to local needs and emerging educational challenges. These papers show how science learning extends beyond classroom boundaries, creating meaningful opportunities for individuals and communities to connect with science in ways that support sustainability, inclusion, and lifelong learning. As science education continues to evolve in response to digital advances and societal transitions, the research presented in this strand underscores the vital role of informal and non-formal settings in expanding access to science and strengthening connections between science, people, and their communities.

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Empowering Elementary School Teachers To Foster Students' Nature Connection: A Study Of Museum-School Collaboration For Horseshoe Crab Husbandry

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Biodiversity and species conservation are core missions of science museum education, yet engaging the public with uncharismatic endangered species remains a challenge. This case study examines a 2024 horseshoe crab care program launched by the National Museum of Marine Science and Technology (NMMST, Taiwan). The program aimed to empower elementary school teachers as catalysts for fostering students' nature connection. Through a collaborative model involving specialized workshops, husbandry kits, and regular expert consultations, the museum supported teachers in integrating live-animal care into the formal 3rd-grade curriculum. The findings indicate that this partnership significantly enhanced teachers' self-efficacy; the continuous technical backing from the museum converted potential pedagogical anxiety into a sense of professional mastery. Consequently, this empowerment trickled down to students, who not only mastered science process skills but also developed a profound sense of stewardship through the long-term "parenting" of horseshoe crabs. The study culminates in a release activity, demonstrating how empowering a single teacher can create a "ripple effect" that strengthens the connection between students, parents, and the natural world. This case provides a scalable model for science museums to move beyond one-time visits toward deep, curriculum-integrated partnerships.

Keywords: Teacher Empowerment, Nature Connection, Museum-School Collaboration

Research Background

Museum's Commitment For Education

National Museum of Marine Science and Technology (NMMST, Taiwan) has been committed to promoting public attention to issues such as Taiwan's maritime environmental protection and marine life conservation. Horseshoe crabs were once a common species along the coast of Taiwan. They have become an endangered species due to economic development in the area. The Industry-Academic Exchange Group of NMMST working with Taiwan Fisheries Research Institute to restore horseshoe crabs. Though Taiwan Fisheries Research Institute develops good horseshoe crab farming technology, to rebuild wild horseshoe crab population needs more social attention for coastal environment protection and no more over fishery. It is hard to track the life of a wild horseshoe crab. The NMMST looked for schools to participate in horseshoe crab breeding program. This program hopes that through the horseshoe crab breeding project, students will pay attention to the survival problems faced by horseshoe crabs through observing horseshoe crab's life cycle.

Conservation Context: The Crisis Of Horseshoe Crabs In Taiwan

Historically, the tri-spine horseshoe crab (Tachypleus tridentatus) was widely distributed along the western and northern coasts of Taiwan. However, this "living fossil" currently faces an existential threat due to anthropogenic pressures. Rapid coastal development for tourism has resulted in the fragmentation of nesting beaches, while the expansion of aquaculture ponds has further encroached upon essential nursery habitats for juveniles. Moreover, the discharge of urban wastewater and industrial pollutants has significantly degraded the water quality of estuarine ecosystems. These cumulative factors have led to a drastic decline in wild populations, making the conservation of this species a matter of national ecological urgency.

The Pedagogical Power Of Uncharismatic Species

In environmental education, public attention is often disproportionately directed toward "charismatic megafauna" (e.g., pandas or dolphins). However, the horseshoe crab serves as a powerful uncharismatic species for transformative learning.

Challenging Aesthetic Biases: Integrating "alien-looking" species like the horseshoe crab into the curriculum encourages students to move beyond superficial aesthetic judgments. This process fosters a deeper, more inclusive ethical stance toward biodiversity, where the value of a species is recognized through its ecological role and evolutionary history rather than its "cuteness."

Facilitating Cognitive Conflict and Curiosity: The unique, prehistoric morphology of the horseshoe crab creates a "cognitive conflict" that stimulates curiosity and scientific inquiry. By caring for a species that initially appears unfamiliar or even "ugly," students undergo a profound shift in empathy—a process that Giusti et al. (2025) describe as shifting social and spatial relationships with nature.

From Alien to Kin: As students engage in the daily husbandry of these organisms, the horseshoe crab transitions from an "uncharismatic alien" to a "vulnerable dependent." This transformation is a critical driver for nature connection, proving that emotional stewardship can be successfully cultivated even for the most unconventional representatives of the natural world.

Integration Of Citizen Science In Science And Environmental Education

Citizen science (CS) serves as a robust framework for bridging formal science education with environmental stewardship. According to Bruckermann et al. (2021), participation in urban wildlife ecology projects significantly enhances participants' scientific knowledge and fosters positive attitudes toward science, which are foundational for environmental conservation. Okada (2024) expands this through the CARE-KNOW-DO model, asserting that "open schooling" approaches strengthen the connection between scientific learning and real-life sustainability challenges. Furthermore, Bruckermann et al. (2023) found that participants' scientific reasoning skills are strong predictors of topic-specific knowledge gain. This suggests that CS provides a high-level cognitive environment where students can internalize ecological literacy through authentic scientific inquiry Bruckermann et al., 2023.

Challenges In Implementing Citizen Science Within Elementary Curricula

Despite its potential, implementing CS in primary school settings presents significant pedagogical hurdles. First, cognitive and skill-based barriers are prominent; Bruckermann et al. (2023) highlight that scientific reasoning is a prerequisite for effective learning in CS. For younger students (Grades 3–6), the complexity of data collection and systematic observation may exceed their developmental stage. Second, Atias et al. (2025) warn of epistemic injustice in school-based CS. This occurs when students are relegated to the role of passive "data sensors" rather than active contributors to knowledge construction, potentially undermining their agency and interest in science. Finally, Okada (2024) emphasizes the logistical burden on teachers, noting that balancing core curriculum requirements with the time-intensive demands of CS projects requires significant teacher empowerment and resource reallocation.

From Scientific Data Collection To Embodied Nature Connection

The integration of science and environmental education in primary schools has traditionally leaned towards citizen science models, which emphasize data contribution and scientific reasoning. However, recent scholarship suggests a critical shift toward prioritizing nature connectedness as a more developmentally appropriate and pedagogically effective goal for young learners.

The Primacy Of Emotional And Embodied Connection

According to Lau et al. (2025), a student's sense of nature connectedness is a more powerful predictor of positive attitudes toward biodiversity than the mere acquisition of factual knowledge. This is further elucidated by Schilhab (2021), who argues through the lens of embodied cognition that learning gains are maximized when children engage in sensory-rich, physical interactions with the natural world. Unlike abstract data-driven citizen science tasks, the long-term "parenting" of live organisms (such as the horseshoe crab) allows students to develop an intuitive, embodied understanding of life cycles, which reduces the cognitive cost of learning while increasing emotional investment.

Pedagogical Feasibility For Non-Science Teachers

A significant challenge in primary science education is the perceived barrier for non-science major teachers. Harris et al. (2025) highlight that fostering nature connectedness can be deliberately developed through pedagogical strategies that focus on "care" and "experience" rather than complex scientific protocols. This approach is more accessible for generalist teachers compared to rigorous citizen science projects, which often require specialized scientific reasoning skills that may exceed the developmental stage of 3rd to 9th-grade students (Bruckermann et al., 2023).

Transformative Space And Stewardship

Giusti et al. (2025) and Graf & Debrabant (2026) emphasize that schools should serve as transformative spaces for "green transition teaching." By shifting the educational objective from being "data sensors" for adult-led research to becoming "stewards of life," teachers can facilitate a deeper relationship with nature. This shift mitigates the risk of epistemic injustice (Atias et al., 2025) and empowers teachers to lead meaningful environmental education without the need for advanced scientific specialization. Consequently, establishing a nature connection provides a more inclusive and sustainable framework for basic school science curricula.

Integrating The Horseshoe Crab Program As A Solution To Epistemic Injustice

Atias et al. (2025) argue that school-based citizen science often suffers from epistemic injustice, where students are treated as mere tools for data collection rather than active epistemic agents. This marginalization can lead to a lack of ownership and a superficial understanding of the scientific process.

The horseshoe crab care program by NMMST provides a pedagogical alternative to mitigate this issue. Unlike traditional citizen science models that focus on data contribution, this program empowers students through a stewardship-based approach. By transitioning from passive observers to active "parents" responsible for the survival of an endangered species, students are positioned as primary knowledge-holders within their classroom ecosystem. This high level of pedagogical agency aligns with Okada's (2024) CARE-KNOW-DO model, where the emotional commitment to "care" for the horseshoe crabs drives the motivation to "know" (scientific knowledge) and "do" (conservation action).

Furthermore, by addressing the cognitive barriers mentioned by Bruckermann et al. (2023), the museum's collaborative support enables teachers to scaffold complex scientific reasoning through tangible, daily interactions with live organisms. This transformation shifts the focus from simply reporting data to fostering a deep nature connection, thereby ensuring that students' voices and actions are epistemically valued in the broader context of biodiversity conservation.

Research Methods

Research Design

This study employs a qualitative case study design to explore how a museum-school collaborative program empowers teachers and fosters students' nature connection. By focusing on the "Horseshoe Crab Care Program," the research investigates the transformative process of integrating live-animal husbandry into the formal school curriculum.

Participants And Context

The program involved 14 schools (8 primary and 6 junior high schools) in Taiwan. The analysis specifically highlights the experiences of elementary school teachers who acted as primary facilitators. The collaboration was structured into two phases:

Professional Empowerment Phase:

Teachers participated in an intensive workshop covering horseshoe crab biology, aquarium ecosystem establishment, water quality monitoring, and egg incubation techniques. A collaborative lesson-planning session was conducted, where teachers co-designed and submitted pedagogical plans tailored to their classroom contexts.

Implementation And Support Phase:

The museum provided essential resources, including horseshoe crab eggs and water quality testing kits. Students closely monitored the biological progression as the eggs developed through four embryonic stages before successfully hatching into first-instar trilobite larvae. Under the teachers' guidance, the students continued the husbandry process until the crabs reached the second-instar stage. At this point, the teachers facilitated the transfer of the juvenile crabs to the Taiwan Fisheries Research Institute (TFRI) for specialized long-term care until they matured into fourth-instar juveniles.

To bridge classroom learning with real-world conservation, the National Museum of Marine Science and Technology (NMMST) collaborated with the TFRI to organize the "Bringing the Horseshoe Crabs Home" release event. Teachers and students who participated in the curriculum were invited to natural sandy beaches—specifically those with historical sighting reports of the species—to release the crabs into the wild. This final act transformed the rearing process into a tangible contribution to species restoration, reinforcing the participants' identity as conservationists. It also provided an emotional milestone for teachers to reward students' dedication, offering a sense of achievement as they completed this critical stage of their environmental mission.

Conservation Action And Reflection Phase:

To conclude the program, the museum organized a series of release activities, where teachers and students returned the juvenile horseshoe crabs they had raised to their natural coastal habitats. This hands-on conservation act transformed the classroom experience from a mere biological project into a meaningful participation in species restoration, deeply reinforcing the participants' identity as environmental stewards. For teachers, the release ceremony served as a vital emotional milestone, providing a sense of closure and fulfillment. It offered a structured opportunity to reward students' long-term dedication with a profound emotional connection to the cycle of life, solidifying the pedagogical transition from scientific knowledge to active conservation commitment.

Data Collection

To ensure a holistic understanding of the program's impact, multiple qualitative data sources were collected:

Pedagogical Artifacts: 14 teaching plans submitted by participating teachers during the workshop, reflecting their initial instructional designs and goals.

Consultation Records: Detailed logs from regular consultation meetings, capturing teachers' real-time challenges, reflections, and anecdotal evidence of student engagement.

Teacher Narratives: Qualitative feedback regarding teachers' emotional shifts, perceived self-efficacy, and observations of students' behavioral changes (e.g., patience, persistence, and stewardship).

Data Analysis

The data were analyzed using thematic analysis. Following the transcribed consultation meetings and document review, codes were generated to identify patterns related to teacher empowerment, pedagogical adaptation, and the emergence of students' nature connectedness. These themes were then triangulated across the different data sources to ensure the validity and depth of the findings.

Findings

The preliminary findings from this case study reveal a distinct pattern of teacher empowerment and age-specific student engagement, categorized into two primary themes:

1. Age-Specific Pedagogical Adaptations And Teacher Empowerment

Teachers demonstrated significant pedagogical autonomy, adapting the program to align with grade-specific curriculum goals. This adaptability highlights a key aspect of teacher empowerment: the ability to contextualize external resources effectively.

Seventh-Grade Teachers (Junior High)

These educators primarily leveraged the program to facilitate inquiry-based learning and experimental design. The investigation of variables in raising horseshoe crabs was often integrated as a structured student project, aligning with a more advanced stage of scientific reasoning [Bruckermann et al., 2023]. Some teachers noted that the standard husbandry tasks were insufficient for the cognitive level of junior high students. For instance, Teacher 1 remarked:

I feel that simply having students observe the changes in the eggs every day and record temperature and water quality data is too simple for junior high school students; there isn't much to explore.

Consequently, these educators shifted the focus toward active experimentation. Teacher 2 described their approach to experimental design as follows:

Although the Fisheries Research Institute already has the best water quality composition, I want students to be able to adjust the pH within a certain range, such as adjusting it up or down by 0.5, and see how much the egg growth period will differ.

Consequently, a divergence in pedagogical perspectives emerged: junior high school teachers viewed the horseshoe crabs primarily as experimental subjects, aiming to have students manipulate growth-related variables through controlled experiments. However, the collaborating aquaculture experts opposed treating these sensitive organisms as experimental animals for middle school students, prioritizing animal welfare and conservation ethics. In response to this constraint, the junior high teachers pivoted their strategy. Instead of structured experiments, they established classroom aquariums and shifted the focus to a voluntary participation model. Students who showed interest could volunteer to perform daily observation, photography, water quality monitoring, water changes, and feeding, thereby maintaining engagement through long-term husbandry and documentation rather than experimental manipulation.

Third-Grade Teachers (Primary School)

In contrast, primary teachers focused on foundational science concepts. They combined the theme of horseshoe crab husbandry with the broader study of aquatic animal movements and life histories, emphasizing descriptive observation and engagement over experimental manipulation.

This interdisciplinary approach was exemplified by Teacher 4, who coordinated with various subject teachers to integrate the horseshoe crab into the third-grade curriculum:

I first asked the science teacher to use the presentation provided by NMMST to introduce the concept of horseshoe crabs to the children. Then, in the language arts class, students read a text about animal tails using teaching aids; we paired this with the museum's dried horseshoe crab specimens. Watching the children touch the different tails while describing and speculating on their functions was brilliant. Since they were unfamiliar with horseshoe crabs, I also asked the computer teacher to let them search for videos or explanations regarding their movement. After attending the workshop, the art teacher even took the initiative to use the simple mobile phone microscopes provided by the museum to have students light and photograph the crabs. ... I am very grateful for the assistance of the science, art, and computer teachers during this period, bringing a bit of the horseshoe crab into different subjects. …At the end-of-term fair, students decorated their horseshoe crab photographs on the classroom windows facing the aisle, along with simple horseshoe crab informational posters to introduce the animal to students from other classes as they passed by. I'm so proud for them.

Interviews with other participating primary school teachers consistently echoed this model of multidisciplinary collaboration, involving joint planning across language arts, science, computer science, art, and even physical education. These educators frequently expressed admiration for their students' performance throughout the process. For primary teachers, raising horseshoe crabs functioned as a pedagogical intersection for diverse subject areas. From this common starting point, students were empowered to apply their existing skills in a real-world context, transforming classroom knowledge into a tangible sense of agency. This process allowed students to experience how their collective academic competencies could be directly channeled into the active conservation of an endangered species, fostering a deep connection between their learning and environmental responsibility.

2. Emotional Investment, Skill Application, And Nature Connection

The findings strongly support the hypothesis that prioritizing nature connection is highly effective at the primary level, addressing the emotional "CARE" component of the CARE-KNOW-DO model (Okada, 2024).

Emotional Connection

Primary school students exhibited a notably higher degree of emotional investment and affective response in observing the growth of the horseshoe crabs compared to seventh-grade students. This intense emotional engagement facilitates the development of a strong nature connection (Lau et al., 2025). The depth of this bond was vividly captured in the observations of Teacher 6, who noted how students took on a parental role and extended their engagement beyond the science curriculum:

The children in my class were very proud to call themselves 'Horseshoe Crab Dads' or 'Horseshoe Crab Moms.' During the process of caring for the eggs until they grew into first-instar larvae, the first thing they did upon entering the classroom every day was check the tasks marked on the husbandry duty roster. The computer teacher also mentioned that they would proactively look for photos or videos related to the crabs' natural habitats during class. ... For the end-of-semester school fair, they even took the initiative to suggest making horseshoe crab conservation bookmarks to the art teacher, printing their photographs to paste onto conservation slogans. I never expected them to be so invested for the entire semester; even after the young crabs were returned to the Taiwan Fisheries Research Institute, their interest persisted.

Through this model of interdisciplinary pedagogical collaboration, primary school teachers expressed significant satisfaction with the profound enthusiasm ignited within their students. The educators were particularly impressed by the sustained nature of this engagement, which remained high from the initial hatching phase until the end of the semester. Furthermore, teachers acknowledged that such a complex, cross-domain curriculum would have been unattainable without the National Museum of Marine Science and Technology (NMMST). The museum's provision of specialized biological knowledge and essential physical resources served as the critical foundation, empowering teachers to venture beyond their individual areas of expertise. This partnership effectively bridged the gap between specialized marine science and classroom practice, allowing teachers to facilitate a sophisticated Interdisciplinary Learning experience that was both scientifically rigorous and emotionally resonant for the students.

Practical Skill Application

The long-term, hands-on nature of the program provided a context for practical application of scientific skills. Primary school students perceived immediate utility in foundational science skills such as weight measurement, volume measurement, and water quality testing, reinforcing the link between abstract classroom knowledge and real-world utility (Schilhab, 2021). This shift in perceived competence was also observed by the educators. Teacher 8 reflected on their initial skepticism regarding the students' ability to maintain scientific rigor in a classroom setting:

Initially, I didn't think elementary students would be able to accurately perform so many scientific process skills, such as weighing, reagent volume adjustment, and interpreting test strip reactions. Especially since they had to do it themselves in the classroom after the initial lessons, I thought they wouldn't be able to stay precise and accurate. But the horseshoe crabs actually survived and hatched. This was the first time I felt so certain that the students had truly mastered the things we taught in science class.

This reflection underscores the profound impact of authentic learning. When the accuracy of scientific skills is directly tied to the survival of a living organism, students' actions transcend mere classroom exercises and evolve into a profound sense of moral responsibility. The "empirical feedback" provided by the successful hatching and survival of the horseshoe crabs not only validates the students' learning outcomes but also significantly bolsters teachers' confidence in implementing inquiry-based instruction within primary education. This alignment between rigorous scientific practice and ethical commitment demonstrates how real-world challenges can catalyze both academic mastery and personal growth.

These findings suggest that while older students can engage in data-driven citizen science, younger students benefit immensely from stewardship-based activities that foster embodied cognition and emotional connection to nature, offering a scalable model for inclusive environmental education.

Conclusions And Implications

This study highlights the pivotal role of museums as teacher empowerees. By providing scaffolded support, museums enable non-science major teachers to lead complex conservation projects. Furthermore, the program demonstrates that when students apply science process skills (e.g., microscopy, pH monitoring, digital micro-photography) to biological restoration, they develop a positive scientific self-concept. This "stewardship-based" model offers a scalable framework for inclusive environmental education that cultivates both scientific literacy and environmental empathy.

This program demonstrated significant potential beyond student learning outcomes, highlighting the museum-school partnership model as a powerful catalyst for teacher professional development (PD). Our findings suggest that the museum's provision of expert scientific knowledge and tangible resources was instrumental in empowering primary school teachers—even those outside the life sciences domain—to successfully implement sophisticated interdisciplinary curricula.

Nonetheless, the long-term impact of this specific collaborative model on sustained teacher professional growth remains a critical area for future investigation. Subsequent research should focus on the following three key domains:

Internalization And Transferability Of Pedagogical Skills:

Future studies should track whether the teachers, post-program, can internalize the acquired interdisciplinary planning skills and scientific inquiry guidance techniques. It is essential to determine if this growth in professional capacity remains dependent on ongoing museum support, or if it successfully transfers into the educators' long-term teaching repertoire across various environmental topics.

Formation And Sustainability Of Professional Learning Communities (Plcs):

The initial "Professional Empowerment Phase" fostered collaboration and co-design among educators. Subsequent research could investigate the longevity of these museum-initiated cross-school professional learning communities. Further study should explore how the museum's role evolves from a primary resource provider to a long-term knowledge partner supporting these sustained teacher networks.

Paradigm Shifts In Educational Beliefs

Our research identified clear differences in perspective between junior high and primary teachers regarding bioethics and experimental design. Longitudinal studies could explore if sustained museum-school collaborations alter teachers' perceptions of the balance between "scientific inquiry" and "biological conservation," thereby influencing their core environmental education values and teaching methodologies.

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Designing Materials Science Activities to Promote Student Engagement with Cutting-Edge Research

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Formal education often cannot provide timely access to cutting-edge research in rapidly evolving fields like materials science, despite its relevance to urgent global challenges. Informal learning environments can bridge this gap, though challenges remain in effectively designing and integrating such experiences. This study investigates how materials science content can be educationally reconstructed and communicated through redesigned educational visits, using the Model of Educational Reconstruction (MER). Materials science researchers, science education researchers and secondary teachers collaboratively developed inquiry-based activities on biomaterials and hydrogels. Seven teachers implemented these materials, with data collected through observations and semi-structured interviews. Findings reveal that while interdisciplinary collaboration is essential, teachers serve as critical mediators due to their intimate knowledge of students' backgrounds and interests. Their reflections provided valuable insights into material effectiveness and visit design. This research demonstrates that successful communication of contemporary research requires both interdisciplinary collaboration and serious consideration of teachers' insights and recommendations.

Keywords: informal education, materials science, model or educational reconstruction

Introduction

Rapid advancements in materials science and their applications are poised to significantly impact future generations, presenting opportunities and challenges for society. These developments highlight ethical, sustainability, and educational issues that require interdisciplinary collaboration and public engagement, as seen with many emerging research topics (Ehrler, 2022). Simultaneously, advancements in materials science are revolutionizing real-world applications such as medical applications which lead to significant improvements in diagnostics, therapeutics, and regenerative medicine. Consequently, fostering scientific literacy among citizens appears essential to empower them to stay informed about scientific advancements but also to make well-informed decisions concerning their health, environment, and other critical aspects of life. In this direction, formal education in schools is expected to play an important role in shaping scientifically literate citizens. However, formal education's approach to scientific development is usually delayed, as it takes a long time before new knowledge is integrated into school curricula (Besley & Tanner, 2011).

In this context, the literature stresses the importance of informal learning spaces, such as research centers and science laboratories, which can complement formal education. These spaces are authentic environments, allowing students to come into direct contact with new knowledge, thus bridging the gap created in formal education (Berg et al., 2021). Communication strategies for cutting-edge research topics in informal learning spaces focus on the active participation of visitors, utilizing contemporary teaching approaches such as inquiry-based learning and interdisciplinary STEM approaches (Schwan, Grajal & Lewalter, 2014). Students' interaction with scientists in these settings helps to form a more realistic picture of scientific activities, while at the same time bringing them into contact with scientific practices, enhancing their interest in related careers (Woods-Townsend et al., 2016).

However, designing and implementing educational visits to informal learning spaces requires close collaboration among experts in science content, science knowledge transformation, and science communication (Giannakoudaki & Stavrou, 2022). This interdisciplinary teamwork highlights the value of integrating various skills and knowledge areas while ensuring the creation of learning experiences that promote understanding and active engagement of students in informal learning spaces (Achiam, 2013). Teachers play a central mediating role in translating educational materials and visit experiences into meaningful learning, as they create inclusive environments, guide scientific practices, and facilitate connections between informal learning experiences and curriculum goals (Cooper & Bolger, 2024). This mediating role is strengthened through collaboration with science center staff and through appropriate preparation of students via activities that link visit themes with the curriculum (Souza et al., 2023).

Based on the above, this paper aims to develop and evaluate a series of STEM activities for informal learning spaces that focus on communicating contemporary scientific developments in the field of materials science to students. Therefore, the research question that runs through this paper is, "How can contemporary scientific knowledge be educationally reconstructed and communicated to students in informal learning contexts?".

Methodology

Research Context

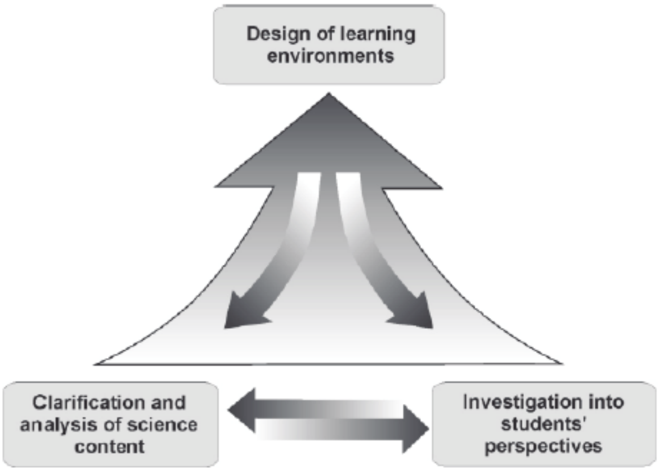
This study was carried out in the context of the MaSCot project, a 24-month cross-departmental project at the University of Crete that aimed to bring together science education researchers and materials science researchers to co-develop learning experiences in out-of-school environments to communicate contemporary scientific research topics to students. The research process was divided into three main phases. In the first phase, initial educational visits hosted in the Department of Materials Science and Engineering (DMSE) were observed to establish a baseline understanding of existing practices and identify areas for improvement. In the second phase, a learning community—consisting of experts in materials science, science education, and science communication—collaboratively developed two sets of inquiry-based STEM activities. These activities were designed to be implemented either before or after educational visits to the DMSE. In the third phase, the in-service teachers participating in the project implemented the developed materials to support educational visits to the DMSE, either as preparation before the visit or as extension activities following the visit.

Theoretical Framework

The Model Of Educational Reconstruction

The methodological framework used in this study is based on the Model of Educational Reconstruction, which consists of three components: (a) clarification and analysis of the scientific content, (b) research on teaching and learning, and (c) design and evaluation of the learning environment. These three components are not independent but dynamically interact continuously, providing reciprocal feedback (Duit et al., 2012).

Figure 1. The Model of Educational Reconstruction.



Application of MER in this Study

For the clarification and analysis of the scientific concepts, group meetings among researchers of materials science and science education were held. They collaboratively identified and discussed the key concepts that are deemed as important to be taught/presented to students. For biomaterials the concepts of biocompatibility, mechanical properties and biodegradation were found as the most prominent. As for polymers and more specifically hydrogels, key concepts relate to their composition, such as cross-linked polymerization, their mechanical and chemical properties, e.g., elasticity or viscous behavior, and the breakdown of polymers, which depends on environmental conditions such as temperature or pH.

The second component of MER, investigation of the literature, revealed several key principles for teaching and learning interdisciplinary topics such as materials science: making connections between disciplinary fields explicit, approaching topics through real-world problems, linking content to everyday experiences, and integrating theoretical knowledge into contexts that simulate authentic research practice (Li et al., 2015; Acosta, 2023; Fagnani et al., 2020).

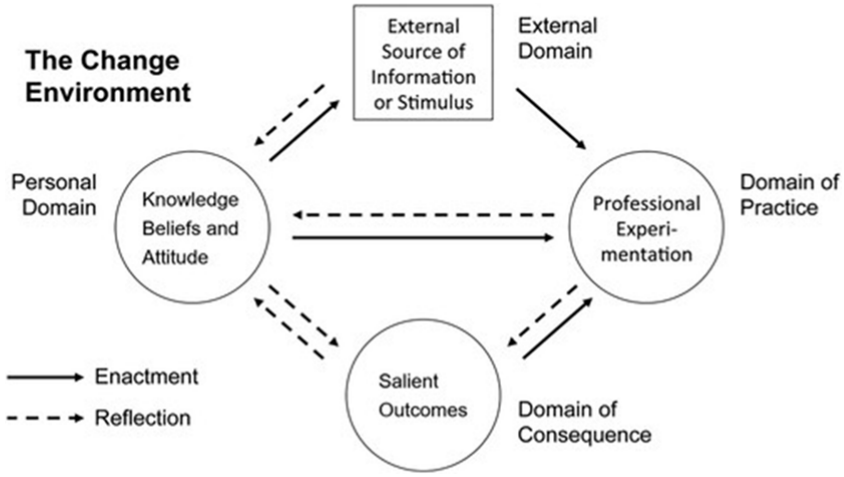
The third component—design and evaluation of the learning environment—emerges from the interaction between the first two, involving the educational reconstruction of identified concepts using contemporary approaches to science communication. In our study, the environment reconstructed is the designed educational material to be used to frame the educational visit (before/after).

The Interconnected Model Of Professional Growth (IMPG)

Professional development is characterized by dynamic interactions across multiple aspects of teacher practice, as conceptualized in the Interconnected Model of Professional Growth (IMPG, Clarke & Hollingsworth, 2002). This framework identifies four interconnected domains: the personal domain (K), encompassing teachers' professional knowledge, beliefs, and attitudes; the domain of practice (P), representing instructional experimentation and implementation; the domain of consequence (S), which captures notable outcomes emerging from instruction; and the external domain (E), comprising influences beyond the individual teacher, including institutional factors, curricular frameworks, and professional development experiences.

These domains are connected through two mediating mechanisms: enactment and reflection. Teachers enact practice by drawing upon their professional knowledge and pedagogical orientations to inform instructional decisions, while reflection enables them to recognize and interpret how shifts in one domain generate changes—or consolidate existing approaches—across others.

Figure 2. The Interconnected Model of Professional Growth.



The choice of IMPG in this study is based on the model's effectiveness for studying teachers' professional learning concerning the development of teaching materials in cutting-edge topics (Sgouros & Stavrou, 2019). Particularly, for the purposes of this study, the IMPG framework serves as an analytical lens for examining how teachers engaged with and evaluated the designed materials. Teacher reflections on outcomes include their direct observations of student responses to the materials and activities, offering meaningful insights into the educational value of the designed materials. Given that teachers function as critical intermediaries between instructional materials and student learning, their professionally-grounded reflections—informed by authentic implementation contexts and direct observation—provide substantive evidence for assessing the quality and impact of the educational materials.

Table 1. Framework for the analysis of current educational visits.

Axes of analysis	Categories	Sub-categories
Structure	Guidance	- Introductory presentation - Guided tour
	Role of Scientists/Researchers	• Model experiments • Explain scientific concepts • Describe potential careers
	Role of Teachers	- Accompany students - Explain concepts
Content of the visit	Scientific Concepts	- Optics & Lasers - Magnetic materials - Optoelectronics
	Scientific Practices	- Demonstration of experiments - Demonstration of equipment

Data Collection And Analysis

Data were collected using an observational protocol based on key aspects of educational visits proposed by Sajons and Komorek (2018), including the purpose of the visit, students' prior knowledge, the orientation of activities, and the roles of staff and teachers. Additionally, data were collected through semi-structured interviews with seven of the participating teachers following their implementation of the redesigned visits.

Due to the exploratory nature of the research, qualitative content analysis methods (Mayring, 2015) were employed. Observational data from the educational visits were analyzed according to visit structure and content, with inductive categories and subcategories presented in Table 1. The interview data were analyzed using the IMPG framework to identify interactions among the four domains, with analytical criteria presented in Table 2.

Table 2. Description of criteria for categorising interactions among the domains of the IMPG model.

Mediating process	Criteria	Examples
External - Personal (reflection)	The teacher reflects on the teaching material or the visit and this reflection influences or reinforces their knowledge, attitudes, etc., related to science teaching.	“In the end, I realised it — I would have preferred if we had seen the main presentation and one laboratory.”
Personal - External (enaction)	When a teacher’s initial perception regarding educational visits affects what is done or said during the Community of Learners meetings or during the visits themselves.	-
External - Practice (enaction)	Stimuli from the material and the meetings lead to the application or adaptation of teaching practices.	“The material was implemented in the first year of upper secondary school.”
Practice - Personal (reflection)	Experience gained from implementing teaching practices leads to reflection and possible change or reinforcement of beliefs, knowledge, or attitudes.	“Perhaps the preparation should have been done differently; we should have found a way to connect things.”
Personal - Practice (enaction)	The teacher’s personal perceptions or knowledge influence how they carry out their teaching and how they act during the visit.	“We had a discussion; I told them some general things that I had in mind from a previous visit.”
Practice - Salient outcomes (reflection)	Something that occurs during the lesson or the visit produces specific outcomes regarding the benefits for the students.	“The students were excited, they participated, they wanted to respond.”
Salient outcomes - Practice (enaction)	A specific outcome influences the teacher’s practices.	“And because the students were motivated, we continued during the next class hour as well.”
Salient outcomes - Personal (reflection)	Observing the outcomes for the students prompts the teacher to interpret the result or to reconsider an initial perception.	“[…] perhaps it is ultimately more beneficial for students to interact with university students rather than professors.”
Personal - Salient outcomes (reflection)	How teachers themselves perceive the benefits for their students.	“I think they took a step further; their horizons widened.”

Findings

Analysis of the Initial Educational Visits

The analysis of the initial school visits revealed that the visits primarily consisted of an introductory presentation providing general information about the department, its research areas (e.g., optoelectronics, magnetic materials, biomaterials), and key research highlights as well as potential career pathways. Subsequently, a guided tour of the university's laboratories took place, including a demonstration of experiments and equipment by the scientists, while also explaining scientific concepts. The role of teachers was found mostly to accompany the students and, in some cases, provide additional information to help students understand the topics being discussed. The presented experiments were neither linked to innovative research activities related to the field of materials science, nor to the school's curriculum. The students were not adequately prepared by their teachers and lacked background knowledge in such specific research topics; hence, they struggled to understand the content, find relevance in the subject matter, and establish meaningful connections with scientists and their roles. Consequently, the innovative nature of the research carried out at the university, the real-world relevance of these applications, and the social implications of these issues were not emphasized.

Redesigned Visits

The structure of the visit itself was identical to the initial visits, with the addition of demonstrative experiments. The selected experiments were chosen based on the meeting discussions and what was convenient for the university to offer. The topics were polymers (specifically hydrogels and thermoresponsive polymers) and hydrophilic/hydrophobic surfaces. The specific experiments varied across visits, reflecting the dynamic nature of ongoing research and teaching in university settings where educational outreach activities are supplementary to core research functions.

The Educationally Reconstructed Material

Two sets of inquiry-based STEM activities were developed for supporting use before/after the educational visit. One of them was focusing on biomaterials and one on polymers, specifically hydrogels. Both sets follow a common structure: an introductory engagement activity, exploration of fundamental material properties, application within an authentic research context, and finally, reflection on societal and environmental connections.

The biomaterials activities were framed within a research scenario where students assumed the role of research team members developing a bone implant like applications in the DMSE. The implant was designed to function as a "bridge," providing a substrate for new bone cell growth and eventually biodegrading completely so the patient develops unified, natural bone.

Activities include: (1) an introductory task on compatibility where students selected the correct charging cable for a mobile device; (2) biocompatibility testing by counting live and dead cells in microscopy images and calculating cytotoxicity using mathematical formulas; (3) evaluating mechanical properties by comparing strength values between the implant and natural bone to determine if modifications are needed; (4) calculating biodegradation rates from mass loss data, creating graphs, and interpreting results; and (5) a reflective discussion on the ethical implications of biomaterial development and use, including the progression from initial design to animal and human testing.

The hydrogel activities began with an orientation task where students identified common characteristics in images (flexibility and water retention capacity).

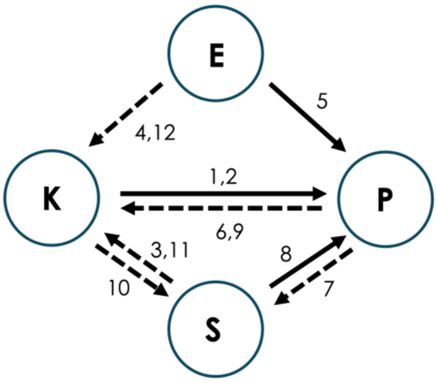
Activities included: (1) modeling polymer synthesis by connecting "macromolecules" to create networks and three-dimensional structures, then analyzing water retention mechanisms; (2)

studying absorption properties using synthetic hydrogel beads, measuring mass before and after water exposure; (3) comparing mechanical properties between natural (agar-agar) and synthetic hydrogels, observing elastic behavior under light pressure and plastic deformation under greater force; (4) examining polymer degradation under high temperature by placing both hydrogel types in boiling water and observing differences; (5) an authentic research scenario where students select appropriate hydrogel samples for different applications (wound dressings, bone implants, drug delivery systems) based on viscoelasticity measurements; and (6) a reflective activity on microplastics in various environments, prompting discussion about the environmental impact of extensive polymer use and the need for sustainable alternatives.

Teacher Case Study

To illustrate the application of the IMPG framework in evaluating the designed materials, we present a case study of one participating teacher (Figure 3). Teachers' professional reflections provide valuable evidence of material quality and effectiveness, as they possess direct knowledge of their students and observe firsthand how students engage with and respond to instructional materials in authentic learning contexts. The selected teacher taught first-grade high school students (ages 15-16) and implemented the biomaterials activity set as a follow-up activity after the educational visit to the DMSE.

Figure 3. IMPG Interactions of Case Study Teacher.



Because teachers' reflections emerged non-chronologically during the interviews, the analysis is organized by domain interactions rather than by sequence of events.

The interconnected nature of the IMPG domains is evident in the analysis above. The teacher's actions stemmed from multiple sources: external factors such as the provision of educational materials, personal beliefs and attitudes, and observations of student interest (interactions 5, 2, 8). Simultaneously, reflections on both student outcomes and on the designed materials or visit structure enhanced her attitudes toward certain practices—for example, implementing more hands-on activities—and generated new pedagogical insights, such as recognizing the value of undergraduate student facilitators with whom school students could more easily identify and connect. The impact of the designed materials is also apparent. The teacher noted that students wanted additional time to complete the biomaterials activities, as one hour proved insufficient, and highlighted the meaningful ethical discussions generated around biomaterials and science more broadly. She characterized the overall visit experience as highly successful, reporting both cognitive gains and positive shifts in students' attitudes toward science, and expressed her intention to continue such practices in the future.

Table 3. Examples of IMPG Interactions of Case Study Teacher.

Mediating process	Examples
External - Personal (reflection)	4 - The teacher chose the biomaterials activity set, citing its practical simplicity and fewer experimental requirements compared to the hydrogels set. 12- The teacher suggested increasing experimental demonstrations during the visit and allocating more time in each laboratory, noting that students expect hands-on experiences and that extended time would allow for on-site implementation of the designed activities
Personal - External (enaction)	-
External - Practice (enaction)	5- The teacher implements the biomaterials set as follow-up activity after the visit
Practice - Personal (reflection)	6- "It was very well adapted to the first year of upper secondary school and aligned particularly well with the topic of forces. For me, as a physics teacher, it integrated smoothly with the visit and provided a coherent framework." 9- The teacher reflected that a reorganisation of the programme would have facilitated the completion of the activities within one continuous session instead of two separate sessions
Personal - Practice (enaction)	1- The teacher provided general information to the students, drawing on prior experience from previous visits. 2- Regarding her actions during the visit, the teacher stated that her role was primarily learning-focused, while also ensuring smooth organisation and students' social well-being.
Practice - Salient outcomes (reflection)	7- The implementation of the material led to a discussion on the social dimensions of science and provided motivation for students to think more broadly about material properties (e.g., silicone strength).
Salient outcomes - Practice (enaction)	8- Due to students expressed interest, the teacher continued the activity in the following lesson.
Salient outcomes - Personal (reflection)	3- Students' references to biomaterials guided the discussion, leading the teacher to select the biomaterials set of activities 11- Positive student feedback, especially regarding interaction with an undergraduate student, prompted the teacher to refine her beliefs about effective mediation during visits, indicating that engagement with undergraduate students may be more impactful than interaction with academic staff.
Personal - Salient outcomes (reflection)	10- The teacher reflected that the activity, in combination with the visit, helped students make meaning of school science, allowing them to move beyond classroom learning and broaden their attitudes towards science.

Teacher Recommendations

Teachers, as key mediators between students and researchers, possess direct knowledge of their students' backgrounds, interests, and capabilities, making their recommendations essential for improving educational visits. In our study, participating teachers emphasized several priorities, as follows. Structural and procedural recommendations: i) ensuring coherence between preparatory materials and the visit itself by aligning worksheets, activities, and demonstrations with the laboratories students will encounter; ii) increasing visit duration to allow deeper engagement; iii) organizing visits around coherent scientific themes rather than broad departmental overviews; iv) ensuring early communication about which laboratories will be included to enable effective student preparation and the selection of laboratories that directly connect to classroom content. Materials and facilitation: i) providing dedicated worksheets for each laboratory station; ii) integrating authentic data and artifacts to strengthen inquiry; iii) involving university students as near-peer facilitators; iv) ensuring that guides are familiar with teaching materials in advance.

Conclusions

The analysis of the initial school visits highlighted several key limitations, such as the weak connection between the presented experiments and cutting-edge research, as well as students' difficulties in relating the content to the curriculum due to limited preparation. As a result, the real-world relevance of materials science and its societal implications often remained underemphasized. At the same time, universities face structural constraints: they typically lack specialized staff in science communication and dedicated resources for educational outreach, while the ongoing and dynamic nature of research makes it difficult to standardize what can be presented to visiting school groups. Consequently, redesigning educational visits in a systematic and sustainable way remains challenging.

Part of the solution lies in the design of educational material to support such visits in informal learning spaces, which can act as a bridge between cutting-edge research and school science, while also helping students make explicit connections to the societal, ethical, and real-world implications of scientific research. In this context, collaboration among teachers, science education researchers, science communicators, and materials science experts is crucial for the effective design and appropriation of such interventions. Educational materials that are purposefully designed can mediate between advanced scientific content and students' prior knowledge, making contemporary research both accessible and meaningful.

As previously discussed, teachers play a central mediating role in educational visits to informal learning environments. However, introducing topics related to cutting-edge research can be demanding, particularly for less experienced teachers, who may feel uncertain or cautious when engaging with unfamiliar scientific content. This highlights the need for professional development programmes, that can strengthen teachers' confidence in these contexts. At the same time, teachers' recommendations, concerns, and experiential insights should be taken seriously, as they offer valuable perspectives for improving both the design and implementation of educational visits in informal learning environments.

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Exploring Non-Formal Science Education: Growing Crystals, Growing Minds

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In the field of non-formal science education, there are still activities that remain under researched. This is the case for crystal growth contests for school students. To address this gap, a four-year longitudinal study was designed to explore the perceptions and experiences of 165 teachers and 559 students from Aragón (Spain), who participated in such a competition. Using qualitative methods with a descriptive and interpretative scope, pre- and post-competition questionnaires containing open-ended questions that allowed participants to elaborate their responses were distributed annually. The data were analysed through qualitative content analysis, identifying categories that provided a framework for interpreting the results. The findings provide an integrated perspective of the benefits that the contest provides to participants and highlights the potential of long-term non-formal activities to bridge formal and non-formal education. Teachers reported improved pedagogical practices and enhanced professional skills, and students gaining a deeper understanding of scientific processes and developing different skills. Students found the competition enjoyable and rewarding, which improved their knowledge and perception of science, provided them with some practical experience, and promoted their skills. Additionally, the relaxed setting fostered stronger teacher-student relationships, contributing to a more engaging and collaborative learning environment. These findings offer valuable insights for designing more effective educational initiatives and provide a foundation for future research on the role of long-term non-formal activities in science education.

Keywords: crystal-growing competition, student perceptions, teacher experiences

Introduction

Non-formal education in the field of science has experienced very strong development over the last decades, primarily because it is less constrained by limitations typically associated with traditional classroom settings. As a result, non-formal education has emerged as a means of extending and enriching both students' and teachers' experiences. These experiences support science learning in ways that traditional schooling cannot (Kisiel, 2014) and address aspects of science education that are often absent in formal education (Jarvis & Pell, 2005).

The literature (e.g., Affeldt et al., 2017; Burke & Navas Iannini, 2021; Nuora & Välisaari, 2018) shows how non-formal teaching is recognised as an element that contributes notably to lifelong learning (Woithe et al., 2022) and provides different types of benefits to participants that are mutually reinforcing, highlighting that such experiences offer various cognitive, procedural, affective-emotional, personal, and social benefits to participants. Indeed, research also demonstrates the positive impact of these activities on teachers in terms of professional development and training.

1. *Cognitive Benefits.* They allow students to be exposed to learning conditions that simply cannot be reproduced in the classroom (Nadelson & Jordan, 2012), thereby providing additional support for learning. Along the same lines, they act as a bridge between knowledge acquired at school and outside of it, promoting the acquisition of new content, concepts (Canovan, 2019; Domenici, 2022), and models (Bell et al., 2009) from a more interdisciplinary perspective (Yu & Yang, 2010). In this way, they not only foster a greater understanding of how scientific knowledge is generated and constructed but also have a

positive effect on academic performance (Miller et al., 2018). Finally, they offer opportunities for students to develop skills, attitudes, and values normally associated with science (Weinberg et al., 2011) and develop their cognitive abilities (Julien & Chalmeau, 2022).

2. *Affective Benefits*. They foster students' interest and curiosity in science (Weinberg et al., 2011) and increase their motivation towards both science itself (Markic et al., 2017; Tisza et al., 2020) and its learning (Affeldt et al., 2015; Raaijmakers et al., 2021). Furthermore, they promote, develop, or generate more positive attitudes and feelings (Nuora & Välisaari, 2018) towards science and its learning, thereby enhancing the appeal of science education and generating positive emotions towards the sciences (Canovan, 2019). Consequently, they have the capacity to induce changes in participants' attitudes towards science (Millar et al., 2019) and contribute to increasing the perception of the social relevance of science and students' commitment to science (DeWitt et al., 2018). Finally, they contribute to the generation of a scientific identity (Burke & Navas Iannini, 2021) and the promotion of scientific vocations (Jones et al., 2011; Wünschmann et al., 2017) and professional orientation towards science careers.

3. *Social Benefits*. They contribute to socialisation because they bring students with common interests into contact, which allows for the generation of a certain sense of community belonging (Millar et al., 2019) where they can be recognised by themselves and others as people of science, which also aids in the consolidation of a scientific identity (Burke & Navas Iannini, 2021).

4. *Benefits for Teachers*. They promote professional reflection and identity (Haatainen et al., 2024) and support teachers in their professional development (Gupta & Adams, 2012; Martín-García et al., 2024). In this sense, they provide an opportunity to broaden, enrich, and diversify teacher training by offering motivating structures for learning and opportunities to practise science teaching in "safe" environments (Avraamidou, 2014; Martín-García et al., 2024). This helps them develop greater confidence in their abilities as educators and improve their self-concept and self-efficacy when teaching science (Martín-García & Dies Álvarez, 2024). Therefore, they contribute to the development of both scientific-content knowledge (Jung & Tonso, 2006) and pedagogical-content knowledge (Kisiel, 2013). Finally, they also help them acquire a greater understanding of the characteristics of their students (Tang et al., 2017).

Knowing these benefits, educational research has long advocated bridging formal and non-formal education (Fallik et al., 2013; Molz et al., 2022; Watermeyer, 2015). However, much of the existing research has focused on short-term, non-formal activities, such as museum visits led by external educators (Avraamidou, 2015). In contrast, the present study centres on a long-term, academic-year-long activity coordinated and implemented by teachers themselves, without the intervention of external educators. This allows for a more direct link between formal and non-formal experiences and helps identify how these experiences relate to the curriculum content and how to integrate them effectively into their lessons

The Present Study

Non-formal education in science is an extraordinarily broad and heterogeneous reality that is difficult to categorise, encompassing highly diverse activities conducted in various contexts and with differing durations and developments. For instance, non-formal activities range from visits of a few hours to specific locations led by external educators, to projects lasting several months where the work is carried out directly with the teacher, such as in science clubs (Martín-García et al., 2025).

Within this second category, we find the so-called crystal-growing competitions for schoolchildren (Whelan et al., 2018), which have been celebrated with great success worldwide (Perret et al., 2014; Van Meervelt, 2014). These are global events organised at a European and international level by the International Union of Crystallography. These events provide an opportunity for students to operate as 'scientific researchers', to investigate something they are curious about, design and implement experiments, collect data and extract meaning from them, draw evidence-based conclusions from the obtained results, and present and explain them to others. The one and only condition is that the projects must include some crystal-growing experiences.

Nevertheless, there is little research that provides empirical evidence concerning crystal growing competitions, as there have been no systematic studies of their implementation and outcomes. Furthermore, prior research seems to be scattered through isolated publications that are generally based on personal anecdotal opinions and subjective perceptions from the organisers rather than data and evidence gathered through research (Perret et al., 2014; Van Meervelt, 2014). This article aimed to fill that gap by providing evidence-based information derived from a four-year longitudinal investigation.

In Spain, crystal-growing competitions are now celebrated all over the country with several regional editions that culminate in a national final. Specifically, in the region of Aragón, where the study focused, the contest, named *Concurso de Cristalización en la Escuela de Arag*ón (CCEA), has held ten editions, reaching more than 10,000 students and over 140 schools from both urban and rural areas.

The contest is divided into three stages, covering almost the entire academic year: an initial stage where the competition, its organisation, development, and functioning are presented to the teachers; a second stage where the students work on their crystallisation projects supervised by their teachers; and a third stage in a congress format where representatives from each school defend their project before a jury of experts and the public attending the final. It is also mandatory for each team to elaborate a scientific poster summarising the project and its conclusions and to exhibit their laboratory diaries as well.

The contest's main objective is to raise students' awareness of science, increase their interest in it, encourage them to participate in scientific activities, and develop their scientific skills and abilities. The competition offers students an opportunity to immerse themselves in scientific investigations as if they were scientists, to design and conduct their own research projects, implement experiments, collect data, and make evidence-based decisions.

Method

Despite the crystal growing competitions have been held worldwide for years, there is a notable lack of empirical studies addressing their formative potential or their impact on teachers and students who participate in them (Van Meervelt, 2014). Consequently, this research was designed with an exploratory and descriptive nature, aiming to understand the experiences and perceptions of those involved in such competitions. Therefore, to align with this objective, a qualitative methodology with an interpretative focus was adopted to give participants a voice and allow their perceptions to be studied directly.

Previous studies (e.g., Garner et al., 2015; Karnezou et al., 2021) indicate that one of the objectives most frequently pursued by educators participating in non-formal activities, at least in the field of science, is precisely to connect the activity with the school curriculum, often being the main reason for determining which activities or projects have potential interest. Building on this basis, the research also aims to analyse how the competition activities fit within the secondary curriculum framework, by analysing the secondary education curricula to determine which of their elements can be addressed within the scope of the contest activities.

In this way, the perspective "from within" offered by the participants' impressions and experiences is complemented by an analysis "from without", conducted using the official normative documents that regulate secondary education in the region of Aragón.

To analyse the participants' perspective, a longitudinal study was conducted between 2016 and 2020, involving 165 teachers and 559 students from various towns in Aragón. For data collection, two ad-hoc open-ended questionnaires were designed each year for the teachers and two for the students: one administered prior to the competition and one afterwards. These questionnaires included open-ended questions that required the participants to construct their own responses, and they were specifically developed for the research and adapted to the context. The first questionnaire was distributed before the experimental phase began. The second, in contrast, was administered once this second phase had concluded but always before the competition final. Both were administered via the Google Forms platform to facilitate the subsequent analysis process.

The textual information contained in the respondents' answers was analysed using content analysis procedures. Specifically, strategies typical of Qualitative Content Analysis (Mayring, 2022) were employed by applying a semantic approach that allowed the identification of codes based on explicit meanings in the data. That is to say, the object of the analysis was not so much the style, composition or the organisation of the discourse, but rather the meanings contained within the transmitted message. This process allowed for the inductive generation of sets of categories representative of the participants' perceptions, providing an explanatory framework from which to interpret participants' responses and comprehend the underlying background. This analysis process was carried out in duplicate: first by considering the responses from each year separately, and subsequently from a more general perspective, considering the responses from the different editions as a whole.

Finally, for the studies focusing on the curriculum, documentary analysis strategies were used (Wotring et al., 2021) on the orders that specify the curriculum. This was done to locate, fix, select, and give meaning to the data collected in these documents, thereby allowing the researchers to discover and describe the central axes and main themes of the curriculum.

Findings

The responses from the teaching staff describe the competition as a beneficial learning context for students, where they can have fun and enjoy themselves, while acquiring knowledge across various subjects and developing a range of skills. Similarly, they regard it as an opportunity to foster a deeper understanding of scientific phenomena and explore science, scientific work, and research. Additionally, the contest is considered beneficial for teachers themselves, as it provides a chance to enhance their professional competencies and improve their role as teachers.

On the other hand, students perceive the competition as an opportunity to gain new knowledge and engage in laboratory work alongside their peers. Many also acknowledge that it has improved their perception of science, as they have discovered it to be more appealing, interesting, less abstract, and more accessible. In terms of content, curriculum analyses indicated that the contest allows for the inclusion of both specific topics and complete blocks of content from various subjects.

Specifically, seven key aspects summarising their perceptions of how the CCEA can contribute to science education have been established from the participants' responses. In this regard, the participants perceive the competition as an opportunity to:

1. **Improve Students' Scientific Education**

Teachers described the competition as an effective tool to foster students' scientific education because it allows them to address content from different subjects and, at the same time, go a step further than the curriculum and work on topics not explicitly included in the normative documents. Similarly, the students acknowledge specific learning achievements, both in the field of crystallisation and in relation to the curriculum of various subjects. The systematic curriculum analysis not only corroborates these perceptions but also reveals how other curricular elements exist that can be worked on beyond those mentioned by the participants. Furthermore, teachers emphasise the competition's ability to integrate knowledge from different disciplines, which allows for offering students an image of scientific knowledge as something that is coherently interrelated. Finally, it also provides an opportunity to promote the development of students' competencies, particularly their scientific competence.

2. **Develop Students' Skills**

According to teachers, participation in the competition provides students with opportunities to develop skills that are challenging to cultivate in traditional classroom settings. These include scientific skills, such as analysing and interpreting data, as well as transferable skills such as teamwork, which are highly valued by both teachers and students. In the case of the students' responses, they highlight how they have not only learned to work as a team but also to plan and organise that work.

3. **Provide Students with A More Realistic Image of Science**

Students feel that participating in the competition provides them with more realistic insight into how experimental sciences operate. They have come to appreciate key aspects, such as the importance of methodology, the need for replicability, and the broader role of science in society. Teachers emphasised that the contest helps students develop a more accurate understanding of how scientific knowledge is created and validated. In this way, students can appreciate the sometimes tentative nature of science and move a little closer to understanding its nature.

4. **Offer Students an Enjoyable Experience in Science**

Many teachers participate in the competition to reward their students by offering them an enjoyable and engaging experience that can help reduce the feelings of stress or anxiety that science sometimes generates and substitute them with a more positive emotional bond that may make students more willing to engage with it. This approach seeks to create a positive emotional connection with science, foster improved attitudes towards the subject, and boost motivation. Students confirmed that they perceived the competition as both rewarding and fun.

5. **Promote Teacher Professional Development**

Teachers regard the competition as an opportunity to complement and extend their training and support their professional growth. Specifically, they acknowledge that the competition is a way to come into contact with new ideas and highlighted that the competition equips them with additional resources and teaching strategies to enrich their educational toolkit. In this sense, they consider that they have gained practical knowledge for their daily teaching practices as well as insights that broaden their scientific understanding especially, but not only, in the field of crystallisation. Moreover, teachers described how the experience has allowed them to better understand the students and become more aware of their abilities and needs, which is very useful when planning and guiding classroom teaching. Finally, they acknowledge that participation in the contest serves as a source of motivation and personal satisfaction because they believe they are doing something beneficial for the students, which encourages them to become involved in other non-formal education activities.

6. Test New Science Teaching Strategies

Teachers view the contest as an opportunity to rethink their teaching practices, giving greater importance to practical laboratory work. They also see it as an opportunity to explore different teaching-learning contexts and situations and a platform for innovation, allowing them to experiment with new methodological approaches and to assess their effectiveness. Consequently, they feel more confident in applying these approaches in the classroom and feel more capable of teaching science.

7. Strengthen Personal Relationships

The findings revealed that the contest fosters a conducive environment for strengthening the bond between teachers and students. In this sense, there is an almost unanimous consensus among teachers in pointing out that the interactions established with students during the sessions dedicated to the contest differ significantly from those habitually generated in the classroom. The more relaxed atmosphere of the event, coupled with students' increased motivation, created a climate of trust and enhanced communication. This enables teachers to gain a better understanding of their students, contributing to a more enjoyable and fulfilling experience for everyone.

Discussion

The findings of this four-year longitudinal study emphasise the significant educational value of crystal growth contests for both teachers and students. The perceptions of participants reveal that the competition is a mutually beneficial experience for both of them alike. For students, it fosters engagement, skill development, and a deeper understanding of science. For example, they themselves highlight the effect of the contest on their image of science and science subjects, acknowledging that this has improved, in some cases because they have discovered a more appealing, entertaining, or interesting science, and in others because they have discovered a less abstract, less complicated, and more understandable science.

For the teachers, it supports professional growth and innovation in teaching practices while it contributes to promoting their content-knowledge, their pedagogical-knowledge, and their knowledge of the students, their characteristics, needs, and motivations. Finally, from the curricular perspective, it is clear that the contest allows for addressing specific content or knowledge in a simple and integrated manner, but also complete or practically complete blocks of the curriculum from different subjects belonging to different areas of knowledge.

However, the development of the contest is not free of problems or situations that must be confronted or resolved, which have led teachers to question certain aspects of it because they do not fully align with their vision of what the project should be. There are other aspects that, in the teachers' opinion, should be rethought or modified; these mainly refer to organisational aspects and not so much to how the contest is conceived or the effects it has on the participants, which are perhaps the most interesting aspects for the research. Thus, the results highlight the multifaceted benefits of participation that extend well beyond disciplinary knowledge to encompass broader educational and developmental outcomes.

These results broadly align with existing research (Affeldt et al., 2017; Burke & Navas Iannini, 2021; Karnezou et al., 2021; Molz et al., 2022; Raaijmakers et al., 2021), highlighting the critical importance of integrating formal and non-formal education to enhance the teaching and learning of science and ensure equitable benefits for all students. However, this study introduces several distinctive contributions that enrich the current understanding of such educational experiences and deepen our understanding of their role in science education.

First, it addresses an activity that, despite its global implementation, has been largely overlooked in prior research. Second, the focus on long-term initiatives marks a departure from the predominantly short-term activities typically examined in the literature. Third, the study adopted a multi-perspective approach to explore the experiences of both teachers and students. This approach, although uncommon, is essential for providing a holistic understanding of educational impact. Finally, the longitudinal design is particularly noteworthy, as studies of this nature remain scarce in the context of non-formal science education activities.

Collectively, these results represent a valuable contribution to the field of non-formal science education, offering new insights into the potential of these activities to enrich both teaching and learning. It is notable that the results of such diverse research, conducted in such different contexts, present so many marked similarities regarding the benefits that non-formal activities offer. This convergence suggests that the elements that are repeatedly observed are crucial for understanding the true significance of participation in non-formal activities for both teachers and students and that these are the aspects that should be attempted to be transferred to the classroom as much as possible.

Conclusions

In synthesis, the School Crystallization Contest, due to its nature as a non-formal activity, its development, the mode of work it promotes, and the final congress format as the culmination of the research and experimentation processes, brings together the best of three worlds:

1. The broad spectrum of possibilities offered by non-formal education, as it involves fewer limitations than formal education.
2. The benefits of methodologies based on inquiry, laboratory work, collaboration with peers, autonomy, and motivation.
3. The complementary nature of public science communication experiences.

The project harmonises these three elements to achieve greater scientific literacy among students, a greater understanding of science and its knowledge, and to continue training science teachers by improving their professional performance. In this process, the experience contributes to fulfilling curricular objectives, to the development of the key competencies that structure the curriculum in Spain and facilitates the addressing of content from different subjects from a multidisciplinary perspective, which rightfully makes the contest an extremely comprehensive training tool.

Therefore, these findings serve as a basis for future research, but also for the development of non-formal education programmes that are more enriching and attractive for teachers, who ultimately decide whether or not to integrate them into their classroom practice. However, beyond their academic value, they also have practical value because they offer the community a clear example of what participation in non-formal education activities can entail in terms of training and personal and professional development.

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Exploring Teachers' Objectives In Science Clubs And Beyond

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Despite the value that teachers place on non-formal activities, their goals and what they need from them remain underexplored, particularly in the context of long-term initiatives. In this work interviews with 19 teachers coordinating school science clubs in Portugal were conducted and their key objectives for the implementation of the club in the school were analysed. These include bringing science closer to students and communities, connecting activities with the curriculum, fostering scientific and interdisciplinary skills, and enhancing student motivation and engagement. In parallel, a literature review was conducted to identify studies examining teachers' goals for non-formal education activities. Thirty relevant studies were analysed, and their findings were compared to the objectives identified in the context of science clubs. The results revealed that teachers coordinating science clubs recognised all the goal types highlighted in the literature but placed greater emphasis on certain objectives which are less frequently mentioned in other types of non-formal activities. The findings underscore that science clubs enable meaningful experiences that complement traditional teaching, fostering interdisciplinary connections and promoting scientific literacy. The study concludes that understanding teachers' beliefs and requirements is crucial for designing activities that not only complement the curriculum but also address challenges within the formal education system. Greater integration between formal and non-formal education can generate synergies, bridging gaps and creating a seamless continuum of experiences that enrich science teaching and learning.

Keywords: non-formal education, science clubs, teachers' goals.

Introduction

There is growing evidence that students' knowledge and understanding of scientific concepts develop across a variety of settings, both within and beyond the classroom (Mujtaba et al., 2018). The benefits of non-formal learning environments for school students have been widely studied in many countries, showing that these activities make significant contributions to science teaching both in the conceptual-cognitive and affective-emotional domains (e.g. Aslan et al., 2023; Haatainen et al., 2024). As a consequence, it has been acknowledged that non-formal learning experiences can support science learning in ways that traditional schooling cannot overcome (Covert et al., 2019; Kisiel, 2014).

Nowadays, teachers increasingly recognise the value of non-formal learning spaces in providing educational experiences for their students (DeWitt and Osborne, 2007). Therefore, the effective integration and utilisation of these environments in science teaching represents an essential step toward fostering a more comprehensive and impactful approach to science education.

The role played by teachers in the integration of formal and non-formal education cannot be denied. Research firmly suggests that teachers and their approaches to non-formal learning play a crucial role in determining the effectiveness of such experiences (Luehmann and Markowitz, 2007; Uppin and Timoštšuk, 2022). Particularly critical is the value teachers attribute to these activities in enhancing their students' learning and abilities, as well as the goals they have for the experience, and the potential such activities offer to establish meaningful connections with the school curriculum (Karnezou et al., 2021). Despite their importance, these factors are often overlooked and limited emphasis has been placed on understanding teachers' perceptions, particularly in the context of long-term scientific activities (Martín-García et al., 2024).

For this reason, understanding teachers' beliefs regarding non-formal activities, what they need, and what they are looking for when entering the world of non-formal education is essential for designing activities that are both effective and responsive to their demands. However, achieving such interrelations and complementarity is considerably more feasible when activities are designed and implemented by teachers themselves and extend throughout the academic year. Examples such as science clubs illustrate this point effectively, as they allow for frequent and meaningful connections between non-formal activities and classroom learning. In Portugal, there is an established network of science clubs known as the "Clube de Ciência Viva na Escola" (The Alive Science Club at School), initiated and supported by the Ministry of Education. Within this framework, science teachers working at participating schools are responsible for coordinating science clubs. Such activities enable a seamless transition from classroom knowledge to application in a non-formal setting, or vice versa, facilitating experiential learning and the construction of knowledge in both contexts (Martín-García, Afonso, et al., 2024; Martín-García, Dies Álvarez, et al., 2024).

The focus of this study is to explore the specific goals established in the context of science clubs, with their unique characteristics, and compare them to the goals set for other types of non-formal education activities. To complement this analysis and establish comparisons with other types of non-formal activities, we conducted a review of 39 studies that explored teachers' objectives and expectations regarding various non-formal education activities to identify the types of objectives typically mentioned by teachers and whether these differ between short-term and long-term activities.

Method

This study is part of a broader investigation examining science teachers' subjective perceptions and experiences with school science clubs in northern Portugal. Following the previously described objectives, the study comprised two main parts: a literature review and a qualitative study using semi-structured interviews. Firstly, a bibliographic search was conducted in the Web of Science database to identify articles addressing the objectives, intentions, and expectations of teachers regarding non-formal education activities. Following a review of the titles and abstracts of the retrieved references, studies explicitly outlining the specific objectives set by the teachers were selected. Finally, the studies were classified based on the type of activity they described, and whether they were short- or long-term initiatives.

In parallel, we were interested in the evaluation of the perspectives of the teachers who coordinate science clubs regarding their goals, expectations, or intentions towards non-formal education. The analysis of teachers' perspectives in the literature often relies on closed-ended questions, which do not allow for a detailed understanding of their views, thus limiting their validity (Jensen and Buckley, 2014). In contrast, in this case, we approached the study using semi-structured interviews with 19 teachers who coordinated school clubs in the northern region of Portugal. The interview script conformed to a set of open-ended questions to invite teachers to elaborate on their answers.

Both the literature findings and the interview transcriptions were analysed using inductive bottom-up content analysis from a semantic perspective. This meant that our codes were directly derived from the data rather than imposed based on an a priori framework (Mayring, 2022). We then grouped codes with similar meanings to generate categories until we had a set of categories that were representative of the types of goals mentioned by the teachers in each case. This set provided an explanatory framework which allowed interpretation and comprehension of their responses.

Findings

The search yielded 30 studies that mentioned concrete objectives for participating in non-formal educational activities. Of these, 22 studies focused on short-term activities, while only 7 examined long-term projects. The study by Tisza et al. (2020) spans several types of activities with differing durations, making it unsuitable for classification under a single category. Specifically, the studies on short-term activities were primarily focused on the context of museums (18 studies), of which 16 were developed as school field trips. Works carried out in outreach laboratories (2 studies) and science festivals (2 studies) also appear. Finally, one of the studies discusses field trips in general, without specifying the type of location visited. Regarding long-term activities, science fairs predominate (3 studies), but there is also mention of projects conducted in aquariums (1 study), crystal growth competitions (1 study), and enrichment programmes (1 study), and even in a science club (1 study). The analysis of these studies allowed us to generate several categories, as summarised in Table 1, which describe the primary types of objectives identified in these studies.

Table 1: Types of objectives for non-formal education activities mentioned by teachers in the 30 selected studies from the literature review. Number of studies conducted in short-term and long-term activities that mention each of the objectives (percentage of the total number of studies conducted in short-term or long-term activities).

Code	Objective focused on	Number of articles	Short-term (n=22)	Long-term (n=6)
O1.	Increasing students' exposure to science	16	10 (45,5%)	5 (71,4%)
O2.	Science content-knowledge	18	12 (54,5%)	5 (71,4%)
O3.	Curriculum connection	14	12 (54,5%)	2 (28,6%)
O4.	Providing new learning experiences	17	14 (63,6%)	3 (42,9%)
O5.	Experimental work experience	10	7 (31,8%)	3 (42,9%)
O6.	Developing of students' skills	9	3 (13,6%)	5 (71,4%)
O7.	More effective teaching	12	7 (31,8%)	5 (71,4%)
O8.	Exposing the students to what the settings uniquely have to offer	9	8 (36,4%)	1 (14,3%)
O9.	Personal interest of the teacher or school demand	8	6 (27,3%)	2 (28,6%)
O10.	Motivation and interest	18	14 (63,6%)	3 (42,9%)
O11.	Enjoyment and engagement	13	12 (54,5%)	1 (14,3%)
O12.	Personal relationships and interactions.	9	7 (31,8%)	2 (28,6%)

Note: Cells shaded in purple indicate content-oriented goals, cells shaded in green indicate affective-oriented goals, and cells shaded in red refer to general education-oriented goals. The total number of objectives does not match for objectives O.1, O.2, O.6, and O.10 because these are the objectives mentioned in Tisza et al. (2020) study, which refers to all types of activities without specifying duration.

The review of the literature reveals a broad range of objectives, suggesting that non-formal activities can serve diverse purposes and address various educational needs. The revised studies include more cognitive objectives, focused on the acquisition of specific scientific knowledge, but also more affective objectives, centred on areas such as motivation, enjoyment, and interest in science. Furthermore, objectives more focused on the immediate educational context also feature, relating to the teaching and learning process, such as the curriculum, the teaching practice, and the type of educational experiences to which students are exposed.

The most commonly mentioned objectives include the acquisition of scientific knowledge and content, as well as the enhancement of student motivation and interest. Additionally, many studies have emphasised the provision of new learning opportunities and exposure to science in ways that allow students to engage more deeply. These findings underscore the teachers' emphasis on connecting non-formal activities with the classroom, whether as complements, extensions, reinforcements, or applications of classroom learning, targeting both subject-specific knowledge and the development of skills and attitudes.

Reviewing short-term and long-term activities separately reveals that all categories derived from the literature analysis are mentioned in both groups. However, there are differences in the types of objectives most frequently cited. For example, in long-term activities, the dominant objectives are "*To increase their exposure to science*", "*Science content-knowledge*", "*Development of students' skills*" and "*More effective teaching*", which appear in 5 out of the 7 articles contextualised in long-term activities (71.4%). In contrast, in short-term activities, the predominant objectives are "*Providing new learning experiences*" and "*Motivation and interest*", appearing in 14 out of the 22 studies found (63.6%). To a lesser extent, "*Science content-knowledge*", "*Curriculum connection*" and "*Enjoyment and engagement*" stand out, being mentioned in 12 studies (54.5%).

The qualitative findings derived from interviews with teachers who coordinated science clubs show that they set a wide variety of different goals for the clubs. The responses could be organised into seven categories, but within the majority of them, several different themes can be identified. Both the categories and the most relevant themes found within them are summarised in Table 2. It is important to note that these categories are not mutually exclusive. More often than not, teachers expressed several goals, and some of them may be classified in more than one category. In fact, all 17 interviewed teachers identified more than one category of objectives. Specifically, three teachers mentioned two categories, three mentioned three categories, nine mentioned four categories, and three mentioned all five categories. This demonstrates the multifaceted nature of these objectives.

Overall, teachers coordinating science clubs recognised all the types of objectives discussed in the 30 reviewed references. That is to say, the goals declared by the teachers are, for the most part, quite similar to those found in the literature. In both cases, objectives aimed at providing concrete benefits to students or improving their learning of science predominate. Table 2 illustrates how the categories constructed in the interview analysis relate to the types of objectives found in the literature review. However, differences are also observed, for example, in the relevance given to the learning of disciplinary content or science. For this reason, our interviews reveal some unique aspects that differentiate the clubs from what is typically reported in the broader literature.

Firstly, it became evident that teachers see the science club as an opportunity to integrate concepts in broader contexts and engage in interdisciplinary activities, a goal that appeared in only one of the 30 references analysed. Secondly, these teachers place strong emphasis on the opportunity to integrate concepts in broader contexts and engage in interdisciplinary activities. This was particularly striking as this specific goal appeared in only one of the thirty analysed references. Finally, teachers placed greater emphasis on goals related to bringing science closer to the community and students—a key objective present in all interviews and thus fostering community and student appreciation of the club's role in promoting science education, an objective that was not captured in the 30 references.

Table 2: Types of objectives mentioned by teachers coordinating science clubs in the interviews: categories, subcategories, and number of teachers mentioning them. Relationships or associations with objectives derived from the literature review analysis (n=17).

Category	Subcategories	Number of teachers	Associated objectives from the literature review
To bring science closer to pupils or the community	Disseminate the study of science. Motivate students and engage them in scientific activities. Promote scientific literacy and scientific culture. Showing that science is important to society.	17	O1.; O2.; O3.; O4.; O10.; O11.
To promote other means of teaching and learning:	Providing interdisciplinary experiences. Connecting with the curriculum. Experience the experimental component of science.	14	O1.; O2.; O3.; O4.; O5.; O7.; O8.; O9.
To develop students' skills and abilities	Scientific skills. Cross-disciplinary skills.	13	O5.; O6.; O9.; O12.
To increase awareness about what the club offers	Supporting students with difficulties or high abilities.	6	O1.; O2.; O3.; O4.; O5.; O6.; O7.; O8.; O9.
To increase students' science content-knowledge		12	O2.; O3.
To promote or improve personal relationships and interactions.		2	O6.; O12.

Discussion

The main aim of this study was to examine the specific goals set within the context of science clubs and to compare them with those established for other types of non-formal education activities. Previous studies in this field seems to be somewhat contradictory. Some studies reveal that although schools and teachers attribute high value to the museum visit, the international literature indicates that teachers hardly define their goals for the museum visit (e.g. Cox-Petersen et al., 2003). For example, Tal et al., (2005) studied 30 teachers in four natural history museums in Israel. They found out that only one-third of these teachers provided specific purposes for conducting the museum visit, explaining how the visit was connected to the school curriculum. Most of the teachers gave general answers about the purpose of the visit, while in many cases teachers stated that others had planned the visit and they were unaware of the purpose. On the other hand, other publications reported that teachers seem to have multiple objectives for activities such as fieldtrips which include both cognitive and affective elements (Anderson et al., 2006; Karnezou et al., 2021; Martín-García and Dies Álvarez, 2022). Other works have also shown how teachers articulated their goals around these two dimensions (e.g. Canovan, 2019; DeWitt and Storksdieck, 2008; Tisza et al., 2020).

The results obtained in this work, both in the literature review and in the teacher interviews, align more closely with these latter studies. Specifically, the analysis of the references found in the literature review evidences that teachers recognise the role such places can play in providing unique educational experiences for their students, both when dealing with short-term and long-term activities. Consequently, they generally establish certain objectives for the activities, although these may sometimes be very generic.

The interview results are generally consistent with the findings derived from the systematic analysis, although they do show certain slightly distinct elements that have not been recorded in the studies analysed in the literature. However, it has not yet been possible to determine whether these elements are inherent and exclusive to the science club as a non-formal education context or whether they are more related to the sustained, long-term nature of the activities carried out.

In any case, given the complexity and diversity of activities encompassed within the domain of non-formal education, teachers' objectives in out-of-classroom learning environments are far from uniform. However, although the activities and their contexts differ, there are some noteworthy similarities with regard to teachers' declared goals. It is notable that the results of such diverse research, conducted in such different contexts, present so many marked similarities. This convergence suggests that the elements that are repeatedly observed are crucial for understanding the true significance of participation in non-formal activities for teachers and that these are the aspects that should be attempted to be transferred to the classroom as far as possible.

There are no major differences between short-term and long-term studies regarding the types of objectives proposed by the teachers. In fact, as indicated, the reviewed studies, as a whole, mention all the categories emerging from the analysis, both when considering only the short-term activities and when considering only the long-term ones. However, our review revealed that much of the existing research has focused on short-term activities such as school field trips, where external educators often lead educational initiatives. In contrast, we identified only two studies that examined long-term activities, where teachers take on responsibility for leading the activities themselves (Longhi and Schroeder, 2012; Martín-García and Dies Álvarez, 2022).

There is growing evidence that students' knowledge and understanding of scientific concepts develop across a variety of settings, both within and beyond the classroom. Therefore, teaching science in the classroom environment should be supported with experiences gained outside the classroom (Aslan et al., 2023). Thus, the appropriate and effective use of non-formal activities in science teaching is very important and it should become a core practice rather than something that teachers do when they have extra time. For that reason, understanding how teachers' beliefs regarding non-formal activities are structured—what they need, seek, and value when engaging in non-formal education—is essential for designing activities that are both effective and responsive to their demands. Activities that truly align with teachers' expectations are more likely to be meaningful and impactful.

For this reason, we agree with authors such as Luehmann and Markowitz (2007) who declare that much can be learned about secondary science classrooms' needs by considering teachers' perspectives because by considering both educators' perspectives, we gain a clearer understanding of the practice. In other words, by considering these perspectives, we gained valuable insights into the perceived gaps in the formal education system. These reflections serve as informal diagnoses of the challenges in science teaching and offer a roadmap for improvement. Similarly, gaining insight into teachers' perspectives is essential not only for designing non-formal activities that effectively address the needs of educators and students but also for promoting stronger integration between formal and non-formal education. In this regard, some of the reviewed references indicate that students learn more and benefit more from non-formal education experiences when they are already familiar with the topics and content addressed, as their prior knowledge seems to condition the learning they can achieve (DeWitt and Storksdieck, 2008). Therefore, such integration between formal and non-formal opportunities can generate synergies that bridge the gap between these two domains, thus creating a seamless continuum of experiences that enriches science teaching and learning.

Furthermore, depending on factors such as teachers' personality traits or teaching styles, the same activity may serve a wide range of purposes, addressing both cognitive and affective goals, which are often interlinked rather than mutually exclusive. In this sense, considering these factors, the same non-formal education activity or context can serve different purposes depending on how it is developed, structured, sequenced, and connected with the work carried out in the classroom. In this context, it is the prioritisation of specific goals over others, rather than the initial establishment of certain objectives, that significantly influences the teachers' practice, the way they deal with the experience, and the overall outcomes of such activities (Karnezou et al., 2021). Nevertheless, even though teachers' agendas dominate the course and outcomes of non-formal experiences, there is always an element of unpredictability in learning in out-of-school environments (Uppin and Timoštšuk, 2022).

Finally, authors such as Garner et al. (2015) consider that it is also important that the students know exactly what is expected of them during the field trip. Nevertheless, they described how research shows that students are often unaware of the overall goals and thus they are unprepared for effective, goal-oriented learning during the activities. An implication of this is that teachers must therefore carefully inform their students about the goals pursued through participation, so that students can know what is expected of them during the activities.

Therefore, when researching within the framework of non-formal education, it is no longer sufficient to merely consider the general objectives of the activity proposed by the teacher, but also which ones are priorities for the teachers, in line with what this last author suggested. This is an aspect that we have not carried out throughout this study, but which would be interesting for future research to consider as a possible line of further investigation.

In conclusion, taking into account both the results of the systematic review and the perceptions shared by the teachers during the interviews conducted in the science clubs, it is evident that further analysis of teachers' perspectives within the specific framework of long-term activities is necessary, as a gap still exists in the literature given that far fewer studies focus on this type of activity.

In this way, we can come to understand the subtle differences that exist between short-term and long-term activities and be able to advise teachers in the best possible way regarding whether to opt for one, with what objectives or purposes, or to achieve what specific goals when choosing the other. It is clear that the characteristics and learning outcomes that can be derived from one and the other can be very different, and therefore, teachers approaching a short-term or long-term activity with the same type of objectives, regardless of how it will be developed, could be a poor choice.

Therefore, it is necessary for us to know what benefits one provides, what achievements are attained, and what those of the other are, so we can better advise and support teachers when choosing what type of activity, they need to achieve their proposed goals, since they are the ones who truly control and know what they seek, what they need, and what options they should offer their students.

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Exploring Science Through Play: Assessing The Impact Of The PIXEL Board Game And Its Game-Based Learning Framework On Students' NOS Perception

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This study evaluates the educational potential of the board game PIXEL – Picture (of) the Universe, designed by the Italian National Institute for Astrophysics in collaboration with the Game Science Research Center. PIXEL, integrated within a Game-Based Learning framework, aims to enhance students' understanding of the Nature of Science, with a particular focus on the social and institutional dimensions of scientific research. The game's mechanics simulate astrophysics research, emphasizing collaboration, resource management, and inquiry associated with image resolution in astrophysics. Through gameplay and associated activities, students explored scientific processes in an engaging, risk-free environment. The study involved 32 high school students participating in a 40-hour program, which included gameplay, facilitation training, reflective diary writing, and feedback sessions. Using qualitative thematic analysis of students' diaries, the research identified significant shifts in perceptions of science and research. In the pre-activity, responses largely reflected formal, textbook-like views of science, emphasizing the scientific method as a rigid process. In the post-activity ones, students displayed a more nuanced understanding, highlighting collaboration, iterative research, and the human aspects of scientific inquiry and manifesting a personal point of view about science and researchers. The study confirmed PIXEL's effectiveness in promoting NOS understanding; it emphasized the importance of integrating games into well-designed educational frameworks, demonstrating the potential of GBL to help learners refine their ideas, increasing their complexity and aligning them more closely with the real practices of contemporary astrophysical research.

Keywords: Nature of Science, Game-Based Learning, Scientific Citizenship

Introduction

This study explores the educational potential of the board game PIXEL - Picture (of) the Universe (Figure 1), developed by the Italian National Institute for Astrophysics (INAF) in collaboration with the Game Science Research Center. PIXEL aims to promote understanding of the Nature of Science (NOS), particularly its social and institutional dimensions, through a Game-Based Learning (GBL) approach. By combining engaging gameplay with scientifically grounded content, PIXEL bridges students' experiences with the methodologies and dynamics of astrophysics research.

GBL is often used as an umbrella term for a wide range of educational practices that involve games. However, the mere use of games in educational settings does not, in itself, constitute GBL. A critical distinction concerns the role that the game plays in the learning process and, more specifically, the degree of agency afforded to learners.

Figure 1. PIXEL - Picture (of) the Universe; game set-up.

A first approach, which can be described as "game-as-tool" for learning, treats games primarily as vehicles for content delivery. In this case, disciplinary knowledge is embedded into gamified formats, such as quizzes or trivia-based games, with the main aim of increasing motivation or engagement. While these approaches may be effective forms of gamification, they do not fully align with the principles of Game-Based Learning, as gameplay remains largely instrumental and does not support deeper meaning-making processes.

A second approach conceptualizes the "game-as-model" of the expected learning outcomes. Here, game mechanics are intentionally designed to embody key processes, structures, or ideas in the domain of interest. Through interaction with the game system, learners can experience simplified or metaphorical representations of complex phenomena. In this case, GBL can occur when gameplay is accompanied by opportunities for reflection and sense-making, allowing learners to connect in-game actions with disciplinary concepts and practices.

A third perspective, which we refer to as "game-as-game", positions the gameplay itself as the core learning practice. In this view, learning emerges from players' autonomous decision-making, negotiation, and strategic action within the game system. Rather than serving as a means to transmit predefined or expected content, the game creates a space in which learners actively construct understanding through participation. From this perspective, the educational value of GBL depends strongly on the level of agency allowed by the game and on the role of facilitation in supporting reflection, discussion, and skills development. This perspective is often used in educational contexts to foster transversal competences, rather than focusing primarily on disciplinary learning.

PIXEL is intentionally designed to support both the game-as-model and the game-as-game perspectives. Its mechanics embody key features of scientific research, while gameplay itself constitutes a meaningful learning experience. When embedded within a structured Game-Based

Learning framework that includes facilitation and reflective practices, PIXEL enables students to explore and make sense of the Nature of Science not through explicit instruction, but through lived and negotiated experience.

Playfulness, Game Design And The Nature Of Science

Play is an inherent and universal aspect of learning across cultures and species, facilitating cognitive development, engagement, and social interaction (Huizinga, 1950; Smith, 2010). Neuroscience literature suggests that play activates brain regions involved in memory, problem-solving, and emotional regulation, fostering the foundations for lifelong learning (Puschmann et al., 2012). Grounded in these principles, PIXEL aims to create a meaningful and enjoyable learning experience that actively engages students in scientific practices and in reflecting on the Nature of Science.

PIXEL is a eurogame, a category of board games characterized by strategic mechanics and minimal reliance on chance. The game's central mechanic revolves around the resolution of astrophysical images, which represents the process of constructing detailed celestial images through observational data. During the observation phase, players must place tiles of different sizes that represent portions of the observed object at incremental resolutions. Players must use resources strategically to improve telescopes, to conduct observations, and to build an image collaboratively. The mechanics emphasize:

1. Iterative research. Lower-resolution tiles are larger and require fewer actions, mirroring the preliminary surveys astrophysicists conduct before focusing on detailed observations.
2. Collaboration and competition. Observational data is shared among players, representing the collaborative nature of scientific research, while maintaining competitive gameplay, representing competition in academia.
3. Scientific practices and professionalism. Winning the game requires players to build a coherent strategy, allocating limited resources to publications, facility improvements, staff growth, and multidisciplinary specialisation, thus reflecting the constraints and trade-offs of real-world scientific research.

PIXEL was designed to embody NOS principles, i.e., the values, practices and social dimensions of scientific knowledge. Among the different approaches addressing it, we chose to use the Reconceptualized Family Resemblance Approach (RFN), which encompasses both cognitive-epistemic and social-institutional aspects of science (Erduran & Dagher, 2014). These include practices, knowledge generation, social organization, and the reward systems of science. A key focus was to present scientific work as a human endeavour, offering students a holistic view of how research communities operate. The study evaluated PIXEL's educational impact through two research questions:

1. Can PIXEL, within a GBL experience, enhance students' understanding of the social and institutional dimensions of research in astrophysics and beyond?
2. Can this GBL experience foster a more personal and humanized perception of researchers and the research process?

Educational Design And Research Methodology

The study follows a qualitative case study design, aiming to validate the educational potential of PIXEL - Picture (of) the Universe in fostering students' understanding of the social and institutional dimensions of science. The board game was implemented within a structured GBL intervention carried out in the context of the Italian PCTO (Pathways for Transversal Skills and Orientation) non-formal program, a national initiative for Italian high school students that requires them to complete a set number of hours of learning in collaboration with external educational or professional partners, in order to achieve a broader educational experience that extends beyond formal learning.

The 40-hour educational program – distributed over 5 to 6 months depending on the local schools – took place in 5 Italian cities and allowed participants to experience the game in multiple roles (as players, facilitators, and reflective learners). The intervention combined gameplay, structured debriefing, and reflective writing to promote NOS understanding. The design explicitly avoided direct instruction about NOS concepts or the social dimensions of science, so that any conceptual change could be attributed to the students' experience with the GBL process itself. Voluntary participation was emphasized to align with the principle of play as a voluntary attempt, fostering genuine engagement and motivation. In the following, we outline the structure of the educational design.

1. Training sessions. Students were introduced to basic GBL principles, to PIXEL's mechanics, and the scientific concepts underpinning the game, such as astrophysical image resolution. Importantly, social and institutional aspects of NOS were not explicitly addressed, allowing these to emerge organically during gameplay and debriefing.
2. Facilitation practice. Students practiced facilitating PIXEL sessions with peers, learning to guide gameplay and conduct debriefs, which are critical for metacognitive learning. To support this, a graphic debrief tool was provided to help analyse player interactions and themes.
3. Reflective diaries. Between interventions, students documented their experiences and reflections by answering open-ended questions in diaries, which served as key data sources for the study. This reflective practice aimed to enhance critical thinking and self-regulated learning.
4. Feedback sessions. Participants engaged with astrophysicists and game creators in two feedback sessions, discussing their progress, challenges, and insights, further deepening their understanding of the research world.

Qualitative Data Collection And Analysis

To explore students' evolving conceptions of science, data were collected through reflective diaries compiled after each session. The diary method was chosen to support a metacognitive, explicit-reflective approach to learning about NOS (Lederman et al., 2002; Abd-El-Khalick & Lederman, 2023). Each diary included 3-5 open-ended questions encouraging students to articulate their views on science, research, and scientists. The first and last sessions contained identical questions – "What is science to you?", "How does scientific research work?", and "How do researchers work?" – allowing for a pre/post comparison of conceptual change. For the purposes of this study, only these sessions are presented in the following sections, as the others were used to track students' progress in understanding and facilitating the game. This qualitative and reflective approach aligns with action research traditions (Lewin, 1948; Cunningham, 1976), in which the act of observation can itself promote transformation. In this sense, reflective diaries were both a learning tool and a data source.

We conducted two complementary analyses: a content-oriented analysis, focused on identifying recurring themes in students' reflection diaries, and an expressive register analysis, aimed at capturing shifts in students' style and tone.

The content-oriented analysis was inspired by the Reflexive Thematic Analysis framework (Braun & Clarke, 2006, 2019). We adopted a primarily inductive approach, allowing themes to emerge from the diaries while remaining attentive to our research questions. The analysis was conducted mainly at a semantic level, focusing on the explicit content of students' writings, though in some cases we drew on latent interpretations. Ten researchers, organised into five pairs, independently coded the data. Each pair identified emerging themes and assigned preliminary keywords to each data entry. A longitudinal perspective was then applied to trace the evolution of themes for each participant. Following these initial cycles, the groups compared results, synthesized the outcomes, and refined them through iterative discussions until a stable pool of themes was established. This process was iterative, involving multiple cycles of code creation, evaluation, and refinement.

In the analysis, we noted significant variation in the tone and style of student responses, ranging from formal, stereotypical formulations to more personal, elaborated accounts. To account for this, we also categorised entries into expressive registers using a latent thematic analysis. Well-structured and elaborate responses were coded either as bookish responses or personal elaboration, whereas superficial, incomplete, or nonsensical entries were tagged separately. This additional analysis provided insight into shifts in students' expressive registers, highlighting a move from bookish, stereotypical formulations to more personal, reflective engagements with science, research, and the role of scientists.

For each question of the first and last sessions, the number of occurrences of each tag was counted across the entire sample to determine how often specific themes were mentioned. The percentage frequency normalized over the number of tags in the pre (45, 35, 45 tags for each question, respectively) and in the post (56, 81, 54) was then calculated.

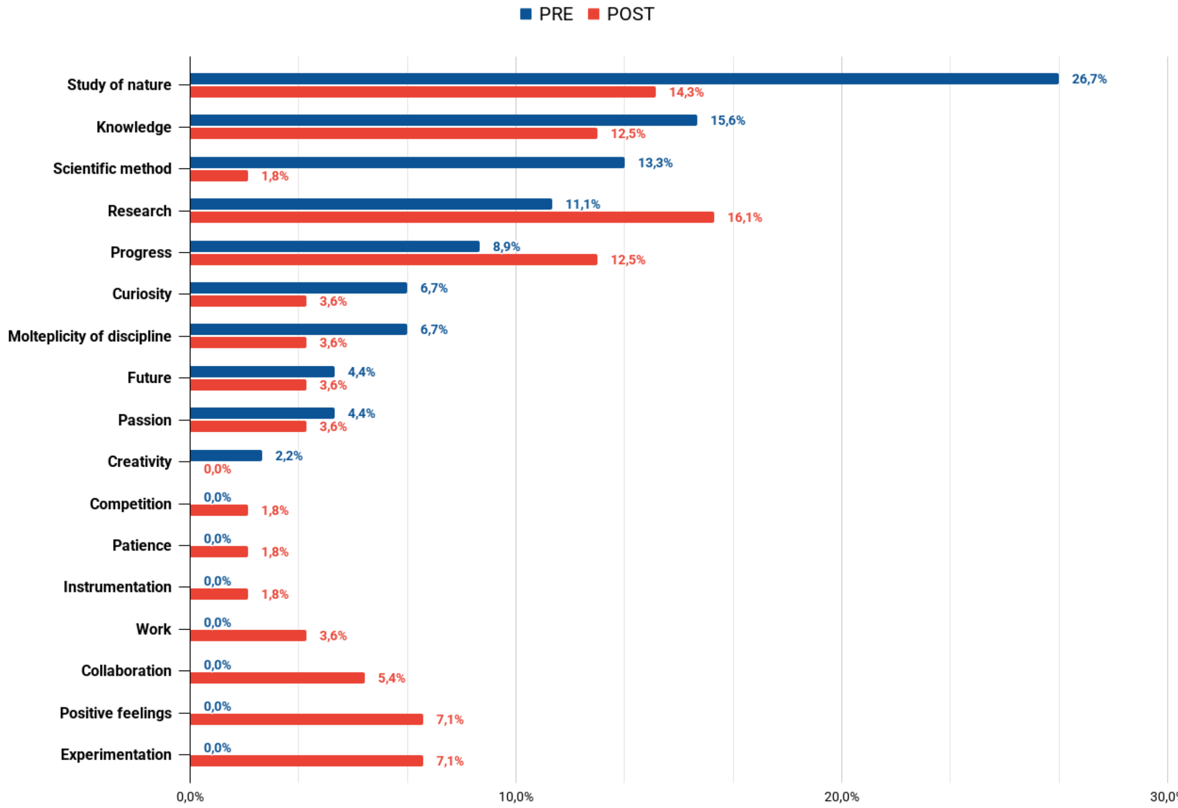
Finally, the tags were grouped within the two systems of the RFN: the cognitive-epistemic and the social-institutional systems.

Results

The findings presented hereafter highlight notable changes in students' perceptions, emphasizing a broader and more nuanced understanding of science and research. The results are introduced by discussing the three questions separately.

Perceptions of Science. Students' responses to the question, *"What is science for you?"*, initially clustered around ten themes, such as **Study of nature**, **Knowledge**, **Scientific method**, and **Research**. By the end, these expanded to 16 themes, reflecting a richer and more diverse understanding. Significant reductions occurred in the themes **Scientific method** (from 6 to 1 occurrences, -11.5%) and **Study of nature** (from 12 to 8, -12.4%), indicating a shift away from narrowly defining science through traditional concepts. Meanwhile, themes such as **Progress** (from 4 to 7, +3.6%) and **Research** (from 5 to 9, +5.0%) grew in prominence, alongside new themes like **Collaboration** (0 to 3, +5.4%), **Experimentation** (0 to 4, +7.1%) and **Positive feelings** (0 to 4, +7.1%), a theme we introduced to count the entries with an explicit sense of positive values associated to science. See the graphic of Figure 2 for the percentage frequency of each theme. These changes suggest that students began to view science as a multifaceted and collaborative endeavour, emphasising discovery and shared passion.

Figure 2. Frequencies of the themes emerged in the answers to the question "What is science for you?" asked at the beginning of the project (blue, pre) and at the end (red, post)



Understanding Scientific Research. The students' understanding of scientific research evolved from 7 themes in the pre-activity phase to 18 themes post-activity, as shown in Figure 3. The theme **Scientific method** dropped dramatically (from 25 to 8 occurrences, -61.5%), while new concepts, such as **Astronomical observation** (from 0 to 6, +7.4%), **Commitment** (0 to 7, +8.6%), emerged, often influenced by the game's design. For example, themes such as **Objectives** (0 to 8, +8.9%) and **Instrumentation** (0 to 5, +6.2%) can be traced back to the game mechanics, where players simulate research goals and resource management. The theme **Replicability**, which disappeared entirely (from 3 to 0, -8.6%), was deemed less relevant in the context of astrophysics, a field where transient and non-replicable phenomena are common. This shift illustrates the "efficiency" of GBL approach to reshape students' perceptions, broadening their understanding of the complexity and human dimensions of research, and in this case, wiping out a concept.

Perceptions of Researchers' Work. Responses to the question, *"How do researchers work?"*, also showed significant variations from pre- and post-activities (Figure 4). The **Scientific method** theme declined significantly (from 12 to 5 occurrences, -17.4%), while themes like **Collaboration** (from 5 to 12, +11.1%) and **Objectives** (0 to 10, +18.5%) grew substantially. The reduced focus on **Objectivity** (from 8 to 1, -15.9%) underscores the game's emphasis on the subjective, strategic, and collaborative aspects of research, challenging the perception of science as purely objective. Students began to view researchers as individuals navigating complex goals and balancing cooperation and competition, an insight that aligns with the educational objectives of the game.

Figure 3. Frequencies of the themes emerged in the answers to the question "How does scientific research work?" at the beginning of the project (blue, pre) and at the end (red, post)

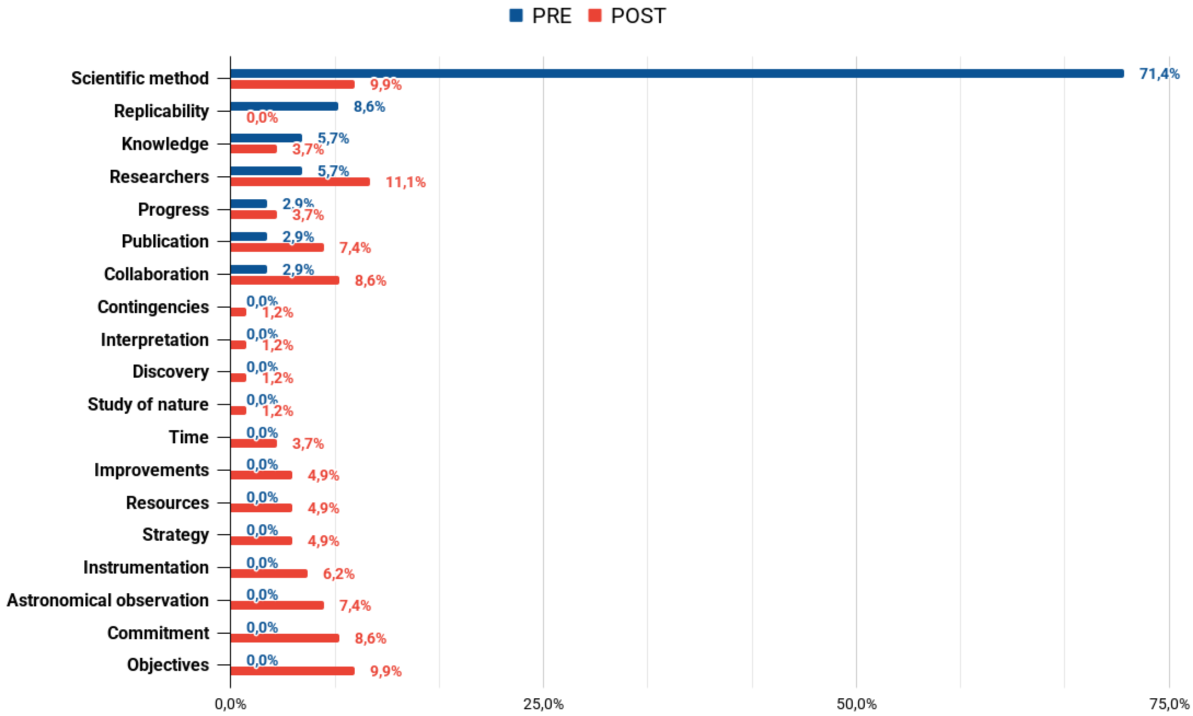
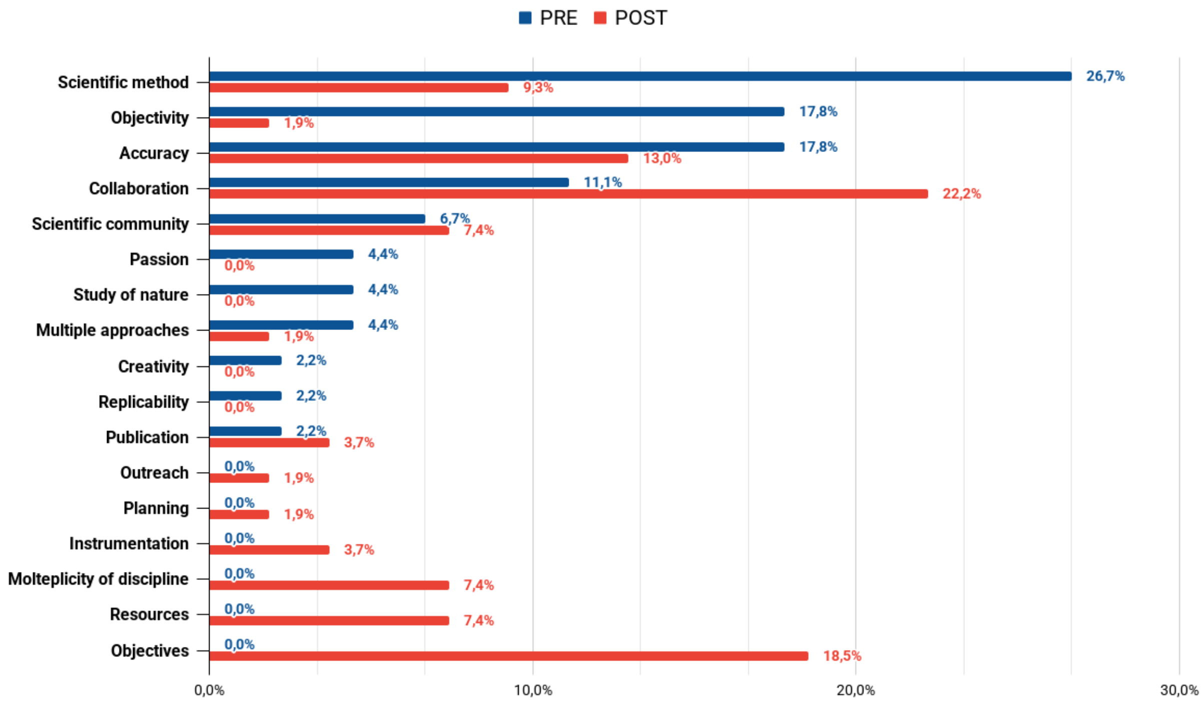
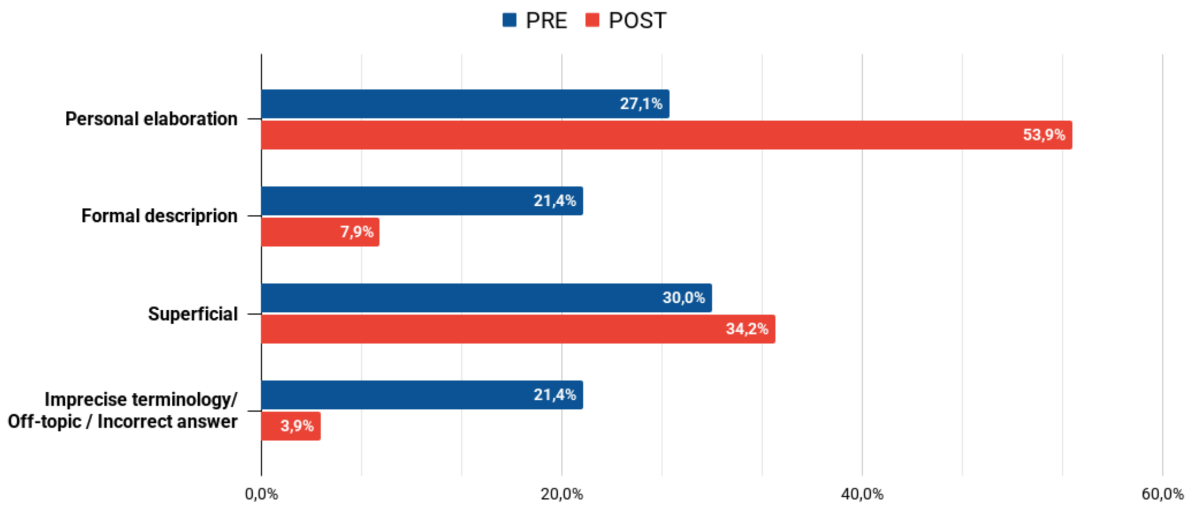


Figure 4. Frequencies of the themes emerged in the answers to the question "How do researchers work?" at the beginning of the project (blue, pre) and at the end (red, post)



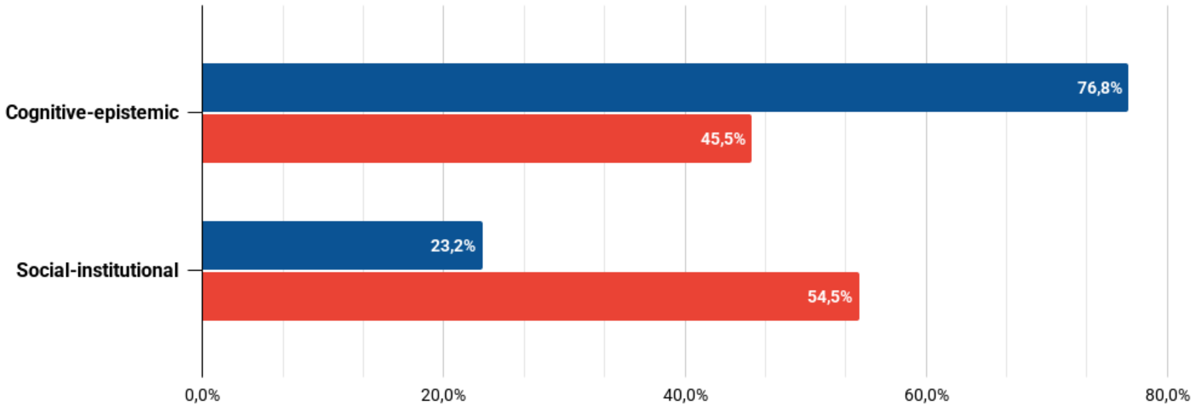
Modal Analysis. A comparative analysis (Figure 5) of response categories revealed a major shift from formal, textbook-like answers to personal elaborations, which increased by 26.8% (from 19 to 41 occurrences). Conversely, formal descriptions decreased by 13.5% (from 15 to 6). This transition reflects a deeper engagement with science, as students moved beyond memorized knowledge to expressing their own perspectives, enriched by the GBL experience. Incorrect or off-topic responses nearly disappeared, highlighting the game's effectiveness in fostering comprehension.

Figure 5. Tag for modal analysis for the three questions (pre-blue and post-red)



RFN mapping. To further examine how the GBL experience influenced students' understanding of the Nature of Science, the themes emerging from their responses were interpreted through the lens of the Reconceptualized Family Resemblance framework. Specifically, each theme was associated with either the cognitive-epistemic or the social-institutional system, and their relative presence was compared across the pre- and post-intervention phases. The resulting distribution is illustrated in Figure 6.

Figure 6. Frequency of the themes addressing the two RFN systems (pre-blue and post-red)



Before the intervention, students' representations of science were largely dominated by themes related to the cognitive-epistemic system, which accounted for 76.8% of all coded occurrences. After the GBL experience, this proportion decreased substantially to 45.5%. In contrast, themes associated with the social-institutional system increased markedly, from 23.2% in the pre-phase to 54.5% in the post-phase.

This redistribution highlights a significant shift in how students conceptualized science. While their initial views emphasized methods and procedural aspects, their later reflections increasingly foregrounded the human, social, and institutional dimensions of scientific work. Such a reorientation suggests that the GBL experience supported a more balanced and comprehensive understanding of science, in line with the integrated view of scientific practice articulated by the RFN framework.

Discussion and Conclusions: Games as an activator for NOS reflection

This study explored the educational potential of the board game PIXEL – Picture (of) the Universe when embedded within a structured GBL framework, with particular attention to students' understanding of the NOS. Rather than focusing on the effectiveness of the game as an isolated artefact, the analysis highlights how the interplay between game design, educational orchestration, and reflective practices can foster more informed, nuanced and humanized views of scientific research.

The findings indicate a clear shift in students' perceptions of science and scientific research, particularly regarding the social and institutional dimensions of NOS. Prior to the intervention, students' responses largely reflected formal, textbook-like conceptions of science, often centred on the scientific method as a linear, rigid procedure. Such views are well documented in the literature and remain a persistent challenge in science education (Abd-El-Khalick & Lederman, 2023). Following the GBL experience, students' reflections became more diversified, articulated, and personal. The increased salience of socio-institutional themes suggests that students began to perceive science as a collective, situated human enterprise rather than an individual, abstract, and decontextualised process. This transformation aligns with previous studies (Buaraphan, 2012; Erduran et al., 2019), positioning GBL as a viable learning strategy for making epistemic and social processes of science visible and discussable. Importantly, these outcomes cannot be attributed solely to the game. As argued by Clark (1994), learning does not reside in the medium itself but in the instructional methods through which it is enacted. In this sense, PIXEL functioned as an epistemic artefact whose educational value emerged through its integration within a carefully designed GBL pathway.

Moreover, this study shows how specific game mechanics can be systematically mapped onto NOS dimensions through the Reconceptualized Family Resemblance Approach, effectively linking game design, gameplay dynamics, and students' reflections. Mechanics such as competing objectives and collective construction made core scientific practices experientially accessible, highlighting tensions between collaboration and competition, uncertainty and decision-making. The findings suggest that the effectiveness of GBL for NOS lies in the coherent alignment of game mechanics, facilitation, and reflective practices, fostering authentic and experience-based understandings of science.

Indeed, the results highlight a shift in students' expressive registers from formal descriptions to personal elaborations, indicating not only conceptual change but also increased agency and epistemic engagement with science. Reflective diaries played a key role in supporting this transformation, enabling students to connect their gameplay experiences with broader perspectives on scientific research and to develop a more confident, personal scientific voice.

In conclusion, the findings underline the potential of analogue board games as effective tools for addressing the epistemic and social dimensions of science, while emphasising that the impact of GBL depends on thoughtful educational design rather than on games as stand-alone solutions. For educational practice, this highlights the need for intentional facilitation, debriefing, and reflection, pointing to the importance of teacher education programs that frame GBL as a comprehensive pedagogical approach.

On the other hand, as a qualitative case study involving a small, self-selected group of students, the findings are not intended to be generalised statistically. While the study is situated within the specific domain of astrophysics, this choice represents a strength rather than a limitation. Astronomy is widely recognised as a "gateway science" (Salimpour et al., 2021), capable of engaging learners and fostering broader reflections on science as a human and epistemic enterprise that extends beyond the disciplinary context.

Overall, this study contributes to ongoing discussions within the ESERA community about how playful and experiential approaches can support learning about the Nature of Science. By combining game design, the RFN framework, and reflective educational practices, the PIXEL GBL experience offers an example of how games can be used not merely to motivate learners but to foster deeper epistemic understanding and personal engagement with science.

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Complexity-Differentiated Learning To Support Students' Lab Work In Out-Of-School Student Laboratories

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Out-of-school student laboratories (OSL) are often hosted by institutions of higher education like universities and aim to facilitate interest in science. A key component of these learning offers is the hands-on experience which for STEM-subjects mainly means conducting experiments. While research has shown that OSL are able to foster situational interest and knowledge acquisition, the effects are rather small and in general do not last over a longer period of time. The integration of digital media and the provision of complexity-differentiated tasks could help promote motivation and aid knowledge acquisition while still staying true to the hands-on approach of the OSL. Therefore, a new method for digital and complexity-differentiated learning in the OSL was developed, implemented and tested. Our recent study focused on the investigation of complexity-differentiation while using this method for lab work in the OSL. One group used complexity-differentiated material based on a differentiation matrix (DM), while the other group was not aware of the complexity-differentiation in the material and conducted station learning (SL). The study was conducted with thirteen 8th grade classes (N=280), evaluating the influence on emotions, expectancy value motivation and knowledge acquisition. In addition, the choice of fields or stations was recorded. The results will be presented in this proposal and possible consequences for the use of likewise methods in the OSL will be shown.

Keywords: out-of-school student laboratories, digital advances, differentiation

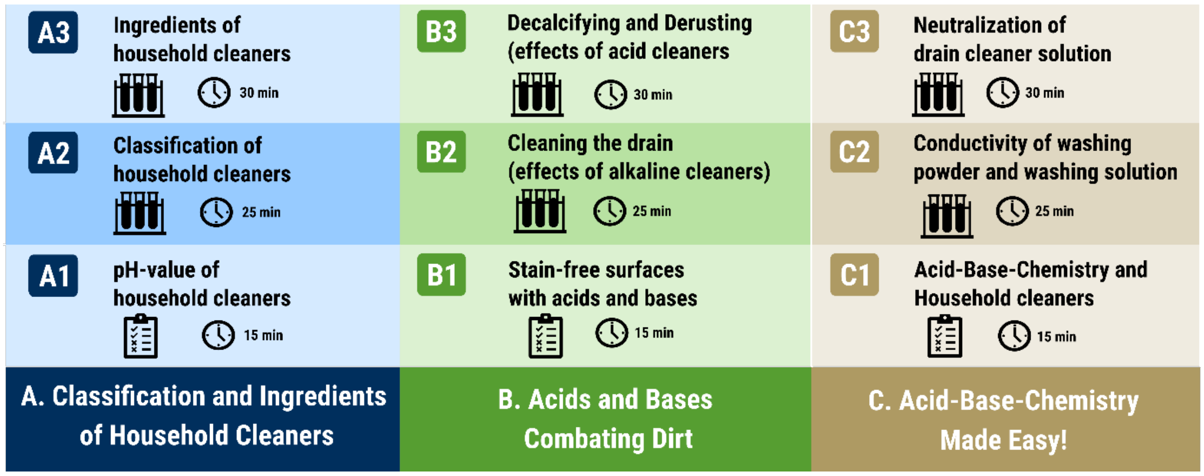
Introduction

Promoting interest in natural sciences is a primary goal of out-of-school student laboratories (OSL). By offering a stimulating and research-related program they aim to motivate students to engage with scientific content and pursue a career in STEM (Stamer et al., 2020). However, empirical studies on the promotion of interest in OSLs often show only short-term effects (Lewalter et al., 2021). One way to improve the effectiveness of OSL might be adapting the courses to different levels of complexity to appeal to more participants (Affeldt et al., 2015). This could be supported by using digital media while thereby increasing motivation and learning outcomes (Hillmayr et al., 2020). The following contribution presents a study that tests the effectiveness of a new method in the OSL combining these approaches: the use of digital and complexity-differentiated learning modules (DCDLM).

Theoretical Foundations

The basis of DCDLMs is a differentiation matrix (Sasse & Schulzeck, 2021), in which tasks are created according to thematic complexity in a horizontal direction and tasks according to cognitive complexity in a vertical direction. The supposedly easiest field is therefore at the bottom left of the matrix, the supposedly most difficult field at the top right. For our OSL we use a 3x3 matrix. In previous tests, this size has proven to be particularly suitable for a three-hour student lab, as a large part of the learning module can be viewed and worked on by students at this time (ter Horst et al., 2024). Two different types of tasks are used: experimental and theoretical fields (see Fig.1).

Figure 1. Differentiation matrix for the exemplary module "household detergents".



Multitouch Learning Books (Huwer et al., 2018) are used for our DCDLMs, which contain the differentiation matrix and the material used per field. The learning environment was designed according to principles of the Cognitive Theory of Multimedia Learning (Mayer & Fiorella, 2014) with the aim of minimising the extraneous cognitive load (Sweller et al., 2011). Learners receive feedback by comparing their answers with solutions and can determine their own approach in terms of content and time (Moreno & Mayer, 2007).

Theoretical Proposals

In addition to the implicit effects of the differentiation (e.g., learning aids) and digitalisation measures used (e.g., tablet as a learning companion), DCDLMs' primary intended effect is through transparent complexity differentiation. This enables students to make an initial assessment of the complexity of the task and, if desired, to adapt it to their self-perceived level of knowledge (Corbalan et al., 2011). The differentiation matrix also gives them an overview of all the tasks in the course, which can help them to bring structure to the topic. This should provide additional clues for the decision in favour of or against a task, potentially leading to better choices (Relan, 1995). By comparing them with solutions, they also receive feedback on their level of knowledge and can then adjust their learning path (Bennett, 2011). To analyse the effectiveness of the method, an exemplary module on the topic household detergents was evaluated.

Aims Of The Study

This study focuses on the complexity-differentiation of the DCDLMs and its potential effectiveness. Therefore, a distinction was made between two settings: one in which the learners are aware of the complexity- differentiation of the learning module (dDM) and one in which they were not (dSL). In a pre-post quasi-experiment, the effects of the learning design on emotions (joy, curiosity, boredom, frustration), expectancy value motivation (expectation of success, utility value) and influences on performance (subject-specific and topic-specific knowledge) were investigated, since we expected emotional-motivational and cognitive benefits from the described learning design. Finally, the choice of fields was exploratively analysed to draw conclusions about possible connections.

Hypothesis 1 (emotions): Both intervention groups show an increase in joy and curiosity (cur) from pre- to post-test and a decrease in boredom (bor) and frustration (fru). The intervention group dDM shows more positive changes in enjoyment and curiosity and more negative changes in boredom and frustration compared to the intervention group dSL.

Hypothesis 2 (expectancy value motivation): Both intervention groups show an increase in expectancy of success (ex) as well as utility value (uv) from pre- to post-test. The intervention group dDM shows a more positive change compared to the intervention group dSL.

Hypothesis 3 (performance): Performance increases in terms of subject-specific (ssk) and topic-specific knowledge (tsk) in both intervention groups. Compared to the dSL intervention group, the dDM intervention group shows a higher increase in knowledge from the pre-test to the post-test.

Research question: How does the choice of fields differ between the two intervention groups (dDM, dSL)?

Method

The study was conducted with thirteen school classes from five schools in Thuringia (N=280) from May to June 2023. In the following, for hypotheses H1-H3 (a), the results for changes across the student lab day are first reported using t-tests for dependent samples. Two complementary statistical methods were then used to test whether the changes in the groups differed from each other (H1-H3): (b) In the change score approach, the difference between pre- and post-scores (post minus pre) is predicted by group membership in a multiple regression (dDM=0 vs. dSL=1). (c) In the ANCOVA approach, the post-test value is predicted by the pre-test value and the group membership (dDM=0 vs. dSL=1). Parametric tests are used due to the respective group size. Table 1 lists the results for (a), (b) and (c). Finally, descriptive comparisons for the research question on field selection are presented.

Results

Looking at emotions, there was a significant increase in enjoyment and a decrease in boredom and frustration across both groups (a). However, the decrease in negative emotions was only significant for the dSL intervention group. Curiosity also only increased significantly in the dSL intervention group. Contrary to our hypothesis, the results for the direct group comparisons (b, c) consistently showed a significantly greater increase in curiosity in the dSL group.

When looking at expectancy value motivation, there was an increase in the expectation of success across both intervention groups, which was also significant for both. Contrary to our hypothesis, a significant decrease in utility value was observed across both groups, although this was only significant for the dDM intervention group (a). The results for the direct group comparisons (b, c) consistently showed, also contrary to our hypothesis, a significantly greater decrease in utility value in the dDM group.

The development of knowledge regarding acid-base chemistry (ssk) showed that it increased significantly both across both intervention groups and for each individual group. There was a significant increase in the development of knowledge regarding household detergents (tsk) across both intervention groups, although this was only significant for the dDM intervention group (a). The results for the direct group comparisons (analyses b and c) showed no group differences.

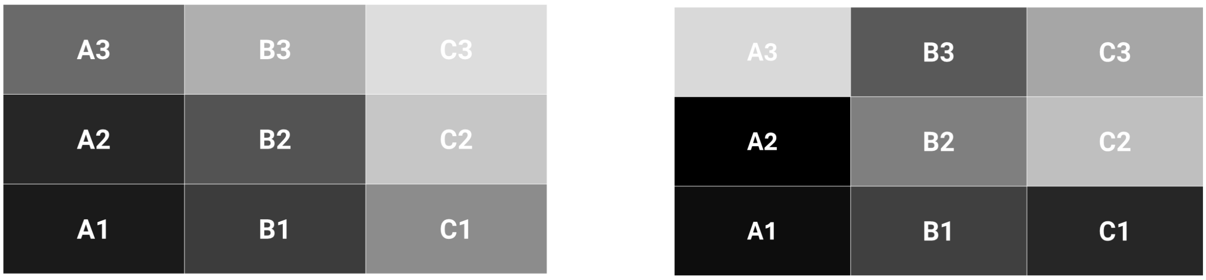
Differences between the two groups can also be described in the choice of fields. The number of fields selected in the dDM group is clearly shifted towards the easier fields. The choice of fields in the dSL group is more evenly distributed and shows a significantly higher proportion of the more difficult fields (Fig. 2).

Table 1. Results of analysis a), b) and c).

	a) t-tests								
construct	**overall**			**dDM**			**dSL**		
	t	*p*	*d*	*t*	*p*	*d*	*t*	*p*	*d*
Emotions (H1)									
Joy	4,37	**0,001**	0,28	2,06	**0,042**	*0,19*	4,9	**0,001**	0,4
Cur	1,14	0,256	0,06	-1,18	0,24	0,09	3,7	**0,001**	0,27
Fru	-2,08	**0,039**	0,13	-1,07	0,143	0,09	-2,03	**0,045**	0,18
Bor	-2,58	**0,01**	0,16	-1,23	0,221	0,11	-2,74	**0,007**	0,23
Expectancy value motivation (H2)									
Ex	5,59	**0,001**	0,5	3,67	**0,001**	0,32	4,6	**0,001**	0,38
Uv	-4,01	**0,001**	0,22	-4,87	**0,001**	0,32	-0,55	0,582	0,05
Performance (H3)									
Ssk	4,39	**0,001**	0,24	3,2	**0,002**	0,2	3,01	**0,003**	0,31
Tsk	3,29	**0,001**	0,26	3,07	**0,002**	0,32	1,39	0,169	0,16

construct	**b) Change-Score**		**c) ANCOVA**	
	β	*p*	*β*	*p*
Emotions (H1)				
Joy	0,104	0,088	0,04	0,491
Cur	0,183	**0,003**	0,12	**0,014**
Fru	-0,046	0,452	-0,004	0,934
Bor	-0,095	0,12	-0,02	0,716
Expectancy value motivation (H2)				
Ex	0,033	0,593	-0,034	0,523
Uv	0,136	**0,027**	0,101	**0,036**
Performance (H3)				
Ssk	0,067	0,288	-0,009	0,861
Tsk	-0,065	0,309	-0,087	0,158

Figure 2. Choice of fields for the dDM (right) and dSL group (left).



Discussion And Implications

The aim of the study was to test the complexity-differentiation of DCDLMs in the OSL for two varying settings. Despite positive results across both groups, the dSL group showed advantages over the dDM group, which is contrary to the hypotheses formulated at the beginning. The different field selection of the groups may offer an initial explanation for this.

The dSL group appears to benefit from the diversified choice of fields of varying complexity showing both affective and cognitive advantages. This may be due to a more interest-driven approach. Knowledge of the varying difficulty of the fields therefore seems to have a negative effect on the participants in the dDM group, as they generally choose unhelpful learning strategies (easier fields).

The reasons for this can be manifold: these include the reduction of effort costs (Flake et al., 2015), inadequate self-evaluations of the level of performance (e.g. due to a low ability self-concept) or difficulties in self-regulation, if the intention was to take the complexity into account. In the discussion at the conference the possibility of a higher cognitive load for the students with the new method was also discussed, due to their unfamiliarity with it.

Thus, there is a need to improve the choice of fields. More specifications could be made to encourage or obligate the students to include more difficult fields. Also, a more precise diagnosis of the level of knowledge could be made at the beginning. As positive results can be found in both intervention groups, the use of DCDLMs in the OSL appears to be potentially useful but requires adjustments to offer advantages over previous didactic concepts.

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How Citizen Science Can Support Teachers And Students In Engaging With Scientific Research: The Citizen Science School Rome Technopole

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Citizen Science can represent an informal and engaging learning method for both students and teachers to explore scientific research. At INFN Frascati National Laboratory we organized, in collaboration with European Citizen Science Association (ECSA), the European Citizen Science Academy and Citizen Science Italia, a Citizen Science School addressed to high school students, teachers, University students and researchers focused on Rome Technopole's research macro areas. The School allowed participants to work on real research projects that provided concrete results and fostered collaborative reflections on the usage of citizen science as an educational strategy.

Keywords: Citizen Science, STEM education, Project-based learning

Introduction

Informal and non-formal learning experiences have been shown to exert a highly positive impact on students, particularly in the context of STEM subjects (Hussim et al. 2024). While formal learning is a well-structured activity within educational institutions, informal learning takes place outside the school environment (Ayar, 2015) and provides unique opportunities to all learners because of the flexibility and ease of access to learning specific knowledge or skills (Jenson et al., 2023). This is even more true for Project-Based Learning (PjBL), where students experience and indulge in complex, real-world tasks, resulting in an idea, a product, or prototypes (Santhosh et al., 2023).

In this context, citizen science approach could represent a very valid ally. Although citizen science (CS) encompasses a wide range of activities and practices (Haklay et al., 2020), making it difficult to define it broadly (Haklay et al., 2021), it can be delineated as the involvement at various levels of the public in scientific investigation and data collection (SEEDS project, 2025) that has a genuine scientific outcome, such as new knowledge, conservation actions, or policy changes (ECSA, 2025a). CS is in fact a way of doing scientific research, that revolutionize the relationship between scientific community and citizens and responds to an Open Science approach, indicated as a priority by the European Commission (European Commission, 2025); in Italy, it has recently become an integral part of the National Plan for Open Science (MUR, 2025) of the National Research Program (PNR) 2021-2027 of the Italian Ministry of University and Research. In addition, CS has great potential for schools. By its very nature, it is perfectly in line with a Project-Based Learning, as it facilitates students' active participation and strengthens the connection between scientific exploration and their personal experiences; in addition, its methodology enhances critical thinking and experiential learning of the scientific method, while establishing meaningful ties with the research community through tangible projects. CS is also beneficial for teachers, who take a more engaged and rewarding role, moving away from the conventional model of knowledge transmission, and emerging as key drivers of change towards a contemporary and dynamic educational community (SEEDS project, 2025b)

For all these reasons, at INFN Frascati National Laboratory we decided to propose a citizen science initiative among the activities carried out by Rome Technopole project: a Citizen Science School addressed to high school students and teachers, university students and researchers. The school was designed to provide first-hand experience of citizen science, through the step-by-step development of real scientific research projects that exploit this methodology.

Methodology

Context And Setting

The Citizen Science School1 was organized at INFN Frascati National Laboratory within the Rome Technopole2 innovation ecosystem in collaboration with the European Citizen Science Association (ECSA), the European Citizen Science Academy and Citizen Science Italia (CSI).

As the largest Italian research center devoted to nuclear and subnuclear physics with accelerators and related applications, the Laboratory proved to be an ideal setting for the School. Its environment allowed participants to engage directly with a cutting-edge research hub that integrates a broad spectrum of disciplines—ranging from particle and theoretical physics to technological development and computational studies—and brings together professionals from both STEM and non-STEM backgrounds. Furthermore, the School drew significant advantage from the Laboratory's long-standing experience and recognized expertise in organizing educational and outreach initiatives aimed at schools and the broader public (Bertelli et al., 2023). The presence of dedicated rooms and facilities further contributed to creating an effective and welcoming learning atmosphere.

Rome Technopole is the Ecosystem of Innovation of Rome and the Lazio region, in central Italy, built among the NextGenerationEU plan and composed of territorial leaders of research and innovation and organized in a network of state and private universities, public research organizations, local authorities, highly qualified and internationally recognized private companies. Overall, it consists of 39 Founder Partners: 7 Universities in Lazio, 4 National Research Centers based in Lazio (CNR, ENEA, ISS, INFN), 2 small and medium-sized enterprises, 17 large companies and multinationals, 3 local institutions (Lazio Region, Municipality of Rome, Lazio Chambers of Commerce), 2 business associations that are members of Confindustria and INAIL, a nonprofit public entity. The core of the project is developed on three thematic areas: Energy Transition, Digital Transition and Health & Bio-Pharma.

Two additional organizations played a crucial role in the design and implementation of the School: the European Citizen Science Association (ECSA), whose primary objective is to support public participation in research across the natural sciences, social sciences, humanities, and the arts, and Citizen Science Italia (CSI), which is committed to ensuring that citizen science is recognized, promoted, and adequately funded and operates in Italy. Both organizations contributed with their expertise and experience in the field of citizen science to the realization of the School.

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[1] https://comedu.lnf.infn.it/citizen-science-school-rome-technopole-2025/

[2] https://www.rometechnopole.it/en/

Participants And Research Groups

The School was addressed to a mixed group of 25 people including high school students (16 years and older, attending the last two years of high school) and teachers from across Europe, university students from European universities, and researchers from Rome Technopole. The choice to target a diverse audience was mainly motivated by the need to simulate as realistically as possible the real case scenario of the citizen science approach, but also by the aim of testing our innovative educational approach with schools and, at the same time, evaluating its effect on scientific community. Participants were randomly selected among those who had applied for registration, considering gender balance and geographical diversity. In total, we involved 20 non-experts participants from 4 different countries (Finland, Italy, Serbia, Turkey): 5 teachers, 8 university students and 7 high school students. These participants were then joined by 5 Italian researchers from the Rome Technopole project, engaged through an open call to all Rome Technopole organization, and 5 citizen science experts of ECSA and CSI who acted as facilitators. During the School, participants worked in 5 groups of 4 people each, comprising at least one university student, one teacher and one high school student, plus researchers. Each group worked separately on a research topic.

The School's Research Projects

Since one of the fundamental ideas behind the School was to provide participants with direct, practical involvement in citizen science, we chose to engage them in authentic, ongoing scientific projects. The selection of research topics was determined by researchers from the Rome Technopole who participated in the initiative, as they corresponded to the main projects they were currently working on. Given the breadth and multidisciplinary nature of the Rome Technopole project, the final research themes were highly diverse and included: Antibiotic resistance; VR/AR/MR environments; Dentistry; Digital and physical spaces in prisons; Physics, energy, and sustainability.

Once the research areas had been defined, the second—and most delicate—phase in the School's design was devoted to addressing these topics through a citizen science approach. To this end, the researchers were invited to reflect, with the support of citizen science experts, on which elements of their studies could benefit from citizen involvement. They were asked to consider whether there were data or observations that citizens could provide, whether citizens might help extend the project's impact or disseminate it within their communities, but also, more broadly, how collaboration with the public could enrich their research perspectives.

Subsequently, the researchers began to outline a preliminary draft of a research program to be carried out during the School. It is important to emphasize that, unlike other outreach activities to which they had previously contributed, they were not asked to define what the participants *should do*. Instead, they were invited to identify the areas in which participants could *meaningfully contribute*—without specifying the activities to be carried out in a prescriptive manner. The intent was to leave ample room for participants to contribute not only to defining the research results, but also to the methodological approach.

The Realization Of The School

The Citizen Science School Rome Technopole was held from February 3 to 7, 2025, with activities running from 9:30 am to 6:00 pm. Given the School's ambition to design and set in motion five citizen science projects within this limited timeframe, the introductory phase was deliberately kept concise: it consisted of a brief overview of citizen science and of the five research areas. Then, the working groups were formed, based on participants' preferences, if any. From that moment on, the groups continued their work independently during parallel sessions, except for two scheduled plenary meetings held each day—one in the morning and one at the end of the day—to review the progress made, exchange reflections, and share emerging ideas, challenges, and experiences. As the days progressed and collective discussions unfolded, it became increasingly evident that the groups were encountering similar difficulties, regardless of their specific research focus. For example, all teams faced challenges in formulating their research question(s) and in defining an appropriate methodology to achieve their objectives. Equally clearly, it became apparent that these issues could be addressed with common solutions or approaches. Another aspect that emerged was that, just like in a real citizen science project, throughout the course of the School, all the actors involved were making different contributions and adopting different stances based on their individual needs, availability, personal dispositions, often stepping outside their typical professional role. Some teachers adopted a more passive role, allowing themselves to be guided; some students assumed leadership responsibilities and organized the work as if they were instructors; and some researchers collaborated closely with the groups, working alongside them throughout the activities and sometimes leaving their role as experts behind.

The final day of the week was devoted to the presentation of project outcomes by all groups, followed by a concluding discussion with the citizen science experts, who identified both the strengths of the work accomplished and areas with potential for further improvement. Each group succeeded in developing innovative strategies to initiate or enhance citizen engagement within their respective research contexts. In some cases, the proposed approaches focused on raising public awareness of specific issues or on collecting data of value to the researchers; in others, the groups formulated practical plans to guide the future evolution of their projects. In two cases, groups also managed to pilot their proposals with a small cohort of acquaintances, providing an initial test of feasibility.

Results

The specific outcomes achieved by each research group are presented in detail below, together with a brief description of the methodology used.

Research Line 1: Antibiotic Resistance

Lead Researcher: Silvia Cammarone, Department of Chemistry and Technologies of Drug, Sapienza University of Rome.

Aim. Raise public awareness and promote responsible antibiotic use by assessing citizens' knowledge, habits, and risk perceptions, and by creating pathways for sustained engagement.

Process and products. The group initially developed a survey aimed at evaluating citizens' knowledge of antibiotics and their use, as well as exploring their perceptions of the issue from both individual and collective perspectives. Then, the team expanded its vision into a larger engagement concept, "IGEA" (cItizen enGagement awarEness on Antibiotics) that included educational programs in schools, online seminars on correct antibiotic use, interactive games for children and a monitoring app concept that should allow users to record cases of infections, antibiotic use, and perceived treatment effectiveness, as well as send water samples to nearby laboratories to check for bacterial contamination.

Research Line 2: User Interfaces For VR/AR/MR Environments

Lead Researcher: Marco Raoul Marini, Department of Computer Science, Sapienza University of Rome.

Aim. Design innovative user-interface (UI) concepts for virtual, augmented, and mixed reality (VR/AR/MR) that enable intuitive, accessible interaction without traditional input devices.

Process and products. The group first analyzed the requirements of UIs in immersive environments and identified possible "hands-free" interaction strategies—such as voice commands, eye movements, gestures, and walking. They then developed prototypes illustrating how these interactions might function within a cooking scenario, with potential extensions to surgical and industrial contexts. As an additional product, the group drafted a survey to assess citizens' familiarity with VR/AR/MR technologies and to explore the situations in which users would be interested in adopting such interfaces.

Research Line 3: Dentistry

Lead Researcher: Lorenzo Arcuri, Department of Life Sciences, Health, and Health Professions, Link Campus University of Rome; Ilaria Cammarota, Department of Chemical Science and Technologies, University of Rome Tor Vergata.

Aim. Increase public awareness of proper home oral hygiene and assess the prevalence of effective practices.

Process and products. In the introductory phase, participants witnessed a self-inspection protocol demonstration for the oral cavity held by the researcher, who gave particular attention to identifying lesions or unusual characteristics of the oral mucosa. After familiarizing themselves with the procedure, they then collaborated on the development of clear informational materials—combining images and text—to make the protocol accessible to a broad audience. The group then designed an initial survey aimed at investigating individuals' habits and lifestyles related to oral hygiene, to be administered alongside the self-inspection instructions. A second questionnaire was subsequently drafted to evaluate the ease of performing the procedure and to record observations made by participants. Over the course of the week, the group also began collecting preliminary responses to the first questionnaire from their personal networks.

Research Line 4: Digital And Physical Spaces In Prisons

Lead Researcher: Serena Cataldo and Luca Mazzali, Department of History, Humanities and Society, University of Rome Tor Vergata.

Aim. Deepen the understanding of prison conditions and spatial organization, examine the transformative impact of educational programmes on prisoners, and develop innovative proposals to improve these environments.

Process and products. At the beginning of the week, the group had the exceptional opportunity to meet a former prisoner who underwent a profound personal transformation by obtaining a university degree while in prison. This meeting laid the groundwork for subsequent discussions with researchers, who shared their work on the functions and meanings of space within carceral environments. Based on these insights, the group decided to focus on designing a study space within prisons that could be used by prisoners and staff. To support this work, two complementary surveys were planned: a quantitative questionnaire for prisoners, to gather data on their study experiences, needs, and aspirations; and a qualitative questionnaire for prison police staff, in order to understand how to improve educational spaces without compromising security and surveillance requirements. As an additional outcome, the group also planned a follow-up phase involving university students to compare their experiences with those of prisoners and jointly design improved educational spaces in prisons.

Research Line 5: Physics, Energy And Sustainability

Lead Researcher: Giovanni Mazzitelli and Ruggero Ricci, INFN Frascati National Laboratory.

Aim. Reflect on the concept of sustainability, understand the physical and technological constraints underlying it, and explore its real-life applications.

Process and products. After an initial brainstorming session aimed at establishing a shared definition of sustainability and analyzing its environmental, social, and economic dimensions, the group examined the physical meaning of sustainability and energy, progressively developing a more technical vocabulary. The group therefore decided to focus on the 2030 Agenda for Sustainable Development and specifically on lighting in private and public spaces. To raise public awareness and collect real data, participants designed a prototype "sustainability calculator", a tool that compares the costs (energy consumption, monetary expense, and CO_2 emissions) of using incandescent or compact fluorescent lamps versus LEDs and includes estimates of production and disposal costs. As a further development, the group proposed targeted applications of the calculator by key stakeholders, such as teachers, students, and industries, alongside a study to assess its impact on these different groups.

Discussion And Conclusion

At the end of the School, the organizers implemented a simplified evaluation procedure aimed at gathering feedback and reflections. This process involved (a) informal discussions with participating students and researchers, (b) two structured questionnaires, one administered to researchers and one to participating students, and (c) a debriefing meeting within the organizing team to review the results and identify areas for improvement. From this evaluation process, several noteworthy aspects emerged.

Firstly, the School successfully achieved its primary goal of engaging participants in citizen science through an innovative and participatory approach to authentic scientific research projects. All participants, despite their varying levels of expertise and different perspectives, actively contributed to the development of the research and had the opportunity to experience first-hand every stage of the scientific process. Participants developed a clearer understanding of both the importance and complexity of dividing the scientific problem into sub-problems, defining research objectives and questions, selecting appropriate methodologies, and sharing tools and preliminary results. They also recognized that scientific inquiry is far from the linear and orderly process often described in textbooks. Instead, it unfolds as a non-linear and sometimes intricate trajectory, characterized by failed attempts, dead ends, and unexpected changes in direction. Within this process, unconventional or interdisciplinary approaches can occasionally lead to effective solutions. Furthermore, regarding citizen science, participants had the opportunity to develop and practice related skills in a stimulating environment that encouraged discussion and critical exchange. This context allowed them to explore firsthand the potential of citizen science both as an educational tool, particularly for teachers, and as a research methodology for the experts involved. Finally, in full accordance with the principles of citizen science, the School has also generated tangible benefits for the research projects themselves. In addition to increasing their visibility, the activities carried out during the School have led to the development of future-oriented roadmaps, some of which can be implemented immediately and have the potential to produce rapid and significant results.

Despite these highly positive elements, we are fully aware that the implementation of the school has also revealed several weaknesses, particularly regarding the lack of more quantitative measures of its impact. A future edition should therefore include a systematic investigation of how the School experience influences students' and teachers' understanding of science practice, as well as the extent to which teachers and researchers intend to integrate the citizen science approach into their teaching practices or research activities. Furthermore, an interesting direction for future development would be to establish mechanisms that ensure the continuity of projects initiated during the School, for example creating a lasting community of students, teachers, and researchers that could collaborate and promote further growth of the research projects.

Nevertheless, we believe that the Citizen Science School Rome Technopole represented an innovative and successful model, with a considerable potential for replication in a variety of other contexts.

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What Does It Take to "Use" a Museum? A Closer Look at Museum Literacy

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In recent decades, museums have undergone a profound transformation from authoritative repositories of knowledge to participatory spaces of exchange, learning, and social engagement. Increasingly positioned as trusted institutions and as so-called "third places," museums now address complex societal challenges, contribute to democratic education, and foster dialogue across diverse communities. Despite these developments, museum audiences remain socially uneven, with educationally and economically disadvantaged groups still significantly underrepresented. This paper argues that improving accessibility and participation requires not only institutional change but also a clearer understanding of how museums can actively support and enable visitors to engage meaningfully with their offerings. To address this gap, the article revisits and expands the concept of museum literacy, originally introduced by Carol Stapp, and develops a differentiated, holistic framework. Drawing on established literacy models from fields such as digital, media, and scientific literacy, museum literacy is sketched as a three-level construct: (1) awareness and basic knowledge of museums and their affordances, (2) the practical application of skills within museums, including socio-cultural and emotional dimensions, and (3) the transfer of museum content to personal and societal contexts beyond the visit itself. Based on a small mixed-method study involving museum professionals, eight key dimensions of museum literacy are identified, ranging from curiosity and motivation to information processing, emotional competence, and appreciation of exhibits. The findings highlight which dimensions are considered particularly relevant and which are perceived as influenceable by museums. The paper concludes that fostering museum literacy is central to strengthening museums' social role, enhancing visitor engagement, and supporting inclusive, reflective, and democratic cultural participation.

Keywords: Lifelong learning, Out-of-school learning, Science Museums

Introduction

The social role of museums has changed significantly in recent decades. Moving away from the traditional image of the museum as a temple of information and knowledge, many museums are reorienting themselves towards becoming places of exchange and participation for all people in our society, increasingly developing into so-called "third places". This role extends far beyond the simple provision of information. Museums are now actively addressing major societal challenges. For instance, natural history and science museums engage with issues such as climate change, biodiversity and energy supply, while museums of cultural history, archaeology o art explore topics including cultural diversity and cultural influences on society, social developments and transformation processes. Ate the same time, they critically examine issues such as looted art, colonialism and the repatriation of objects. In this expanded role, museums function as mediators between different parts of society: they connect history with politics, the economy, and contemporary social issues. They promote exchange between different cultures and groups, as well as dialogue between art, culture and society at large. Particularly significant is the increasing attribution of a role in democratic education. By providing spaces for critical reflection, dialog, and participation, museums contribute to the strengthening of democratic social structures. As a result, their range of functions is expanding considerably beyond their traditional tasks.

As informal learning environments, museums address people of all ages. They act as an interface between leisure activities and education, providing low-threshold, flexible opportunities for learning and fostering dialogue on social issues. Another important aspect is the high level of trust museums enjoy among the public – not only in Germany, but internationally (Wilkening, 2021; Grotz & Rahemipour, 2024). Alongside changes in museums' self-conception, reflected in the revised ICOM definition of a museum (ICOM, 2022), museums are increasingly gaining importance for local communities as so-called third places (Dauschek, 2022). Nevertheless, despite these developments, many museums continue to primarily attract academically educated audiences, while educationally and economically disadvantaged groups remain significantly underrepresented (Hooper-Greenhill, 2006; Thoma et al., 2022; Wegener, 2016).

In order to enhance the accessibility of museums and facilitate more effective use, access, and understanding of their offerings, a multifaceted approach is necessary considering both institutional conditions and visitor-related factors. On the institutional side, museums must create environment that are welcoming and accessible to all segments of society. This includes measures such as reducing entrance fees, fostering inclusive and organizational cultures, implementing broad and effective communication strategies, and diversifying content by incorporating a wider range of knowledge, achievements, and perspectives that reflect societal diversity. Equally important is ensuring that museum staff more closely mirrors the diversity of society itself, thereby promoting representation within the institution. From the visitor's perspective, it is essential that individuals feel confident and prepared to engage with museums. This includes being aware of available content, activities, and learning opportunities, as well as possessing strategies to navigate and meaningfully use of what museums offer. Such preparedness enhances both the relevance and the depth of the museum experience.

There is little doubt that museums are intended to function as inclusive spaces for public engagement and, by definition, should be accessible to all individuals regardless of background or prior knowledge (BVMP, 2024). However, the concept of "accessibility without prerequisites" warrants critical examination. For example, extensive explanatory texts are of limited value to individuals who cannot read, even when written in simplified language. Conversely, oversimplifying information to accommodate broader audiences inherently diminishes the richness of content provided to visitors who possess foundational knowledge, owing to spatial and attentional constraints. The central challenge for museums therefore lies in developing differentiated offerings that address the needs of diverse audiences while enabling meaningful engagement across demographic groups. Layered communication strategies offer one possible approach to reaching the broadest possible audience.

In this context, a conceptual framework that highlights relevant dimensions of engagement may be helpful – both to support a greater inclusivity by minimizing unnecessary prerequisites while enhancing offerings, and to strengthen visitor competencies and foundational skills that enable deeper and more comprehensive use of museum resources.

The term museum literacy was first introduced in 1984 by Carol Stapp, who defined it by analogy to the more established concepts of "computer literacy" and "library literacy":

> By analogy, basic museum literacy means competence in reading objects (visual literacy), but bill museum literacy signifies competence in drawing upon the museum's holdings and services purposefully and independently. Museum literacy therefore implies genuine and full visitor access to the museum by virtue of mastery of the language of museum objects and familiarity with the museum as an institution. In a word, the museum literate visitor is empowered. (Stapp, 1984)

Stapp also pointed out that, while the use of libraries and computers is commonly taught within school curricula, the use of museums generally is not. However, her work does not provide a detailed description or operationalization of museum literacy. Although later initiatives – such as the EU project "museum literacy" (Gazzeri & Brown, 2010) - offer illustrative examples, a comprehensive and clearly defined conceptual framework remains lacking.

Adopting a holistic perspective, this article seeks to capture the various facets of the construct of "museum literacy". Specifically, it asks: What are its core components, and can these components be differentiated in ways that allow them to be systematically addressed, fostered, and measured?

Approach And Definition Of Museum Literacy

Current research demonstrates that literacy is fundamentally shaped by the cultural, political, and historical contexts of the communities in which it develops. Literacy is not only embedded in language and society, it also exists along a continuum across multiple levels that ultimately reflect an individual's cultural identity. Bélisle (2006) distinguishes three complementary approaches to literacy: an autonomous model, which conceptualizes reading and writing as technical skills; a sociocultural model, which emphasizes that literacy is always socially and ideologically embedded; and a "strong claim model", which represents the most far-reaching perspective and is based on the innovative potential of structured thought processes, thereby enabling the creation of something fundamentally new.

In a recent article (Kampschulte et al, 2025), we analyzed literacy models across various domains, including digital literacy (Martin & Gruziecki, 2006; Iordache, Mariën & Baelden, 2017), media literacy (Trültzsch-Wijnen, 2020; De Smedt et al., 2009), AI literacy (Long & Magerko, 2020) or scientific literacy (Gräber et al., 2013; Fischler, Gebhard & Rehm, 2018; Henriksen & Frøyland, 2000). Across all of these models, an elemental composition of literacy is always apparent, literacy consistently comprises a) a body of (subject-specific) basic knowledge, b) the abilities and skills required to use and apply this knowledge – typically in conjunction with tools – , and c) the application of this knowledge in private and/or social life contexts. Building on these discussions and with a view to the interpretation commonly used in English-speaking countries, this project adopts a concept of literacy that draws particularly on the digital literacy definitions proposed by Martin and Gruziecki (2006) as well as Iordache, Mariën, and Baelden (2017):

> Museum literacy consists of three components that build on each other: the basis is the organizational and content level, an awareness of the existence of museums, and basic knowledge about the affordances of museums and how they can be utilized. The second level is characterized by the ability to practically apply specific knowledge and skills in museums, including socio-cultural and emotional dimensions (e.g., being able to experience suitable emotions). The third level is the ability to apply the museum content in different life contexts – inside and outside the museum. This includes personal added value and, for example, the ability to engage in current discourses and thus participate in society.

Together, these three components increase the likelihood that individuals will use museums and benefit from them as spaces for personal development, social interaction, and participation.

The explicit inclusion of socio-cultural and emotional dimensions represents a specific feature of museum literacy. These aspects are far more central to museums than to other literacy concepts such as digital, or scientific, or computer literacy being used by Carol Stapp in the original definition. At this level, museums open up completely different channels of communication that run parallel to learning processes. In principle, these channels can support learning, they are also crucial for achieving other visit objectives, such as social interaction during group visits or intense emotional experiences, for example when visiting memorial sites.

Study On Museum Literacy From A Museum Perspective

Table 1. Eight dimensions of museum literacy as found in the study.

	Dimension	Description
1	Curiosity, motivation, volition	Curiosity, motivation and the will to do something in the museum at all are the central basis for using a museum. Curiosity, especially intrinsic curiosity, is the desire to learn new things and discover hidden things. Motivation summarizes all motives that lead to a willingness to act. The deliberate, purposeful transformation of goals and motives into actions - and therefore results - is known as Volition. All three facets are closely linked to emotions and control the behavior in a museum.
2	Location and behavioral competence	This dimension encompasses the knowledge and skills needed to orient oneself in a museum in terms of time and space, to structure the visit and to behave appropriately in the location.
3	Information (processing) competence	The ability to use the information provided in a self-determined, confident and targeted manner.
4	Visual competence	The ability to interpret, evaluate and use information in the form of an image, sign or visual medium. Visual literacy is based on the idea that images can be "read" and that meaning can be discovered through this process of reading.
5	Prior knowledge and experience	This dimension includes both subject-specific knowledge and general prior knowledge that is relevant to the classification and understanding of the content offered, or experience that facilitates understanding.
6	Social competence	The ability and willingness to communicate and interact with other visitors or museum staff as appropriate to the situation.
7	Emotional competence	The ability to (correctly) perceive, understand and influence one's own and others' feelings. This includes emotional self-regulation in particular, but also the ability to allow emotions in the museum.
8	Appreciation of exhibits	Objects of cultural heritage are the basis of museums. Appreciation for these exhibits can arise in different ways (an object was selected for the museum vs. I know about the historical significance of the object) and increases the relevance for users.

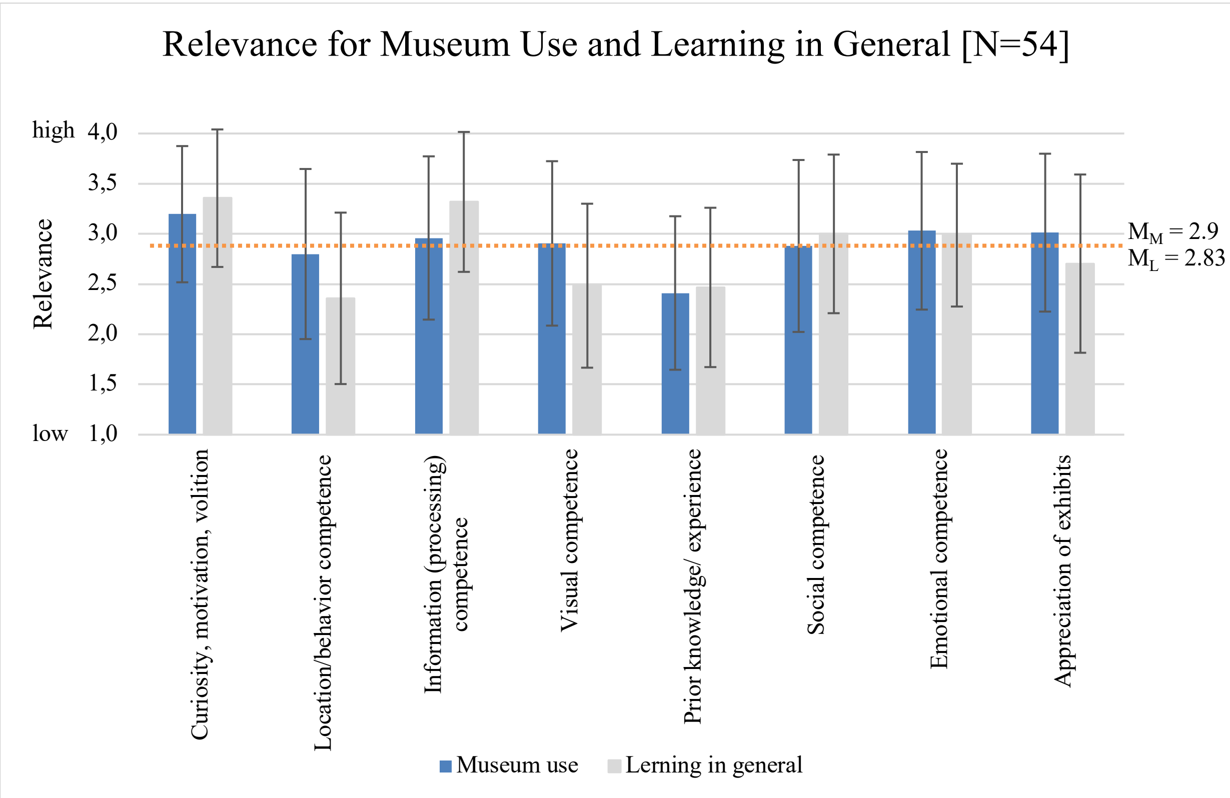
To gain a deeper understanding of the skills and prerequisites required of museum visitors for museum literacy, we conducted a study aimed to identifying the knowledge implicitly or explicitly embedded in museums: In a first step, approximately 25 museum professionals and educational researchers participated in a round table discussion to identify what they considered to be the most important skills and prerequisites. These were grouped into seven overarching topics and further refined through an iterative, anonymized online survey process. In a second step, the experiences and perspectives of 15 purposively selected museum experts were collected for each of the seven topics, summarized, and analyzed using a qualitative online format.

Dimensions Of Museum Literacy

The results of the quantitative survey of museum experts revealed in the end eight dimensions that are relevant to the use of museums:

In the third phase of the study, these eight dimensions were evaluated by a larger group of museum professionals. A total of 54 participants were presented with the eight dimensions identified in the first phase and asked to assess their relevance. The aim was to distinguish whether the dimensions were perceived as more museum-specific or more general. The aim was to find out which factors could be particularly influenced by museums, either by improving e.g. their offers or communication, or with the aim to develop targeted opportunities to develop e.g. knowledge or skills.

Figure 1. Evaluation of the eight dimensions of museum literacy by museum experts in terms of their relevance to museums specifically or their relevance to learning in general.



Overall, the average relevance ratings for museums and for learning in general are very similar (MM = 2.9 for museums; ML = 2.83 on a 1–5 Likert scale). Museum professionals rated prior knowledge and experience as the least relevant dimension for both contexts. For a meaningful “use” of museums, curiosity, motivation, and volition were considered most important, followed by emotional competence and appreciation of exhibits. The largest differences between museums and learning in general – apart from location and behavioral competence – were found in the dimension of visual literacy. Visual literacy was rated as moderately important for museum use but considerably less important for learning in general. Information (processing) competence showed the opposite pattern: it was rated as slightly above average in importance for museums, but as highly important for learning in general. These differences provide initial indications of which dimensions may be particularly promising starting points for further development on the museum side.

Discussion

Ultimately, all of these dimensions contribute to museum literacy and thus to a stimulating visitor experience. Of course, not all dimensions need to be fully developed in order to experience a good museum visit. Rather, they define a space of possibilities in which visitors can be situated. Which dimensions are activated, and to what extent, varies across museums, individuals, and visits. A six-year-old child, for example, will engage with different dimensions and with a different intensity than an adult who visits museums several times a month. Differences can also be observed within target groups: some visitors approach museums in a structured, knowledge-oriented manner, while others place greater emphasis on social or emotional dimensions.

Some of the dimensions outlined above are highly general in nature. Curiosity, motivation, and volition, for instance, play a role in most learning processes in everyday life. Other dimensions, by contrast, are highly museum-specific, such as location and behavioral skills. Given that the dimensions presented here were derived from a sample of museum professionals, they are strongly shaped by an institutional perspective. The next logical step is therefore to examine these dimensions from the visitors' perspective and to compare internal external viewpoints. Established evaluation models from other literacy domains can serve as a basis for this process and be adapted to the museum context.

In a changing social landscape, museums are widely regarded as trusted institutions, placings them in a strong position to act as independent and reliable sources of information. At the same time, this trust cannot be taken for granted, particularly as political influence on cultural institutions becomes increasingly visible. Museums therefore need to actively maintain and strengthen their credibility – by remaining spaces of enjoyment and inspiration, while also functioning as dependable sources of knowledge and as platforms for open dialogue and critical reflection.

The promotion of museum literacy plays a pivotal role in achieving these objectives. From an institutional perspective, it supports the development of more inclusive programs tailored to the needs of diverse audiences. From the visitors' perspective, individuals are supported in effectively accessing, understanding, and making use of the resources and experiences offered by museums. By bridging gaps in understanding and accessibility, museum literacy contributes to a more informed and interconnected society.

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A Scoping Review On Using Virtual Reality To Visit Informal Environments In Primary Science Education

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Virtual reality (VR) is progressively being explored as a means of facilitating access to informal learning environments in primary science education. These environments, such as museums, science centres, and natural settings, are widely recognised for supporting engagement, inquiry, and meaningful science learning, yet remain inaccessible to many schools due to logistical and financial constraints. This study presents a scoping review of literature published between 2014 and 2024 to map patterns and developments in the use of VR for visiting informal learning environments in primary science education, as well as to identify emerging challenges and opportunities. Guided by the Informal Science Learning framework, 25 empirical studies were systematically analysed. The preliminary findings indicate a growing emphasis on immersive virtual field trips using technologies such as 360-degree video and head-mounted displays to enhance learner engagement and inquiry-based learning. The review also highlights persistent challenges related to cost, technical infrastructure, health concerns, and teacher preparedness, alongside opportunities for improving accessibility and inclusivity in science learning. By synthesising current research, this scoping review provides an overview of how VR is being used to extend informal science learning opportunities for primary learners and identifies key considerations for educators, researchers, and technology developers.

Keywords: Out-of-School Learning, Primary Science Instruction, Virtual Reality

Introduction and Conceptual Framework

Virtual reality (VR) is increasingly being integrated into educational contexts, offering immersive and interactive learning experiences that extend beyond the constraints of traditional classroom-based instruction (Lopes et al., 2024). In primary science education, VR has attracted growing scholarly attention for its potential to simulate access to informal learning environments such as virtual museums, science parks, zoos, and natural ecosystems (Han, 2021). Through these virtual experiences, learners can explore scientific phenomena and contexts that may be geographically distant, logistically inaccessible, or financially prohibitive, thereby addressing persistent barriers related to cost, safety, and time constraints in school-based science learning (Han, 2021; Lopes et al., 2024).

Research suggests that VR-supported learning can enhance learner engagement, conceptual understanding, and motivation by enabling experiential and inquiry-oriented approaches to science education (Won et al., 2023; Xie & Zhang, 2024). The affordances of VR allow learners to observe dynamic processes, manipulate variables, and interact with representations of complex scientific concepts that are difficult to visualise through textbooks or static media alone (Han, 2021). These features are particularly valuable when VR is used to replicate informal learning environments, where exploration, curiosity, and learner-driven inquiry are central to knowledge construction and the development of critical thinking skills (Won et al., 2023).

Considering its pedagogical potential, the integration of VR into primary science education is accompanied by notable challenges. Studies have reported barriers related to hardware costs, technical infrastructure, limited teacher training, and concerns about learner well-being, including cognitive overload and motion sickness (Barrett et al., 2023; Han, 2021; Mohale, 2024). At the same time, VR presents important opportunities to support inclusive and equitable learning by accommodating diverse learning needs, providing multimodal representations, and broadening access to high-quality informal science experiences that may otherwise remain unavailable to many learners (Lampropoulos & Kinshuk, 2024; Lopes et al., 2024).

To synthesise and make sense of this growing body of literature, this scoping review is guided by the Informal Science Learning (ISL) framework as articulated by the National Research Council (2009). The ISL framework conceptualises learning as a socially mediated, interest-driven process that occurs across diverse contexts beyond formal classrooms, including museums, science centres, outdoor spaces, and digitally mediated environments (National Research Council, 2009). It emphasises key dimensions such as learner engagement, meaning-making, participation in scientific practices, and the role of learning environments and tools (Photo & Shabalala, 2025). Framing this review through the ISL lens enables a systematic mapping of how VR has been used to facilitate access to informal science learning environments in primary education, while also illuminating the patterns, developments, challenges, and opportunities that have emerged in this field between 2014 and 2024. Guided by the Informal Science Learning framework, this scoping review addresses the following research questions:

1. What patterns and developments are evident in the use of virtual reality to facilitate access to informal learning environments in primary science education between 2014 and 2024?
2. What challenges and opportunities have emerged in using virtual reality for informal learning environments in primary science education during this period?

Methods

This scoping review employed a systematic methodology to gain an in-depth understanding of previous research on the use of VR to facilitate access to informal learning environments in primary science education and to identify gaps for further exploration. Following the framework proposed by Gough (2017), the review was guided by clear research questions. It included systematic activities such as the identification of relevant research, study selection, screening, synthesis, and the formulation of evidence-based claims. The focus was on publications released between 1 January 2014 and 31 December 2024, providing perceptions on how the field has evolved over this period.

Study Selection And Screening

Study Identification

This scoping review followed PRISMA principles (Liberati et al., 2009). The initial search was conducted using EBSCOhost and included databases such as Academic Search Premier, Education Source, and Applied Science & Technology Source. The search terms incorporated variations of "virtual reality," "informal environments," "primary science education," and related keywords such as "outdoor learning," "field trip," "nature reserve," "science park," and "natural environment" to capture the range of contexts in which virtual reality is implemented. The review focused on studies published between 2014 and 2024, reflecting recent advancements in VR technology and its applications in education. The initial search yielded 389 articles, and after the removal of 154 duplicates, 235 studies entered the screening phase for further evaluation (see Figure 1).

Manual Screening

Following the initial identification of 235 articles, a manual screening process was conducted. Articles were included if they (1) focused on virtual reality technologies in informal learning environments, (2) pertained to primary science education, and (3) were peer-reviewed empirical studies. Non-peer-reviewed articles, unrelated fields, and incomplete records were excluded.

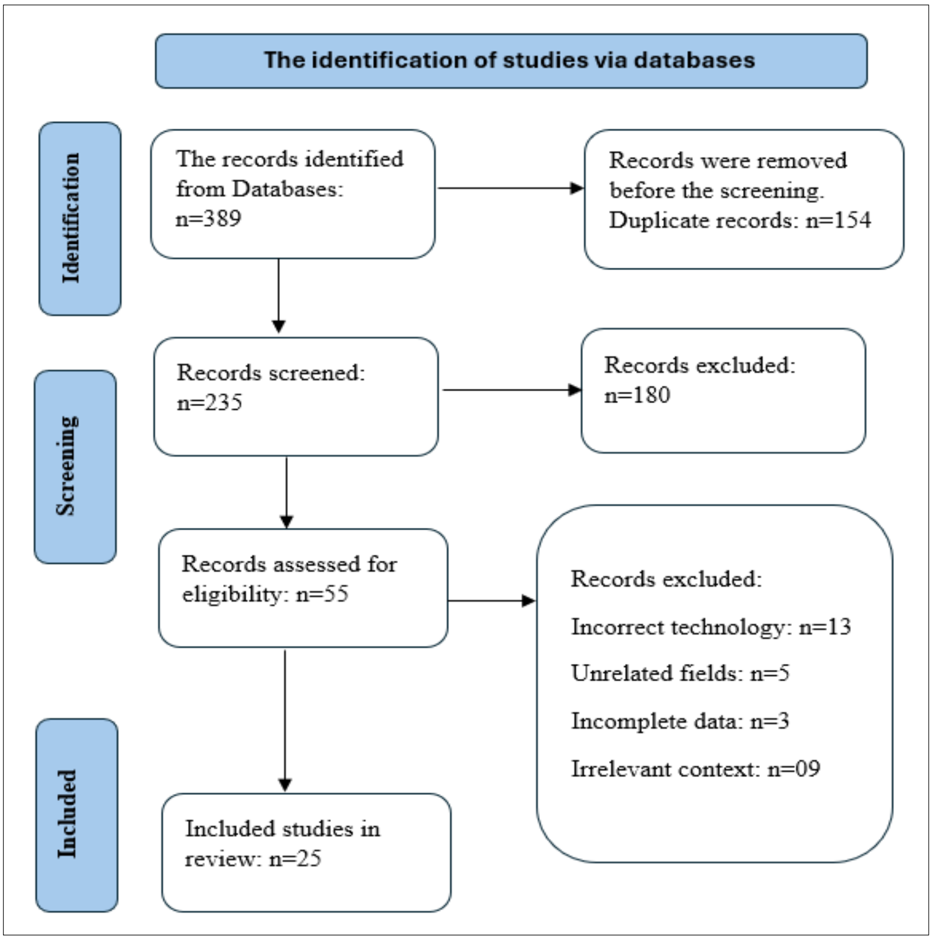
Eligibility

The first author conducted the full-text screening of the remaining 55 studies. Only studies written in English, peer-reviewed, and published between 2014 and 2024 were included. Based on the eligibility criteria, 30 studies were excluded: 13 for incorrect technology (Calvert & Abadia, 2020), 5 for unrelated fields (Goff et al., 2018), 3 for incomplete data, and 9 for irrelevant context (Huang et al., 2019). After the full-text review, 25 studies were included in the final analysis.

Data Extraction

Study characteristics were extracted and coded to address the research questions. The coding process was conducted inductively by the first author and verified for consistency. Each study was analysed for its purpose, framework, participant population, type of VR used, informal learning environment context, methodology, setting, and reported challenges and opportunities.

Figure 1: PRISMA Flow Chart (Liberati et al., 2009)



Preliminary Results And Discussion

Following a systematic scoping review process, 25 studies examining the use of virtual reality (VR) to facilitate access to informal learning environments in primary science education were identified and analysed. These studies, published between 2014 and 2024, reflect a steady growth in scholarly interest in VR as a means of extending science learning beyond the formal classroom into digitally mediated informal contexts. Consistent with the aims of a scoping review, the findings focus on mapping key patterns, developments, challenges, and opportunities rather than evaluating the effectiveness of interventions.

RQ1: What Patterns And Developments Are Evident In The Use Of Virtual Reality To Facilitate Access To Informal Learning Environments In Primary Science Education Between 2014 And 2024?

Emergence Of Immersive Virtual Field Trips (Vfts)

A prominent development across the reviewed literature is the widespread adoption of immersive virtual field trips (VFTs) as a primary application of VR in informal science learning. Many studies reported the use of VR to simulate visits to museums, science centres, natural habitats, and geographically remote environments. Han (2020) demonstrated that VR-supported VFTs effectively addressed logistical and financial barriers associated with traditional field trips, while still providing learners with meaningful experiential learning opportunities. Technologies such as 360-degree videos and head-mounted displays (HMDs) were commonly employed to enhance learners' sense of presence and immersion, which studies associated with increased engagement and curiosity (Cheng, 2022; Garcia et al., 2023).

Beyond access, several studies indicated a shift towards designing VFTs that support exploration and inquiry, allowing learners to navigate environments, observe scientific phenomena, and interact with contextualised content. This trend reflects a broader movement toward experiential and learner-centred approaches in primary science education, aligning closely with the principles of informal science learning.

Addressing Accessibility And Inclusivity

Another notable pattern concerns the use of VR to promote accessibility and inclusivity in primary science education. Multiple studies highlighted VR as a practical alternative for schools facing financial, geographical, or safety-related constraints that limit participation in physical field trips. Garcia et al. (2023) reported that VFTs offered scalable solutions for under-resourced schools, while Cheng (2022) emphasised the value of localised and culturally relevant VR content in making science learning more meaningful for diverse learner populations. Collectively, these findings suggest that VR-mediated informal learning environments can contribute to more equitable access to high-quality science experiences.

RQ2: What Challenges And Opportunities Have Emerged In Using Virtual Reality For Informal Learning Environments In Primary Science Education During This Period?

Technical And Pedagogical Barriers

Regardless of the documented benefits, the reviewed studies consistently identified technical and pedagogical barriers to the effective use of VR. Health-related concerns, including motion sickness, eye strain, and physical discomfort, were frequently reported as limitations affecting sustained learner engagement (Han, 2020). In addition, the cost of VR hardware and supporting infrastructure remains a significant obstacle, particularly for schools with limited budgets (Liu et al., 2020). From a pedagogical perspective, several studies pointed to challenges related to curriculum alignment and insufficient teacher preparation. Ramsurrun et al. (2024) noted that teachers often lacked the confidence and professional support required to integrate VR meaningfully into science learning activities, highlighting the need for targeted professional development.

Fostering Engagement And Inquiry-Based Learning

At the same time, the literature reveals substantial opportunities for VR to enhance informal science learning through engagement and inquiry-based approaches. Klippel et al. (2020) demonstrated that relatively low-cost VR solutions, such as 360-degree environments, can still provide immersive and interactive experiences that support exploration and critical thinking.

Several studies emphasised that VR environments encourage learner curiosity, sustained attention, and active participation, particularly when aligned with inquiry-oriented tasks. These opportunities position VR as a promising tool for enriching informal science learning experiences in primary education when implementation challenges are adequately addressed. Table 1 provides a consolidated overview of the key patterns, challenges, and opportunities identified across the 25 studies included in this scoping review.

Table 1: Summary of Key Patterns, Challenges, and Opportunities Identified

Focus Area	Key Findings from Reviewed Studies
Dominant VR Application	Immersive virtual field trips simulating museums, natural environments, and science centres
Technologies Used	360-degree videos, head-mounted displays, and interactive VR environments
Educational Purpose	Enhancing access, engagement, exploration, and inquiry-based learning
Accessibility & Equity	Reduced logistical and financial barriers; scalable alternatives to physical field trips
Technical Challenges	Hardware costs, motion sickness, and infrastructure limitations
Pedagogical Challenges	Curriculum integration difficulties, limited teacher preparedness
Key Opportunities	Increased learner engagement, inquiry-based learning, and exposure to otherwise inaccessible environments

Practical Implications

The preliminary findings of this scoping review suggest that virtual reality has considerable potential to enhance learner engagement and support inquiry-based learning in primary science education by facilitating access to informal learning environments. For teachers, these initial insights indicate the value of incorporating VR-supported virtual field trips and exploratory activities into lesson design to stimulate curiosity, observation, and conceptual understanding, particularly in contexts where physical access to informal science settings is constrained. For researchers, the findings highlight the need for further empirical work that examines scalable and sustainable implementation models, with particular attention to challenges related to cost, infrastructure, and learner well-being. From a development and policy perspective, the preliminary evidence points to the importance of designing affordable, portable, and curriculum-aligned VR tools that are responsive to the realities of resource-limited school contexts, thereby supporting more equitable access to informal science learning opportunities.

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EUROPEAN SCIENCE EDUCATION RESEARCH ASSOCIATION ESERA 2025 Copenhagen

Gaining Insight Into Rural, Underserved Students' Experiences Of At-Home, Justice-Centered STEM Kits And Books

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Out-of-school activities have the potential to broaden participation in STEM, especially for groups with less access to school-based opportunities. In this exploratory, mixed-methods study, at-home STEM kits were mailed to rural middle school students to address inequities in STEM access. The kits included nonfiction trade books featuring the stories of underrepresented minority STEM professionals and content-aligned STEM kits. The quasi-experimental design used repeated measures over four sets of mailed-home STEM kits to gauge students' responses to generic prompts (control) compared to those that addressed social justice constructs (intervention). Morales-Doyle's justice-centered science pedagogy framework was adapted as Justice-centered STEM Framework (JCSF) and guided the data analyses. The research question was: How did students respond to the at-home intervention, and were there differences between the intervention group and the control group? Findings indicate that the at-home STEM kits led to similar responses between both student groups. Overall, the analyses revealed how these students operationalized salient aspects of the JCSF around critical consciousness, academic success, and cultural competence. Within these three elements, themes were coded that highlighted students' perceived reactions: STEM identity, self-efficacy, authentic STEM, enjoyable/engaging, learning, familial sharing, quality materials, learning, awareness, and inspiring. Implications and lessons learned are discussed.

Keywords: social justice, STEM kits, trade books

Introduction

In the Spring of 2020, many teachers had to switch from in-person, synchronous teaching to remote, asynchronous classrooms overnight (Sun et al., 2020) as a result of the global pandemic. Many schools in the United States (U.S.) did not return to in-person instruction in the 2021-2022 school year following the initial impact of COVID. In addition to in-school impacts, the pandemic impacted after-school activities, which were suspended almost immediately (Moody, 2020) and were slow to return in many parts of the U.S.

One promising way to address this programming shortfall was through at-home interventions. In prior research, students and their family members had received high-quality STEM materials at home, which they completed with family members they found highly engaging (Gutierrez et al., 2025). However, sending home materials necessarily involves family members, who may be unclear about their role (Garcia-Reid, 2007; Hill & Torres, 2010; LaRocque et al., 2011). In addition, parents of children in educational systems that have underserved students, from lower socioeconomic (SES) homes, and who are racial/ethnic minorities are often distrustful of school systems (Hill, 2011). Multicultural literature can assist these students in their identity formation (Hseu & Hetzel, 2000), giving them a sense of belonging and acceptance in society. This study aimed to engage rural middle school students in the southeastern U.S. with an at-home intervention that included a hands-on STEM kit and a related trade book featuring multicultural characters, and to investigate whether social justice-oriented prompts affected their perceptions of these STEM materials.

Literature Review

Science Trade Books

Science trade books are important curriculum materials that can be used in K-12 science classrooms to strengthen students' literacy skills, assist students in learning science content, and ultimately increase participation in the STEM workforce (NSF, n.d.). In 1973, the National Science Teaching Association (NSTA), in cooperation with the Children's Book Council (CBC), created the Outstanding Science Trade Books for Children, a list of recommended trade books (NSTA, n.d.). Some criteria for selection include books that contain clear, up-to-date science content that is not oversimplified. Also, the books are free of gender, ethnic, and socio-economic biases; they are at the appropriate level for the audience and contain illustrations that are accurate in size, scale, and color (Texley, 2008). The science trade books provide opportunities for students to learn science practices (Texley & Ruud, 2017).

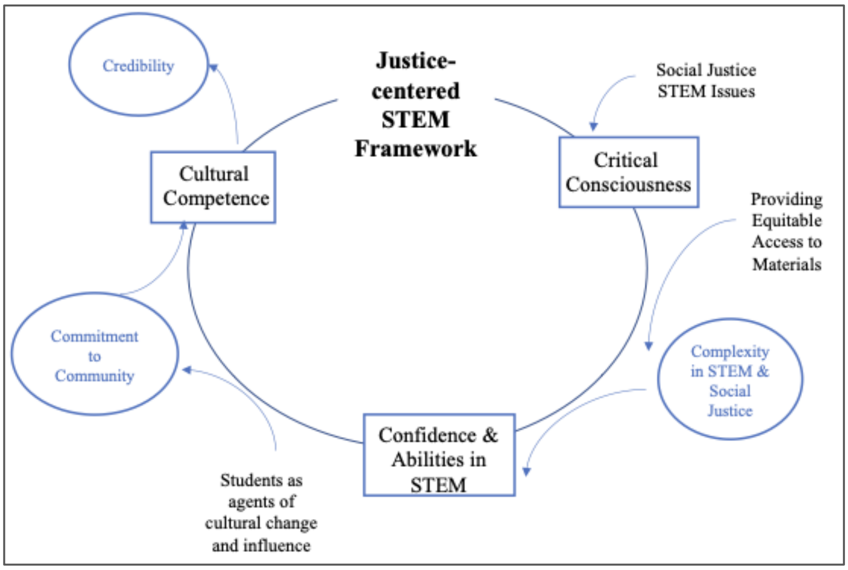
STEM Kits

Prior research has shown that students prefer learning science through activities with kits rather than just using textbooks (Houston et al., 2008). Analyzing qualitative and quantitative data from 588 elementary students (grades 3-5), Houston and colleagues discovered that using science kits was associated with more effective science instruction in terms of greater student satisfaction. In informal STEM settings, such as after-school programs and STEM camps, the use of STEM kits can broaden the participation in STEM of underrepresented groups (Newton et al., 2020).

Theoretical Framework

Justice-centered science pedagogy (Morales-Doyle, 2017; Figure 1) is a framework built on culturally relevant and critical pedagogy to address inequities in science education and potentially lead to social transformation. Drawing upon prior work (Ladson-Billings, 1995), culturally relevant pedagogy requires students to 1) experience academic success, 2) develop cultural competence, and 3) develop critical consciousness, challenging the current social order. The third criterion relates to Freire's work with critical pedagogy, emphasizing *conscientizacao*, a process by which people begin to view themselves as capable of eliminating oppression by transforming reality (Freire, 2020, 2021a, 2021b; Freire & Macedo, 2005). People develop a critical consciousness from education that elucidates the historical and political conditions that created inequitable social circumstances.

Figure 1. Justice-centered STEM Framework (modified from Morales-Doyle, 2017).



Research Design

This study used a convergent mixed methods design (Creswell & Plano Clark, 2018). The study collected repeated measures from students from five middle schools over six months to assess whether there would be differences in perceptions of justice-oriented constructs (e.g., critical consciousness, commitment to community) depending on whether they were responding to a neutral (control) or a justice-oriented prompt (intervention). Students received up to four STEM kits and justice-oriented trade books. Two of the five schools were randomly assigned to receive justice-oriented question prompts, while the remaining three schools received neutral question prompts for the STEM kits and trade books. Surveys included quantitative data from 6-point Likert-scale items and a qualitative open-ended question. The quantitative and qualitative data were collected simultaneously but analyzed separately, and the results were merged to address the third research question (Creswell & Plano Clark, 2018).

Research Questions

This study sought to understand how students participated in and responded to social justice-oriented trade books and STEM kits mailed to their homes during COVID-19.

1. How did the participation compare between students who received neutral (control) prompts and those who received social justice-oriented prompts (intervention)?

2. How did survey responses compare between students in the control and the intervention groups?

3. How did students describe what they gained from their experiences, and did they differ by group?

4. How do the qualitative themes map onto the justice-centered STEM framework?

Methods

Project Design

This project aimed to promote meaningful student and parent discussions around diversity, equity, and inclusion in STEM by increasing their awareness of, interest in, and positive perceptions of STEM professionals, fields, and careers. Built on pilot work conducted with rural middle school students (Blanchard et al., 2023; Gutierrez et al., 2025), this innovative project extended academic activities into the home by mailing home an interesting and challenging multicultural, nonfiction trade book with a STEM kit for at-home STEM-related investigations and reading.

Rationale For Materials Selected

The books were selected to highlight individuals who are traditionally underrepresented in STEM fields, to serve as role models (Table 1). The featured individuals revealed aspects of their lives, their character, and their choices, and highlighted adversities they may have faced. Two African American Females and Two Males (one African American and one Hispanic) were the subjects of the selected non-fiction historical trade books. For this study, all four books had these six common characteristics: 1) contained a simplified version of a story, 2) demonstrated a non-stereotypical appearance of a scientist, mathematician, or engineer, 3) were age-appropriate, 4) focused on the process of science, math, or engineering (struggles and perseverance) in contrast to science, math, or engineering as a miraculous event, 5) contained accurate information, and 6) had colorful illustrations (Delgado, 2021; Kibler & Chapman, 2019). Kiwi Crate Kits (Kiwico, 2022) were selected based on their quality, success, affordability, and ability to be mailed. As seen in Table 1, the book and STEM kits were paired on a related topic.

Table 1. Kit-book sets.

Kit	Book	STEM Kit
1	*Counting on Katherine* by Helaine Becker	Bottle Rocket
2	*The Boy Who Harnessed the Wind* by William Kamkwamb	Hand Crank Flashlight
3	*Seeds of Change* by Jen Cullerton Johnson	Drip Irrigation
4	*Esquivel! Space-Age Sound Artist* by Susan Wood	Light Up Speaker

Research Context

Five middle schools in the southeastern U.S. (partners in a STEM club project) agreed that kits could be mailed to their students' homes. All participating schools were classified as Title I, a U.S. federal education program that provides additional funding to schools with a majority of low-income students (Elementary and Secondary Education Act, 2015). The majority of the students (86% to 95%) identified as underrepresented minorities (URM), and 98% of the students at three of the participating schools qualified for free or reduced-price lunch (School Digger, 2022). Historically, end-of-grade test scores were significantly below those of their state (except for one school).

Participant Recruitment & Participation

The school's science teachers and academic coaches invited approximately 30 students from each of the five middle schools, grades 5th-8th, to participate in the project. Students received welcome letters with QR codes and a web link to a Qualtrics survey to sign up to participate in the project. Kits were mailed to the students' specified guardian, or (if requested) mailed to the student's school, to then be taken home by the student. A liaison teacher at each school encouraged students to participate.

Each kit and book had an associated survey that students could access through a web link or a QR code, to take after completing both the kit and the book. Once students completed both surveys, they were mailed the following kit and book. Students could receive up to four packages, each with a STEM kit and a related book. Due to lower-than-expected student enrollment, teachers at four schools received a classroom set of kits and books to share with their students approximately halfway through the Spring semester. One school incorporated the kits into its after-school STEM Club program and included a total of three kits in its club activities. A spike in survey responses on one date suggests that these kits and books were done during a club meeting, but otherwise, no data were collected that could verify the location of the reading and kit activities. Reminder postcards were mailed to students approximately two weeks after each kit/book mailing to encourage student participation.

Survey

The survey prompts were developed by the first and second authors, based on constructs of the modified Morales-Doyle framework (2017). Before distribution, the survey items were shared with other science educators (i.e., faculty, graduate students) and middle school students to provide face and content validity for the items (Sartori & Pasini, 2007). Through Qualtrics, survey questions utilized a 6-point Likert scale, with 1 represented *Completely disagree*, while 6 reflected *Completely agree*.

The students from two randomly selected schools received neutral survey prompts as a control group, reflecting activity completion and comprehension. As an intervention group, students from the other three schools received prompts informed by Morales-Doyle's justice-centered science pedagogy framework (2017; Table 2).

Table 2. Book and kit survey questions.

	Neutral Survey Items	Justice-Oriented Survey Items	Justice-Oriented Construct
Book 1	The main character faced opposition or challenges in the story.	Sometimes doing what is right, or ethical, is difficult.	Critical Consciousness
Book 2	The main character was very successful.	Others in the community were impacted by the abilities of the main character.	Commitment to Community
Book 3	The main character became well known.	The main character was committed to making their community a better place.	Commitment to Community
Book 4	This story made me think that the lead character was pretty special.	This story made me believe that if I wanted to, I could become a mathematician [varies by book].	Confidence & Ability in STEM
Book 5	People who impact the community are important.	This story made me believe I can impact my community in a positive way.	Commitment to Community
Book 6	I read all of the book.	I read all of the book.	Equitable Access to Materials
Book 7	I shared the book with a friend or a family member.	I shared the book with a friend or a family member.	Commitment to Community
Book 8	This was a biography, a story about someone's life.	This book is an example of how science [varies by book] can change the culture or habits of one's community.	Cultural Competence
Kit 1	I enjoyed working on the kit.	Working on the kit made me feel like I could overcome other challenges that I face.	Critical Consciousness
Kit 2	After doing this kit, I am looking forward to the next one.	After doing this kit, I gained confidence in my abilities in STEM.	Confidence & Abilities in STEM
Kit 3	This kit made me feel capable.	I think I could do some things in STEM that could improve my community.	Commitment to Community
Kit 4	I completed all of the kit.	I completed all of the kit.	Equitable Access to Materials

Open Response Coding

An inductive process was used to identify the themes from the open response items. Two coders read through all the comments and identified possible themes. Common themes that emerged from the statements about the kits included: STEM identity, self-efficacy, authentic STEM, enjoyable/engaging, learning, and familial sharing. Statements for the books repeated several previous themes, including enjoyment/engagement, learning, familial sharing, and self-efficacy. New themes also emerged, such as awareness, quality materials, and inspiring. After the codes were determined, one of the coders read through the statements and broke them into discrete units to delineate coding segments, a process referred to as unitization (Campbell et al., 2013). After the statements were segmented, the two coders independently assigned codes. After all items were coded, the codes were compared between the co-coders. A rate of 90% agreement was calculated for interrater reliability. Disagreements were then discussed until 100% agreement was reached for all statements (Patton, 2015).

Analyses and Findings

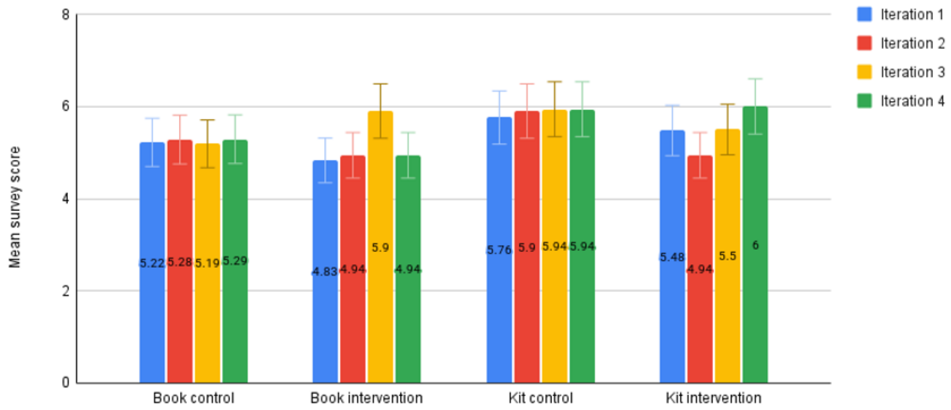
RQ1: Project Participation And Attrition

The project participants ($N = 110$) for both groups primarily self-identified as URM. The neutral group was more likely to be female (58%) and enrolled in 6th grade (44%). The justice-oriented group was more likely to be male (54%) and in 7th grade (71%). Comparing the survey completion rate of books to kits, students completed more kits across all interactions, except for the justice-oriented group in the fourth iteration, after the kits were mailed to teachers. The neutral group participated more throughout the project than the justice-oriented group, except for trade book 3 (*Seeds of Change*) and trade book 4 (*Esquivel! Space-Age Sound Artist*).

RQ2: Quantitative Analysis: Students' Responses To Justice-Oriented Survey Items

Kit scores were higher than trade book scores on the justice-centered survey constructs, except for Kit 2, Intervention. All scores were considered high as values represented *mostly agree (5)* or *completely agree (6)*. Mean scores for the surveys increased across the iterations. Trade book means were lower than kit means. The justice-oriented means were lower than the neutral means for most data points, though the values differed only slightly in both conditions. The greatest difference between neutral (M=5.90) and justice-oriented (M= 4.94) survey means occurred with Kit 2, with a difference of 0.96 points. Statistical tests were conducted through t-tests, but no statistically significant relationships were found (Figure 2).

Figure 2. Book and Kit Survey Means.



RQ3: Qualitative Analysis: Themes From Open-Response Items

Both groups of students wrote positive comments toward the books and kits, and their responses aligned with the social justice concepts within the books, regardless of their group. The common themes that emerged from the statements included: STEM identity, self-efficacy, authentic STEM, enjoyable/engaging, learning, and familial sharing (Table 3). New themes that emerged with the book included awareness, quality materials, and inspiring.

Table 3. A Priori Codes in Open-response Analysis.

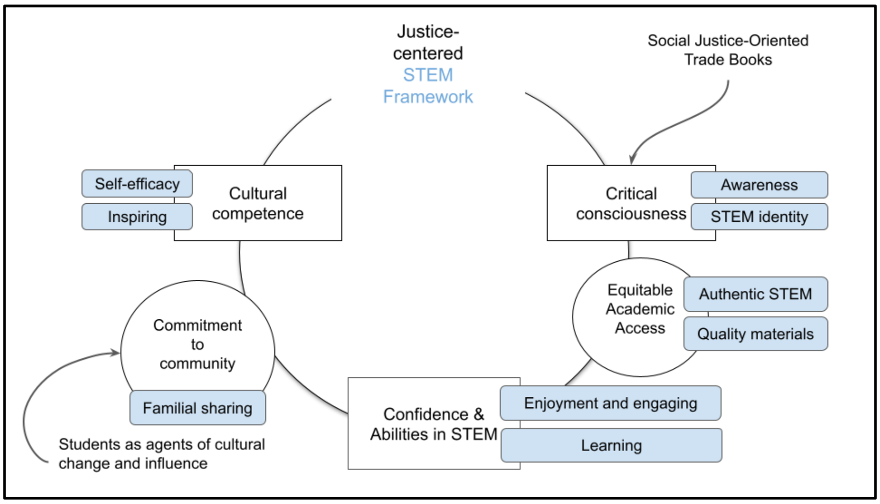
Code	Definition	Exemplar Statements
Learning	Learning new information or about STEM concepts.	***…****it tells about the environment and how we are hurting it.* (*Seeds of Change*, 8th grade, Hispanic Female)
Self-efficacy	Students expressed motivation to do something, take action, especially within their community.	*…the book was great…****to think how to make a change in the world.*** (*The Boy Who Harnessed the Wind*, 8th grade, Hispanic Female)
Enjoyable & Engaging	Fun or engaging experience in completing the activity/reading the book.	*Working on the STEM kit I thought it was very fun and creative.* (Bottle Rocket, 8th grade, Black Female)
Authentic STEM	When students spoke about experiencing STEM as it would occur in a lab, in contrast to a scripted experiment.	*My seeds grew a lot but when I took them out to the sun they died so I will plant more.* (Drip Irrigation, 6th grade, Hispanic Female)
STEM Identity	Positive beliefs toward their competence and performance in science, as well as believing others will recognize them as a scientist, engineer, or mathematician.	*It is bringing my dream of being able to build electronics true.* (Crank Flashlight, 6th grade Male, unknown race/ethnicity)
Familial Sharing	Students shared these experiences with their families.	*I also got to do it with my younger siblings, which was nice.* (Bottle Rocket Kit, 8th grade, Hispanic Female)
Quality Materials	Appreciation for the narrative and quality of materials.	*I think the book was really good* (*Esquivel Space Age Sound*, 6th grade, Hispanic Female)
Inspiring	Books gave rise to positive or creative feelings.	*I found this book inspiring because it showed that no matter what comes your way, you should never give up for what you believe in.* (*Counting on Katherine*, 8th grade, Black Female)
Awareness	Greater awareness toward critical issues with race, gender, and life situations.	*It helped [me] realize that everyone can do anything as long as you work hard.* (*The Boy Who Harnessed the Wind*, 6th Grade, Hispanic Female)

Themes Integration With A Justice-Centered STEM Framework

The fourth research question asked how the themes from the open-ended responses mapped onto the justice-centered STEM framework. The themes identified in the students' statements correlate with the concepts of the JCSF (Figure 3). The themes of STEM identity and awareness are aspects of the component **critical consciousness**, as students could visualize themselves as real STEM professionals through the kits and relate to the social, racial/ethnic, and gender aspects of the characters in the stories. The themes of authentic STEM and quality materials reflected **equitable academic access** as students could complete real STEM experiences and learn about the challenges STEM professionals faced in the trade books. Prior research supports using quality STEM experiences in out-of-school activities as learning tools to reach underserved students (Blanchard et al., 2023).

The framework component **confidence and abilities in STEM** was reflected by two themes, learning and enjoyable/engaging. These components were critical in helping students persist in tasks and gain confidence in their abilities, as shown in prior research (Blanchard et al., 2023; Morales-Doyle, 2017). Familial sharing was the theme that related to **commitment to community**, as students wrote about sharing their experiences with their siblings and parents. In prior research, high school students reflected on this component when they presented their soil project at a family science night (Morales-Doyle, 2017). Lastly, **cultural competence** was reflected in students' sense of self-efficacy and inspiring themes as students wrote about how they could be agents of change and have critical roles in the future of STEM. This finding resonates with the effects of Laughter and Adams (2012) in their study of middle school teachers who used a short story, The Space Traders, to create classroom discussions about scientific bias and their larger societal contexts.

Figure 3. Components of the Justice-centered STEM Framework, with themes.



Note. The coded themes are included in rectangles shaded in blue. Blue font reflects changes from the original justice-centered science pedagogy model of Morales-Doyle (2017).

Limitations

A major limitation was the participation attrition, likely a result of an inability to communicate directly with parents or guardians, limited involvement of teachers, and the apathy that followed extended issues from COVID. Another limitation is the relatively small sample of students who participated in the study, all of whom were enrolled in rural middle schools in underserved communities.

Discussion

This at-home STEM intervention began as a response to COVID; none of the middle schools felt able to carry out STEM club activities when navigating the logistics of students returning to the classroom. Although it was anticipated that students would be excited about the kits and books and eagerly participate, student participation in the kits began slowly, and it took multiple reminders via postcards mailed to homes to try to increase the level of participation. Of the students who began the project, a limited number continued past the second kit. These findings are similar to findings in another study, when students from an active STEM club carried home STEM kits (Gutierrez et al., 2025).

It was anticipated that the repeated measures of justice-oriented prompts might lead, over time, to increased student perception of their agency and involvement in their communities. However, findings revealed insignificant differences in participation, completion, and responses between the neutral and justice-oriented groups. The lack of difference in the findings between the two groups suggests that the project materials themselves - the STEM kits and the social justice-oriented trade books - were what led to students' perceptions, rather than the difference in the prompts (Blanchard et al., 2021; Smith, 1995; Steiner, 1998).

It also was anticipated that the students who received prompts that explicitly related to justice-oriented ideas would, over time, have responses that were more aligned with these constructs. The mean survey scores increased with iterations, potentially reflecting greater engagement and increased agreement with justice-oriented prompts as the project progressed. Yet, the analyses of the students did not reveal any statistically significant differences. It was hoped that students would share the trade book and/or kit with family members, yet they reported that they mostly did not. This was unlike the Gutierrez et al.'s (2025) study, in which students were explicitly asked to work with their family members and audio record the interactions.

Conclusions And Implications

The findings of this study lead to several conclusions and implications. First, students responded very positively to the at-home STEM kits and the social justice-oriented trade books. This suggests that the curriculum materials were of the right difficulty level and relevant or of sufficient interest for the students. Second, student participation fell off quickly. This was likely the result of a lack of strong ties to an active STEM Club or instructor support. Increased contact with the guardian and liaison teacher may have improved student participation. Third, although interest was quite positive, overall, interest seemed to vary based on the kit and book. It seems likely that the lack of choice related to perceived personal interest may have undermined completion. Fourth, despite the researchers' anticipation of the role of the social justice-oriented prompts, the differences in the prompts did not lead to differences in students' responses. This suggests that the social justice-oriented trade books, as well as the STEM kits, were more influential than the prompts; that they were able to stimulate elements of culturally relevant pedagogy (Ladson-Billings, 1995; Morales-Doyle, 2017), including students' cultural competence and critical consciousness. Finally, students gave positive and encouraging comments, reflecting that the intervention positively impacted students' sense of capability and future career aspirations in STEM. The role models from the trade books seemed to resonate for many of the students (Blanchard et al., 2023; Clark et al., 2024).

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Exploring the Perspectives of Families Following Their At-Home STEM Tinkering Experiences

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This qualitative study explores the experiences and perceptions of nine families who participated in STEM Home Edition, a year-long at-home STEM learning program designed for middle school students and their families. The program aimed to foster STEM engagement and conceptual understanding through hands-on activities, including Circuit Scribe, Meccano robots, Germ Glo and Achoo! and Steve Spangler's Larry's Lab. Using the Learning Dimensions of Making & Tinkering framework (Bevan et al., 2017), this study analyzed family interactions across five dimensions, with a focus on Creativity & Self-Expression (LD4) and Social & Emotional Engagement (LD5). Data were collected from interviews and pre- and post-activity reflections with nine families. Findings revealed that Creativity & Self-Expression was the most often described Learning Dimension (45%), characterized by youth and adults expressing joy, constructing explanations, and setting personal goals. Social & Emotional Engagement followed (25%), emphasizing family members' perceptions of collaboration, confidence, and pride in the outcomes. Other Dimensions—Conceptual Understanding (15%), Initiative & Intentionality (12%), and Problem Solving & Critical Thinking (3%)—highlighted families' reflection on their ability to control variables, persist through challenges, and troubleshoot. The study also observed the demographic diversity of participants, with most families led by mothers and including a mix of racial/ethnic backgrounds and educational levels. These findings provide novel insights into at-home STEM engagement and underscore the potential of family-centered STEM programs to enhance learning, build confidence, and foster STEM identity. The study contributes to research on informal STEM education, offering practical insights for future program design and implementation.

Keywords: Out-of-school contexts, STEM education, Qualitative research

Importance Of Study

Engaging families in informal STEM learning fosters interest and participation in STEM fields (Dabney et al., 2016; Lin & Schunn, 2016; Roberts et al., 2018). Informal STEM activities, such as museum visits, zoo trips, and hands-on home experiments, enrich classroom learning and provide extended engagement opportunities (Roberts et al., 2018; Blanchard et al., 2020). Family involvement is also linked to improved academic outcomes for middle and high school students (Hill et al., 2018). However, parental engagement in STEM education presents challenges. Many parents face time constraints (Jeynes, 2006, 2010, 2012; Mapp et al., 2008) and barriers to school involvement (Bhargava & Witherspoon, 2015; Hill et al., 2018). As children enter adolescence, parents often step back to encourage independence (Hill et al., 2018). Yet, at-home STEM activities can increase students' motivation, confidence, and appreciation of STEM, similar to other informal learning experiences (Lin & Schunn, 2016). Encouraging parental participation in STEM at home can enhance students' engagement, knowledge acquisition, and career planning (Epstein, 1986).

Tinkering is commonly described in the literature as an interdisciplinary, inquiry-driven approach that integrates STEAM domains and emphasizes creativity, iteration, and problem solving, despite variation in how the term is defined. Vossoughi and Bevan (2014) characterize tinkering as a mindset that spans making and engineering, highlighting experimentation, learning through failure, and iterative design. Tinkering often engages learners in open-ended exploration rather than predetermined outcomes and is most frequently studied in informal learning environments such as museums, camps, and afterschool programs.

Research demonstrates that tinkering can effectively support engagement with engineering concepts and practices. Marcus et al. (2021) found that family-based engineering design challenges fostered playful exploration and iterative testing, particularly when participants were provided with activity-specific guidance and access to testing stations. Similarly, Simpson et al. (2020) reported that elementary students in an informal afterschool STEM program demonstrated meaningful engagement with electricity and circuitry through hands-on tinkering projects. Although these activities aligned with NGSS expectations, the informal contexts afforded learners greater flexibility, time, and resources to enact science and engineering practices than is often possible in formal classroom settings. Together, these studies highlight tinkering's potential to support authentic STEM learning and family engagement in informal educational spaces.

This qualitative study examines the experiences of nine families participating in the STEM Home Edition program over ten months. This work extends previous work (Gutierrez et al., 2025) by detailing how these families interacted during STEM at-home activities. By exploring family reflections through interviews about their engagement in at-home STEM activities, this study provides insight into how informal STEM learning contributed to families' STEM engagement and development.

Conceptual Framework

The *Learning Dimensions of Making & Tinkering* framework (Bevan et al., 2017) served as a guide to document how families reflected on their participation in STEM activities at home. This framework consists of five key Learning Dimensions, as illustrated in Table 1. Multiple dimensions were often referenced simultaneously during family interviews, reflecting their interconnected and overlapping nature rather than existing as isolated or distinct categories. Initiative and Intentionality (LD1) captures evidence of self-directed learning, goal setting, and persistence. For this study, "organization of materials" was added to represent at-home activity contexts better. Problem Solving and Critical Thinking (LD2) includes experimenting with strategies, seeking assistance, and refining approaches; "building and assembly" was added to reflect hands-on construction practices. Conceptual Understanding (LD3) focuses on how participants generate explanations and use material properties to meet design goals. Creativity and Self-Expression (LD4) encompasses aesthetic responses, playful exploration, and novel uses of materials; "expressing negative emotions" was incorporated to capture affective responses observed in the data. Social and Emotional Engagement (LD5) reflects collaboration, mutual support, confidence building, and expressions of ownership.

Research Design And Research Question

This study used a qualitative study design (Creswell, 2013) to investigate the experiences of nine families who participated in at least three of the four at-home STEM activities. The after-school STEM Club students attended one of two rural, Title I middle schools in the southeastern US, and participated in a STEM Club at their school (Blanchard et al., 2023).

The research question for this study is: *How did families reflect on their tinkering experiences after an at-home STEM intervention?*

Table 1. The Learning Dimensions of Making & Tinkering (adapted from Bevan et al., 2017)

Dimension	Indicators
LD1: Initiative & Intentionality	a. Setting one's own goal b. Taking intellectual and creative risks c. Complexifying over time d. Persisting through failure e. Adjusting goals based on feedback f. Organizing materials*
LD2: Problem Solving & Critical Thinking	a. Troubleshooting through iterations b. Moving from trial-and-error to inquiry-focused refinement c. Developing work-arounds d. Seeking ideas, help, and expertise e. Building and/or assembly*
LD3: Conceptual Understanding	a. Controlling variables as projects complexify b. Constructing explanations c. Using analogies and metaphors d. Applying material properties to design
LD4: Creativity & Self-Expression	a. Responding aesthetically to materials b. Connecting projects to personal interests c. Playful exploration d. Expressing joy and delight e. Using materials in novel ways f. Expressing negative emotions*
LD5: Social & Emotional Engagement	a. Remixing or building on others' ideas b. Teaching and helping one another c. Collaborating in teams d. Developing confidence e. Expressing pride and ownership

Note: Indicators added by the authors are designated with an asterisk.

Methods

STEM Home Edition Program

The *STEM Home Edition program* (pseudonym) was implemented in the homes of students who were members of an ongoing after-school club and took place over one academic year. Each student began by bringing home a STEM kit to share with their family. Kits included STEM materials, snacks, activity instructions, career and post-secondary information, and pre/post-activity reflection prompts (Gutierrez, K. S. & Blanchard, M. R., 2018). The four activities were: 1) Circuit Scribe kit, 2) Meccano robot, 3) Germ Glo and *Achoo! The Most Interesting Book You'll Ever Read About Germs*, and 4) Steve Spangler's *Larry's Lab* (water-soluble polymers). Families kept the materials and received the next activity after submitting data. Up to four activities could be completed sequentially. At the program's end, families participated in interviews. Transcribed interview data totaled 82 pages and were coded using a priori categories from the *Learning Dimensions of Making & Tinkering* framework in Atlas.ti, with additional codes for family context, such as “Family Dynamics” and “Family Relationship.”

Participants

The demographic data reflect the diversity of families in the STEM Home Edition program. Most participants were White (5 families), followed by Black (3) and Multi-Racial (1). Slightly more were female (5) than male (4), with ages ranging from 11 to 13, and most (5) were 11 years old.

Mothers were the primary participants in eight families, with two families involving fathers and one with both parents actively engaged. Educational backgrounds varied: three adults held graduate degrees, three had undergraduate degrees, three had some college, and one had a high school diploma. Most families had one or two children involved, though one had four and another had three. This overview highlights the varied family contexts in the program.

Findings

Through the family interviews, the analysis of activity learning dimensions that was guided by the Learning Dimensions of Making & Tinkering framework, highlights the diverse ways participants engaged with STEM activities (see Table 2). *Creativity & Self-Expression* (LD4) was the most frequently observed dimension, accounting for 45% of codes (114 instances). For example, reflecting on the Circuit Scribe activity, the daughter from the Murphy family expressed, “*Well, it was very entertaining, and it - I thought it was really cool how, like, the electricity would flow through the little, like, parts where you draw on the paper. I thought that was really interesting.*” Reflecting on the Germ Glo activity, the mom from the Brown family said “I liked the germs one because I was amazed to see what was on our hands [...] it was amazing.” This dimension reflects participants’ joy, aesthetic responses, and creative use of materials. Key indicators included both youth and adults expressing joy (44 and 32 instances, respectively), youth constructing explanations (18 instances), and youth setting goals (13 instances).

Table 2. Percentages (and Frequencies) of the Learning Dimensions [and Indicators] of Making & Tinkering Reflected on During Family Interviews.

Activity	Learning Dimensions		Most frequent indicators
Family Interview	LD4: Creativity & Self Expression (114)	45%	Youth Expressing joy and delight (44)
	LD5: Social & Emotional Engagement (63)	25%	Adult Expressing joy and delight (32)
	LD2: Problem Solving & Critical Thinking (8)	3%	Youth constructing explanations (18)
	LD1: Initiative & Intentionality (31)	12%	Adult constructing explanations (16)
	LD3: Conceptual Understanding (38)	15%	Youth setting own goal (13)

Social & Emotional Engagement (LD5) was the second most prevalent dimension, comprising 25% of codes (63 instances). The dad from the Jones family reflected on the program saying, “*It enhanced my team-building skills, so that's what I can use later in life, more or less… that, and working with my son.*” This dimension highlights building confidence, teamwork, and pride in outcomes.

Other dimensions were less frequently observed but still enriched the learning experience. *Conceptual Understanding* (LD3), accounting for 15% of codes (38 instances), focused on controlling variables, constructing explanations, and connecting materials to achieve design goals. The mom from the Mueller family shared "*I had never heard the word polymer before, even though we had had the Orbeez, I didn't, again, read the directions that came with the Orbeez. I did not realize they were called polymers.*"

Initiative & Intentionality (LD1), representing 12% of codes (31 instances), highlighted goal-setting, persistence, and adapting plans. The son in the Wilson family noted, *"I learned a bit more about the jobs I'm interested in and a bit more about some of the jobs I'd rather not go for and still see how they're interesting to me sometimes too.*"

Problem Solving & Critical Thinking (LD2), the least observed dimension at 3% (8 instances), emphasized troubleshooting and creative workarounds. Reflecting on troubleshooting, the mom and daughter from the Baker family shared:

Daughter: *Circuits didn't really work.*

Mom: *Well, it took a little working with it and making sure to get it - to do things appropriately.*

These findings demonstrate how multiple dimensions often overlap, creating a rich, multifaceted learning environment where each dimension was evidenced at varying degrees of frequency.

Discussion

This study highlights the impact of family-centered STEM programs like STEM Home Edition in fostering engagement, learning, and confidence. Using the Learning Dimensions of Making & Tinkering framework (Bevan et al., 2017), findings reveal diverse family interactions with STEM activities. *Creativity & Self-Expression* emerged as the most prominent dimension, reflecting the joy and curiosity sparked by hands-on exploration. At-home STEM activities can enhance intrinsic motivation and creative problem-solving. *Social & Emotional Engagement*, the second most observed dimension, emphasizes collaboration, confidence-building, and emotional investment in STEM learning.

Less frequent but still significant, *Conceptual Understanding* and *Initiative & Intentionality* highlight the value of applying scientific concepts and persisting through challenges. The limited presence of *Problem Solving & Critical Thinking* suggests a need for more complex, iterative tasks within at-home programs.

Conclusions And Recommendations

These findings suggest several practical recommendations. Program designers should prioritize activities that integrate creativity, collaboration, and conceptual understanding to enhance engagement and learning. Providing resources to guide goal-setting and problem-solving may strengthen Initiative & Problem Solving. The program's demographic diversity underscores the need for culturally responsive design to ensure relevance across backgrounds. Lastly, involving families in STEM education fosters STEM identity and long-term interest. Schools and community organizations should adopt family-centered STEM models to connect informal and formal learning.

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Bridging Educational Landscapes – Out-of-School Learning in Biology and Its Complementarity with Formal Curricula

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Out-of-school education is considered to play a major role in teaching biological content and the acquisition of corresponding competencies. Still, the educational goals of out- of-school learning settings and their complementarity to those of school-based biology learning are almost unidentified. This research project is concerned with identifying the educational objectives used by out-of-school learning environments. In a qualitative case study, the out-of-school learning environments of a national STEM-cluster (N = 34) were analysed regarding their educational objectives concerning biology education. These objectives were ascertained through guided interviews with staff members of the environments and through the systematic collection and analysis of the educational materials of the learning environments. In addition, the similarities and differences between these and the educational objectives of school-based biology learning were identified. For this purpose, the collected educational objectives of out-of-school learning were compared with the educational objectives described in the national educational standards in biology by content analysis. The results of this study indicate that a common ground already exist between school-based and out-of-school biology learning within the STEM-cluster, particularly in developing competencies related to 'content knowledge' and 'decision-making'. However, the study also reveals untapped potential for further integration of school-based and out-of-school learning environments, which could enrich the biological education.

Keywords: Out-of-School Learning; Competencies; Complementarity

Theoretical Background

From the perspective of biology education, out-of-school learning environments are associated with numerous characteristics that support learning biology: Children and young people learn in diverse places, through various activities, and in different (social) constellations. They experience a real, practical connection to the subject matter and learn in an activity-based, independent way (Sauerborn & Brühne, 2020). The development of networked thinking and learning through multiple sensory channels is also at the core of out-of-school learning environments (Sauerborn & Brühne, 2020). According to Sauerborn and Brühne (2020), these aspects contribute to the long-term retention of acquired skills. They also prevent diminishing interest in scientific topics: Numerous studies on the effectiveness of out-of-school learning environments have shown that they can positively influence motivation and interest in science (overview in Bell et al., 2009). However, in the public's perception, schools are at the center of education. This perspective is also reflected in the research landscape, where school-based learning is studied far more frequently than out-of-school learning environments and is often clearly separated from learning outside of school. However, Birmingham and Calabrese Barton (2014) outlined the lack of a clear distinction between school and out-of-school learning: learners constantly cross the boundaries between learning in the context of school and situations of learning experienced in everyday life or out-of-school contexts – regardless of the place they are in.

For this reason, the consensus on a sharp differentiation of learning sites is shifting to a discourse on learning in which the boundaries between formal and informal education and between different educational institutions are blurred (Dierking & Tal, 2014). Bell and colleagues (2009) postulate that most people build their understanding of science throughout their lives by gathering and processing information from many places and contexts for a variety of reasons. Learning in general, and science learning in particular, according to this view, occurs over time through a person's countless experiences, including learning opportunities within the context of school or at out-of-school learning environments (Dierking & Tal, 2014).

Approaches to conceptualise school-based and out-of-school biology learning in a complementary way remain largely superficial (e.g., Favre & Metzger, 2019). This is partly due to the fact that the design of out-of-school learning environments often lacks a deliberate connection between the educational objectives of these environments and those of formal school-based learning, preventing the full potential of these visits from being realized (Eshach, 2007). Furthermore, the integration of both learning environments could be hindered by a lack of clarity regarding the educational goals of out-of-school learning environments, which – unlike school-based educational institutions – do not have curricular guidelines.

Key Objectives

Based on the state of research, this study aims at giving a frame for a common perspective of school-based and out-of-school biology learning. Therefore, the study focuses on the comparison of the educational objectives of school-based learning with the educational objectives of didactically designed out-of-school learning environments. Since out-of-school learning environments do not follow curricular guidelines, their educational goals must first be identified. For this purpose, out-of-school learning environments of a national STEM-cluster are examined. Only learning sites that stated to teach biological contents and competencies are included in the study. Through a content-analytical comparison of the surveyed out-of-school educational objectives with those of school-based biology learning, already existing correlations as well as 'white spots' regarding complementarity and thus opportunities for stronger interconnections can be identified. This comparison is made against the background of the following questions:

1. What are the similarities and differences between the educational objectives of out-of-school and school-based biology learning?
2. To what extent do possible differences result in synergistic potential in the sense of a stronger interconnection of the learning environments?

Research Design

In the region of the STEM-cluster, 34 out-of-school learning environments were identified that (among other things) aim to address biological competencies. They can be assigned to the learning environment categories defined by Möller and colleagues (2023) (see Table 1), i.e., the learning environments can be distinguished in various settings – from nature parks to organic farms to environmental education centres – where biological topics are addressed in an engaging and experiential way.

The educational goals of the learning environments were elicited through guided interviews (Helfferich, 2011) with one site staff each. The interviews included five guiding questions that focused on the framework, the content, and the educational objectives of the environments. Each guiding question was further divided into two to six sub-questions to gain deeper insights. To gain a comprehensive understanding of the educational objectives of the learning sites, the guiding questions were formulated as narrative prompts. The interview questions had been piloted in spring 2023. Data collection for the main study was conducted from April 2023 to July 2024. The N=34 interviews ranged in duration from 28 to 46 minutes. In addition to the interviews, a systematic screening of existing educational materials (e.g., exhibition materials) from the out-of-school learning environments was conducted to further identify and analyse their educational objectives.

Table 1. Learning environment categories with corresponding sample sizes.

Categories of learning environments	Number of environments in the sample
Zoos/Wildlife Parks	3
Nature Parks/Gardens and Protected Areas	6
Museums	5
Environmental Education and Experience Centres	7
(Agricultural) Farms	10
Youth Centres or Clubs	3

The content analysis of the interviews and materials of the learning environments is based on the qualitative content analysis method according to Kuckartz and Rädiker (2023). Therefore, a deductive category system was established based on the educational objectives outlined in the national educational standards for school-based biology education (Sekretariat der KMK, 2005). These objectives are divided into four competence-areas: ‘content knowledge’, ‘procedural and epistemic knowledge’, ‘communication and interaction’ and ‘decision-making’, which also represent the main categories of the deductive category system. The educational goals of the out-of-school learning environments – those identified through interviews as well as those obtained through the systematic screening of educational materials – were classified within the deductive category system. Educational goals of the out-of-school learning environments that could not be assigned to the category system are included in the analysis as inductive categories. As a result, the deductive and inductive categories contain the educational goals of school-based and out-of-school learning in the region under study.

The similarities and differences between educational objectives of out-of-school and school-based learning can then be taken from the category system: Filled deductive categories indicate a pre-existing match of the two types of learning sites. Unfilled deductive categories and categories inductively generated from the material of the out-of-school learning environments show where the educational goals of both environments (so far) diverge. Against the backdrop of a common perspective, these differences will be discussed in terms of the potential for greater intertwining.

Findings

Results show that the educational objectives of school-based and out-of-school learning in the region predominantly overlap in terms of ‘content knowledge’ and ‘decision-making’ competencies. Regarding other competence-areas, the fit is less pronounced: the learning environments pursue different learning objectives, particularly when it comes to developing skills for acquiring ‘procedural and epistemic knowledge’. Many out-of-school learning environments focus on original encounters and general experiences of nature, for example through criteria-based observation of living nature. These competencies are not pursued by the governmental educational standards of school-based learning. The competence-area ‘communication’ also shows less overlap. This is due to the fact that only a small proportion of communication-related competencies of school-based biology learning and also a small proportion of own communication-related competencies are pursued by the out-of-school learning environments. This area of competence is underrepresented at out-of-school learning environments in the region studied. In addition to competencies that can be assigned to the competence-areas of biology learning at school, the out-of-school learning environments also address competencies that cannot be assigned to any of the competence-areas of school-based biology learning. These include

- taking responsibility for living organisms,
- establishing connections between biological phenomena and other (scientific) disciplines,
- perceiving biological phenomena with all senses,
- gaining a (practical) understanding of biological phenomena through learning in real-world contexts,
- articulating the relevance of biological phenomena for one's own personal life context, and
- developing environmental awareness and sensitivity.

These additional competencies therefore mark a further point of divergence from school-based biology learning.

Conclusion

At its core, this study challenges the dichotomy between school-based and out-of-school education and argues for a more integrated approach. The limited overlaps between school-based and out-of-school learning regarding the competence areas 'procedural and epistemic knowledge' and 'communication' open up potential for synergies, as different approaches to develop competencies can be combined.

Beyond these partially shared competence areas, the study highlights that out-of-school learning environments address a range of independent competencies that are not explicitly covered by the competence framework of school-based biology education. These competencies, which often emerge from experiential, context-based, and sensory-rich learning situations, represent an additional potential for synergy. Integrating such competencies into school-based learning processes could contribute to a broader understanding of biology education that extends beyond curricular knowledge acquisition and supports more holistic learning processes.

By recognizing and leveraging the multiple strengths of both school-based and especially out-of-school learning, educators can provide a more comprehensive and engaging educational experience. In doing so, they can foster a generation of learners who not only have a deep understanding of biological concepts but also develop a profound connection to the natural world. As we move forward, it is essential to recognize the similarities and differences and explore their potential for collaboration to shape a truly effective and impactful biology learning.

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