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Ten Years of Three-Dimensional Science and Its Implementation in the Secondary Classroom: A Scoping Review

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ABSTRACT

In the decade following the release of the Next-Generation Science Standards in the United States, many efforts have occurred to reform K-12 science teaching. While not all states have adopted NGSS, 48 of 50 have adopted standards that are consistent with the underlying philosophy and research base of NGSS: three-dimensional (3D) science. This scoping review explores the research activity on classroom implementation of 3D Science in secondary schools in the US. The findings reveal that research about 3D Science implementation also touches on a wide array of adjacent issues, including professional learning, teacher knowledge, teacher attitudes and beliefs, assessment, and administrative support. Future research should continue to investigate the impacts of actions taken in one level of the system (i.e. professional development for teachers) on other levels of the system (i.e. classroom practice, student learning), as well as the challenges and barriers that hinder classroom implementation of the new standards.

KEYWORDS
3D science; classroom implementation; enactment; next generation science standards; professional development; science teaching

Introduction

A Framework for K-12 Science Education (National Research Council, 2012) put forward a new vision for teaching and learning that integrates three dimensions: Disciplinary Core Ideas, Science and Engineering Practices, and Crosscutting Concepts. This vision and the accompanying research-based principles were operationalized in the Next Generation Science Standards (NGSS) as performance expectations for science learning in grades K-12 (NGSS Lead States, 2013). There is a range of adoption and adaptation decisions made by different states, with some adopting NGSS as written, while others wrote new standards that reflect the same philosophy and research foundation but are not identical to NGSS. Due to this range of adoption, we will use the term three-dimensional (3D) science teaching rather than NGSS.

3D science teaching represents a significant shift from traditional classroom practice, requiring teachers to support students' engagement in science sensemaking (NSTA, 2024) while investigating phenomena, using science practices, and applying cross-cutting concepts. Teachers must re-conceptualize their approach to science content and student

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learning (Achieve, 2023). Ultimately, if the vision of the *Framework* is fulfilled, classroom practices will become more 3D, and students will have richer science learning experiences.

In this context of science education reform, we sought to understand the impact of new standards on science teachers' classroom practice over the decade following the publication of the *Framework* and NGSS. This scoping review responds to the following research question:

(1) What is the extent, range, and nature of research activity related to classroom implementation of 3d science in secondary science classrooms?

Definitions

3D Science integrates three dimensions: crosscutting concepts (CCC), science and engineering practices (SEP), and disciplinary core ideas (DCI). The concept of 3D science originally came from the *Framework* (National Research Council, 2012). CCCs are ideas that are encountered in all fields of science (patterns, stability and change, cause and effect, etc.). SEPs are skills and processes that professional scientists and engineers use to study the natural world (asking questions and defining problems, analyzing and interpreting data, using mathematics and computational thinking, etc.). DCIs are the specific science concepts that students learn (genetics, ecology, conservation of matter, etc.). When all three dimensions are integrated, students build a deeper understanding of science that they can continue to develop throughout their lives (Achieve, 2013). Each NGSS performance expectation includes all three dimensions. Likewise, 3D science standards other than NGSS, incorporate the three dimensions in each articulated standard for student learning.

Phenomenon-based learning is a productive way for students to use SEPs, CCCs, and DCIs to make sense of real-world phenomena (Achieve, https://www.achieve.org/; Storylines, https://nextgenstorylines.org; and STEM Teaching Tools, http://stemteachingtools.org/). Using phenomena in teaching provides students with a rich environment where they can engage with concepts and apply the skills of a scientist (Achieve, 2016). Often referred to as sense-making, students ask questions, analyze data, design solutions, and implement what they discover to help them figure out a phenomenon. As students engage in this way, their learning is elevated from simply knowing about something to being able to make sense of something (Schwarz et al., 2017). Implementing phenomenon-based learning also has the benefit of bringing in scenarios that are culturally or personally relevant to students, which is one way to promote equity in STEM education (NSTA, 2024).

History and adoption

Before the NGSS, most states' K-12 science standards were based on the National Science Education Standards written in 1995 (National Research Council, 2012). By 2010, these standards were viewed as outdated both in terms of current scientific knowledge and in terms of research on the teaching and learning of science (Inouye & Houseal, 2018). Consequently, the National Research Council created *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas* in 2012 (National Research Council, 2012) using the most current research to propose 3D Science as the foundation of science instruction. The 2013 release of the NGSS, which used the *Framework* as a guide in its development (NGSS Lead States, 2013), provided new standards that states could choose to adopt or adapt.

The writing of NGSS was a state-led project with a 40-member writing team representing 26 different states and various fields of science and education. There was no funding or involvement from the federal government. Because of this, the adoption of the NGSS has varied by state. Twenty states have adopted the NGSS as originally written, and 28 states have adapted the NGSS to create a unique set of 3D science standards (NSTA, 2023). These states are classified as early adopters (those that adopted in the first 4–5 years) or late adopters (those that adopted after the first five years until the present) (NSTA, 2014; Smith, 2020). Because this effort was not led by the federal government, there was no predetermined timeline for implementation and no cutoff by which states needed to decide whether to adopt these new standards. The remaining two states still have the option to adopt or adapt 3D science standards in the future.

The adoption of NGSS or 3D science standards is more than teaching new content. The NGSS define a vision for science education that demands fundamental changes to the way teachers teach science and how their students learn science. The *Framework* (2012) states that for students to fully experience and engage with 3D science, there are "many other players and components of the system that will need to change, often in dramatic ways." Implementation requires new lesson plans, teacher collaboration, and professional development (PD), all of which have varied across states (Smith, 2020) depending on timelines for adoption or adaptation and available resources. The National Research Council (2012, Chapter 10) outlines the components of the system requiring changes to support implementation, including curriculum and instructional materials, teaching and learning activities, teacher understanding and learning, teacher development, professional development, and assessment. These suggested components influenced our interpretation of the literature and the categories we used to classify manuscripts.

Methods

When researching the literature, we chose to perform a scoping review (Arksey & O'Malley, 2005), to investigate the extent, range, and nature of research activity related to classroom implementation of 3D science in secondary science classrooms. Scoping reviews are used for examining emerging evidence, to provide a "snapshot of a particular area" (Booth et al., 2012, p. 9). With 3D science and NGSS being relatively new, we chose a scoping review to capture the essence and key characteristics of the published literature on this subject. Following the steps outlined by Arksey and O'Malley (2005) we identified the research question, identified relevant studies, selected studies according to inclusion and exclusion criteria, analyzed the manuscripts, charted the data and summarized the results. This strategy allows us to present the literature, identify the focus of existing research, and determine where more research can be conducted. This also acts as a precursor to systematic reviews once an overall picture of the research has been compiled.

In this scoping review, we seek to understand how 3D science has been implemented in the secondary science classroom since the publication of *A Framework for K-12 Science Education* (National Research Council, 2012) and the associated NGSS (NGSS Lead States, 2013).

Identifying relevant studies

We utilized the ERIC Database. We completed four thesaurus searches in February 2024 using a Boolean/phrase search mode and the following keyword options:

(1) “Science education” OR “Science teaching” OR “Science instruction” OR “Science teachers” (Resulted in 122,824 papers)

This was to target manuscripts about science teaching and acted as a broad initial filter.

(2) “NGSS” OR “Next generation science standards” OR “Three-dimensional science” (Resulted in 1,333 papers)

This was to target work related to the NGSS and filter out manuscripts that considered science teaching in a general context.

(3) “Secondary education” OR “Secondary school science” OR “Secondary school students” OR “Secondary school teachers” OR “Secondary schools” OR “Secondary science” (Resulted in 461,864 papers)

This was to target secondary science teaching (grades 6–12), as that is the focus of our scoping review.

(4) “Teacher professional development” OR “Classroom teaching” OR “Instructional improvement” OR “Classroom enactment” OR “Teaching practice” (Resulted in 56,066 papers)

This was to target manuscripts related to the improvement and practice of classroom teaching. While true that not all professional development results in changed classroom practice, high-quality PD that emphasizes higher-order skills, is ongoing, collaborative, and embedded within schools does impact teacher practices (Porter et al., 2000). Thus, we chose to include “teacher professional development” along with the other terms focused on classroom practice.

When all these individual thesaurus searches were combined (#1 AND #2 AND #3 AND #4), there were 126 papers in the results (see the supplementary information for a complete list of articles included in the review). This set of combined search terms was used to identify literature on the classroom implementation of 3D science within secondary classrooms.

Limitations

This scoping review targeted literature about the classroom implementation of 3D science in secondary schools. The fourth search criterion included classroom implementation, synonyms for classroom implementation, and professional development, which often has a focus on improving classroom implementation. Because of this emphasis, the scoping review results will not provide a complete picture of the available practitioner-focused articles, or studies about curriculum resources, assessment, or measurement. Results related to those topics did occur, and are not excluded from the results. Additional literature searches may be necessary to further explore the relevance of these topics in relation to 3D science.

Study selection

We inspected these 126 papers and applied inclusion/exclusion criteria as follows. One of the manuscripts was a book with multiple chapters by different authors. We treated each chapter as a separate manuscript which increased our number of manuscripts from 126 to 144. From this list, we eliminated duplicates (3), non-systematic reviews (2), and theoretical or commentary papers (1). Additionally, we excluded those studying education outside the United States (1) or comparing education across different countries (1). Because of our focus on secondary school classrooms, we also excluded papers focusing on pre-service teacher education (1), elementary education (7), university education (2), and informal education (1). Finally, some manuscripts were excluded because of a primary focus on mathematics education (3) or another aspect of science education unrelated to NGSS or 3D science (7). These exclusion criteria resulted in 29 papers being excluded from the scoping review leaving us with 115 included manuscripts.

Classification process for manuscripts

Initially, manuscripts were classified based on their titles, providing a broad overview of the content (Mateen et al., 2013).

The three authors independently read and analyzed 10% of the manuscripts (Mak & Thomas, 2022). This subset was chosen to allow for an initial exploration of the data and to identify emerging themes or categories. After this initial analysis, the authors met to discuss their findings and decisions on classifications. During this meeting, they compared their classifications, resolved any discrepancies, and established consensus on the definitions of each category (Hill et al., 2005). This process established consensus on classification definitions and how to classify future manuscripts and thereby enhanced the reliability of the categorization process.

The additional manuscripts were each analyzed by at least one of the authors using the agreed-upon classification scheme (see Table 1). This approach ensured consistency in the application of categories across the entire dataset (Hill et al., 2005). If an author was unsure of the classification of a particular manuscript, they reached out to another member of the team for a second opinion. This peer-checking served as a safeguard against bias and further ensured the accuracy of the classifications (Carter et al., 2014).

Analysis and refinement of categories

During the above-detailed analysis of the manuscripts, the authors recognized the need to refine the initial categories. This refinement process involved reevaluating and, when necessary, modifying the categories to better reflect the nuances and diversity of the included studies (Saldaña, 2021). For example, the category of English Language Learners was added later on in the analysis process due to it not being explicit in any of the titles but emerged as a focus when manuscripts were being read in their entirety. Through this iterative process, the final categories were developed (see Table 1 for category descriptions).

Table 1. Definitions of manuscript categories.

Category	Definition	Number of Manuscripts
Teacher Knowledge/ Understanding/PCK	The manuscript described research about teachers' content and/or pedagogical knowledge related to 3D Science, at a single time point or investigating changes over time.	56
PD Program	The manuscript described a professional development program as a key component. Research participants were also participants in the PD program.	55
Classroom Implementation	The manuscript gathered and analyzed data about classroom practice, including observations or field notes, interviews, or surveys about classroom practice.	55
Teacher Attitudes/Beliefs	The manuscript collected and analyzed data about teachers' attitudes or beliefs about 3D Science, at a single time point or investigating changes over time.	37
Challenges/Barriers	The manuscript explicitly addressed the challenges or barriers to the implementation of 3D science for teachers or students.	25
Student Learning Focus	The manuscript emphasized student learning by examining student work or using student data to inform or guide instructional practices.	15
Practitioner Article	The manuscript provided a resource, tool, or lesson plan for teachers to use in their classrooms. The intended audience was in-service teachers rather than researchers.	15
Program Evaluation	The manuscript summarized external evaluations of 3D science-focused work including assessments of success and lessons learned.	14
School/District Leadership	The manuscript reported on efforts to engage building or district administrators in better supporting 3D science teaching and learning in their schools.	10
Curriculum Resources	The manuscript described the development of curricula, or curricular materials or resources such as lesson plan outlines were provided.	9
Assessment	The manuscript described the development, pilot testing, or implementation of assessment tools for students to measure their learning of 3D science, for example types of formative assessments	6
Measurement	The manuscript described the development or use of instruments designed to measure 3D science teaching, teacher or student attitudes, or student learning, for example observation protocols	5
English Language Learners	The manuscript described adaptations, supports, or resources specifically for English Language Learners learning 3D science.	5
PD Resources	The manuscript provided resources, tools, instructions, or other artifacts that could be utilized by others who develop or deliver professional development.	4

Findings

Following the steps for a scoping review, we collated, categorized, and organized the literature (Arksey & O'Malley, 2005). Here, we present a summary of what we found related to classroom implementation of 3D science in secondary science classrooms.

Figure 1 shows the number of manuscripts in this scoping review by year of publication. The year 2019 shows a sharp increase in the number of manuscripts, while those numbers significantly decreased in the following years.

Table 1 lists the 14 categories used to classify the literature included in this scoping review, the definitions we used to classify the manuscripts, and the number of manuscripts included in this scoping review that align with each category. Most manuscripts were classified in more than one category, so the listed numbers are greater than the total number of manuscripts considered.

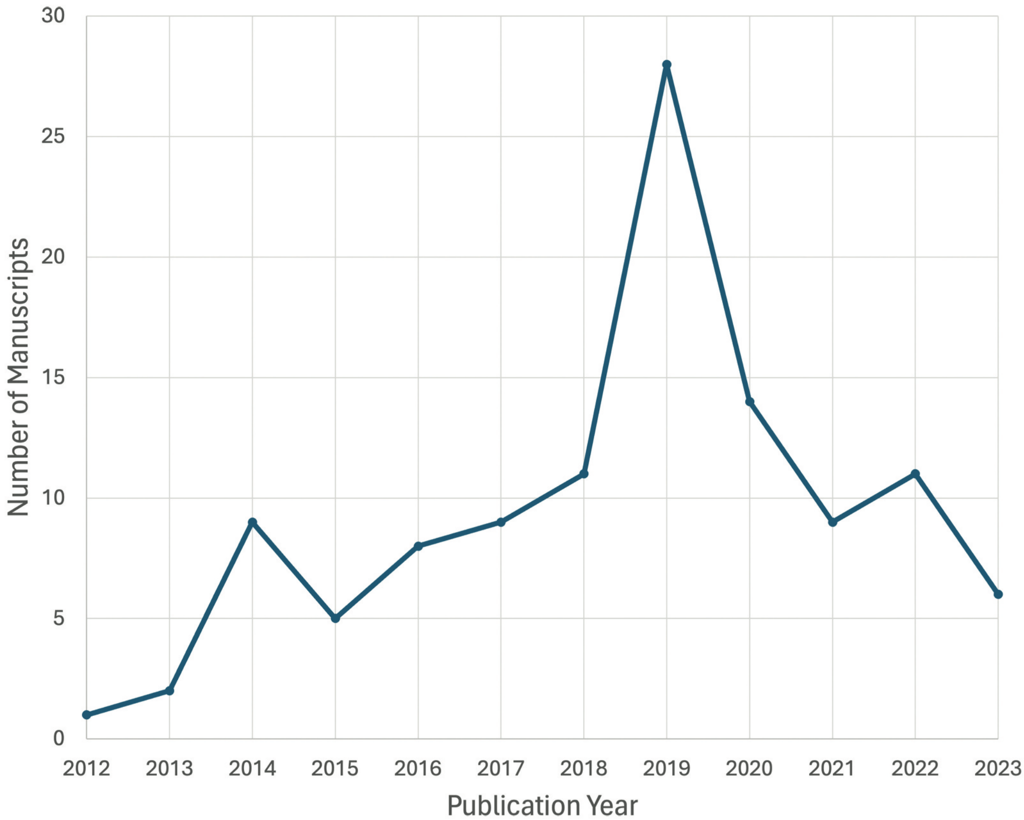

Figure 1. Manuscripts published by year.

Teacher knowledge/understanding/PCK

With the introduction of new standards, teachers need to develop new knowledge and understanding about how to teach science effectively. The manuscripts in this category generally identified a starting point and then investigated how the intervention impacted teachers' knowledge or teaching practices. Bowden (2018) provided insight into science teachers' perceptions and understanding of the new standards and how it impacts their daily practices. Nugent et al. (2016) described a PD program that resulted in teachers' increased knowledge and improved teaching practice. Other manuscripts explored how teachers understand and develop knowledge of specific SEPs such as planning and carrying out experiments (Duschl & Bybee, 2014).

PD program

Manuscripts that focused on PD programs generally described their purpose, the structure of the program, the data collected, and the impact or outcomes of the program. For example, one paper described a program to support the inclusion of engineering in high school chemistry. Their findings indicated that including engineering activities in their classrooms could increase secondary science teachers' use of learner-centered teaching methods through their science teaching (Boesdorfer, 2017). Another manuscript described a research-practice partnership with quarterly NGSS professional development meetings, implemented over three years. The teacher participants took surveys to investigate the impact of the PD and the changes to their teaching practices (McGee & Nutakki, 2017). Herrington and Daubenmire (2016) outlined strategies to support productive collaborations among high school teachers and researchers that resulted in meaningful change.

Classroom implementation

Manuscripts that investigated classroom implementation aimed to study how teacher learning translates into classroom practice. For example, de Los Santos (2017), explored teachers' sensemaking in conjunction with NGSS implementation. Some manuscripts used classroom implementation as a gauge of the effectiveness of a PD program. For example, Bancroft et al. (2019) compared two cohorts of PD participants and non-PD participant teachers using surveys to understand how they were implementing 3D science. Manuscripts included teacher-reported surveys (Bowden, 2018; Lowell & McNeill, 2023), classroom studies/observations (ie. Christensen, 2023; Glenn, 2019), or both (Macias, 2022; Watson, 2022).

Teacher attitudes/beliefs

Manuscripts that described teacher attitudes and beliefs tended to survey teachers before and after an intervention and report changes over time. Nugent et al. (2016) studied changes in teachers' self-efficacy and teaching beliefs after participation in a coaching program for rural science teachers that emphasized the SEPs. Other studies looked at relationships between teachers' beliefs and their teaching practices at a single point in time through large-scale surveys (S. B. Boesdorfer et al., 2019; Bowden, 2018).

Challenges/barriers

Manuscripts that addressed the challenges and barriers of NGSS and 3D learning often paired this with discussing the opportunities and benefits (Nagle & Pecore, 2019, Ammah-Tagoe et al., 2021). Some manuscripts focused broadly on the challenges teachers face, such as needing an in-depth understanding to implement 3D science or the scarcity of curricular resources (Robelen, 2013). The Inquiry into Science Writing Project (Ammah-Tagoe et al., 2021) identified specific challenges in a focused area, such as introducing argument writing into their science classrooms.

Student learning focus

Manuscripts with a student learning focus generally included an intervention that would impact student learning, which was measured. For example, Spycher and Haynes (2019) provided teachers with strategies to support student engagement with argumentation. Teachers used these strategies in their classrooms and measured changes in students' abilities to write scientific arguments. Another study examined middle school science teachers' enactment of student epistemic agency by drawing on their funds of knowledge and found that when students take cognitive responsibility, the students are empowered to make sense of scientific phenomena (Macias, 2022). Another way they measured student learning was by using student performance scores. Marshall and Alston (2014) found that students from inquiry classrooms performed better on standardized science tests than students from traditional classrooms.

Practitioner articles

Practitioner articles targeted an audience of practitioners rather than researchers. These included narratives of teachers describing how they provided quality science instruction to their students (McNeill & Reiser, 2018), strategies to support teachers' use of the new standards (O. Lee et al., 2015), and lesson plans that practitioners can use (Krajcik & Merritt, 2012; Taylor et al., 2019). Apple et al. (2021) presented several narratives of physics teachers engaged in professional learning about computational modeling reflecting on how their thinking and teaching practice changed as they learned more about that SEP.

Program evaluation

Manuscripts categorized under program evaluation included external evaluations of 3D science-focused work including assessments of success and lessons learned. Tyler, Estrella, et al. (2020) described NGSS instruction as a powerful lever for equitable learning and provided evidence of the importance of 3D science professional learning for administrators. Some evaluations described challenges and variability with classroom implementation (Estrella et al., 2019; Glenn, 2019). Other evaluation reports focused on administrators' and district leaders' understanding of NGSS (Estrella et al., 2019) and teacher leadership related to NGSS implementation (Tyler, Iveland, et al., 2019).

School/district leadership

Manuscripts addressing school and district leadership examined the roles of school administrators in the success or failure of 3D science implementation efforts. Estrella et al. (2019) evaluated a program's ability to provide future opportunities for administrators to learn about the standards. Another study examined the characteristics and behaviors of the leaders in schools with successful NGSS implementations to gain insights into the role of school leadership (M. E. Thomas, 2018). Tyler, Britton, et al. (2019) argued that administrators, district leaders, and teacher leaders must have knowledge and understanding of NGSS and that building teacher leaders' capacity around NGSS has benefits for collaboration and change.

Curriculum resources

Curriculum Resources manuscripts included articles that provided lesson plan materials as part of the main report or were available as supplementary materials. Beardsley et al.

(2022) described a course available for teachers who are teaching general or AP biology that aligns with NGSS. Taylor et al. (2019) presented a story of a high school earth science teacher who participated in PD and implemented an NGSS-aligned unit in their classroom, which was made available in the supplementary materials. Another manuscript described an NGSS-aligned lesson plan on conservation biology (Conklin & Clair, 2019), while McNeill and Reiser (2018) presented OpenSciEd, an extensive collection of open-source curriculum materials aligned with NGSS and freely available to all science teachers.

Assessment

Manuscripts categorized in assessment described the development, pilot testing, or implementation of assessment tools to measure student learning of 3D science. Lyon (2017) focused on secondary science teachers' enactment of assessment practices. Teachers were observed before and after a professional development workshop targeting assessments of NGSS performance expectations. A rubric to measure formative assessment practices and debriefing interviews were used to understand teachers' assessment decisions, especially as related to English language learners. Furtak (2023) published a book written for science teachers to support their efforts to write good formative assessments of NGSS and guide instruction in their classrooms. While the book has a practitioner focus and includes vignettes from real classroom discussions and student work, it also includes a significant emphasis on the theoretical background behind assessment practices.

Measurement

Measurement manuscripts described the development or use of instruments designed to measure 3D science teaching, or teacher or student attitudes. The PESTL Observation Protocol is an example of a measurement tool that quantifies instructional practices observed in classrooms. The protocol rates teachers' use of science knowledge and instructional skills in shaping classroom instruction in 3D science (Blank & Moulding, 2019). Another manuscript (Martínez et al., 2022) described the development of a scoring rubric aligned to NGSS that could be used to evaluate teachers' reflective e-portfolios.

English language learners

Manuscripts that focused on English language learners emphasized the language skills needed to engage with SEPs like argumentation from evidence or constructing explanations. Lyon (2017) observed teachers before and after a professional learning workshop where a rubric was used to understand teachers' assessment decisions, especially as related to English language learners. Another study focused on providing teachers with language support strategies useful for both fluent English speakers and English learners (Spycher & Haynes, 2019).

PD resources

Manuscripts that focused on PD Resources described the PD program in a way that could be replicated by others. Lewis et al. (2014) described a PD program for building professional learning communities in science education. By following their teaching model for adapting lessons, the teachers were better able to meet the NGSS and facilitate greater interdisciplinary learning. Lee et al. (2023) proposed a framework useful while creating PD that could be utilized with teachers implementing NGSS.

Discussion

The purpose of this scoping review was to understand the research activity related to classroom implementation of 3D science in secondary classrooms. The findings demonstrate extensive research activity in this area (Christensen, 2023; Glenn, 2019; Williams, Krikorian, et al., 2019; Williams, Singer, et al., 2019), and a wide range of related topics such as professional development (Richman et al., 2019), student learning (Murphy et al., 2018), measurement (Blank & Moulding, 2019), and assessment (Mark et al., 2020). There has been an increase in the amount of research over time, although the large-scale disruption to education during the COVID-19 pandemic likely impacted important work related to classroom implementation, and caused a drop after 2019 in the number of publications (see Figure 1). The overall increase in research over time indicates both more awareness of and priority placed on NGSS and 3D science implementation. Some insight into the nature of research on classroom implementation of 3D science in secondary science classrooms can be gained by examining the overlapping areas of investigation represented by the manuscripts included in this scoping review.

Classroom implementation

Classroom implementation manuscripts used classroom-based data including observations, field notes, video recordings, or transcripts of classroom discussions to measure the implementation of 3D science (Couling, 2018; Furtak, 2023; Kawasaki & Sandoval, 2019). In most categories, roughly half of the manuscripts addressed classroom implementation. However, Challenges/Barriers and Practitioner Articles had relatively fewer manuscripts addressing classroom implementation. Challenges and barriers to implementation, and their effect on various teaching practices, have been well-studied (Aldabbus, 2018; Dorier & García, 2013; Hamdan et al., 2016). However, the lack of representation of manuscripts studying both classroom implementation of 3D science and challenges or barriers to implementation may indicate that the strategies researchers use to learn about challenges and barriers are different than those used to learn about implementation. Researchers may need to develop studies that explore both areas concurrently to better understand how challenges impact implementation in real classrooms. Most practitioner articles did not include data about classroom implementation, although in some cases (Apple et al., 2021; O. Lee et al., 2015) they did include narrative accounts of individual teachers' classroom experiences. This may be caused by the different audiences for practitioner articles, and classroom implementation measurements being associated with research rather than practice. Additionally, the practitioner-focused articles may share other aspects of teachers' work such as lesson planning or reflection.

Practitioner articles and curriculum resources

Although the focus of this scoping review is on classroom implementation of 3D science, curricular resources aligned with 3D science are generally seen as a significant supportive factor for implementation (Henigman, 2017). Furthermore, to be impactful, those curricular resources should be shared with practitioners and easily accessible. Unfortunately, only four of the 15 manuscripts describing a curriculum resource were targeted toward a practitioner audience (Best & Dunlap, 2014; Blank & Moulding, 2019; Furtak, 2023; O. Lee et al., 2015; Taylor et al., 2019). The lack of practitioner articles sharing curriculum resources may result from the limitations of our search or may indicate that teachers lack time to publish, are less likely to partner with researchers, or that curriculum development has been led primarily by researchers rather than teachers. There is a need for increased access to curriculum resources. Fostering greater collaboration among researchers and teachers could help meet this need.

PD programs

Manuscripts reporting on professional development programs had a high overlap with classroom implementation (Christensen, 2023; Lowell & McNeill, 2023), teacher attitudes/beliefs (Kawasaki & Sandoval, 2020; Watson, 2022), and teacher knowledge and understanding (Harman et al., 2020; Peters-Burton et al., 2023). 31 of the 55 manuscripts categorized as describing PD programs were also coded as investigating classroom implementation. While an overarching goal of PD is to change classroom practice (Germuth, 2018), each PD program had unique goals. There were 12 manuscripts describing PD programs that focused specifically on classroom implementation along with teacher knowledge and understanding. An additional nine manuscripts addressed all four of the above-mentioned categories. Figure 2 shows the distribution of articles addressing one, two, three, or all four topics: classroom implementation, professional development, teacher knowledge, and teacher attitudes. The effort to reform K-12 science education with 3D science is complex and challenging (Kawasaki & Sandoval, 2019). Existing PD programs are attempting to address this complexity by investigating impacts on teacher knowledge, attitudes, and classroom implementation.

Of the 55 manuscripts categorized as describing PD programs, only five also had a student learning focus. This result may be due to the nature of our search, which emphasized classroom practice and implementation, and may have inadvertently excluded work related to student learning outcomes. However, the lack of overlap between PD programs and student learning measures may also be an indication of the challenge inherent in change efforts (Crawford, 2023; Kawasaki & Sandoval, 2019; Ruvalcaba, 2019). It would be unusual to encounter a single project carrying out high-quality PD, studying changes in teachers' knowledge and attitudes, extending that to classroom practice, and ultimately measuring impacts on student learning. This silo effect may be attributed to funding mechanisms that separate teaching from learning (National Science Foundation, 2023). In addition to the research done by Holloway (2006) more investment in studying the mechanisms by which impact travels from PD to student learning is warranted and could be a focus of future research (Hill et al., 2020).

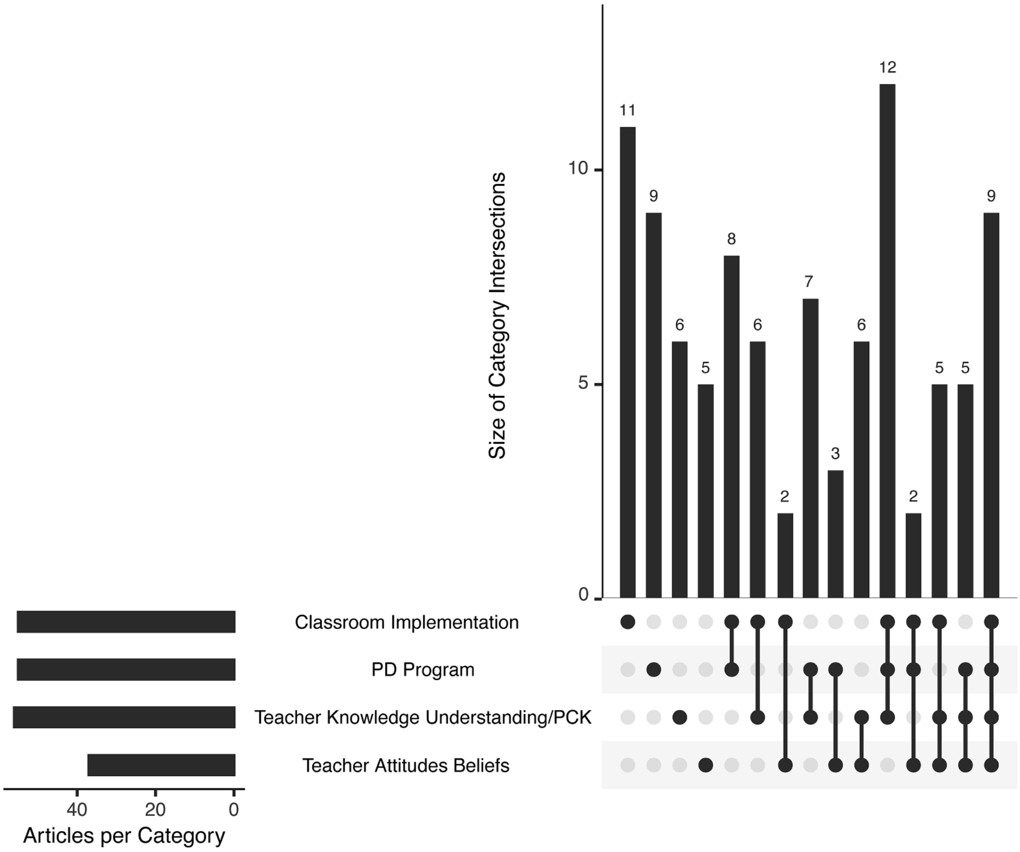

Figure 2. UpSet plot (Conway et al., 2017) of the category intersections among classroom implementation, PD program, Teacher attitudes & beliefs, & Teacher knowledge and understanding.

Implications for research and practice

Classroom implementation of 3D science within secondary schools has been lower than anticipated nationwide (Smith, 2020). This may be caused by the complex interplay of a variety of forces, including the availability of professional development and curriculum resources, teacher knowledge and attitudes, and administrative support. Future research on classroom implementation must be designed for the complexity that teachers face when attempting to implement 3D science. Studies should investigate as many facets of implementation as are feasible, and call attention to the specific challenges and barriers that present themselves when teachers seek to change their practice. Workable theories of action for the process of translating professional learning to implementation should be an area of future study (Kennedy, 2016).

Providers of professional development that intend for changed classroom practice to be an outcome of the PD should attend to the variety of supports that are needed to promote implementation, including administrative support, curriculum resources, and assessment. PD providers should design interventions based on the principles of effective professional learning, including a sustained duration, the ability to collaborate with teachers of the same subject, opportunities for reflection and feedback, etc (Darling-Hammond et al., 2017). Additionally, PD providers should directly address the specific needs and challenges that exist for their teachers, seeking to understand those challenges and find creative solutions that will support greater implementation of 3D science.

Conclusion

The goal of this review was to find the extent, range, and nature of research activity related to the implementation of NGSS and 3D science in secondary schools. We completed a scoping review (Arksey & O'Malley, 2005) which resulted in 115 manuscripts meeting the inclusion criteria. The intent and vision of the *Framework* (NRC, 2012) was to change science instruction in schools across America, creating richer, more engaging, and more equitable science learning for students. The COVID-19 pandemic likely slowed efforts to adopt or adapt the standards in many states, along with the associated research on implementation. Nonetheless, in the decade that followed the publication of NGSS (NGSS Lead States, 2013), there has been a significant amount of research investigating classroom implementation, with additional themes including teacher knowledge, attitudes, and beliefs, curriculum resources, practitioner articles, supporting implementation via school leadership and administration, impacts on student learning, and assessment and measurement.

Importantly, there have been efforts to link classroom implementation to adjacent areas of research, such as professional learning for teachers and student learning. However, approaches that interrogate multiple levels of the educational system (i.e. PD, classroom practice, student learning, administration, etc.) are more difficult and expensive to accomplish, resulting in them also being uncommon. This is an important area for future research related to 3D science if we hope to understand the mechanisms of action by which professional learning and administrator actions impact classroom practice and improve student learning.

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