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Pathways to understanding nanotechnology for elementary students: Implications for teaching with web-supported problem-based learning

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ABSTRACT

This article reviews the affordances of multimedia-based Problem-based learning (PBL) and its applications for the teaching and learning of nanotechnology to elementary students. The content of a web-supported module on nanomaterials is reviewed, and its effectiveness for guiding informed decision-making among elementary students choosing between sunscreens containing nano-sized particles and regular-sized particles is discussed. Outcomes of the module include significant gains in elementary students' science conceptual understanding, attitude towards science, and societal risks and benefits of nanotechnology. The use of multimedia-based modules may provide instructional support to teachers who hope to inform students of the importance of hands-on science and the scientific method that should drive the decision-making process by elementary students. Recommendations for teaching are discussed with implications for policy and integrating artificial intelligence into PBL

Introduction

Efforts to reform school science education have no geographical boundaries. In the European Union, the *Science Education Now: A Renewed Pedagogy for the Future of Europe* (European Commission, 2007) calls for more problem-based inquiry learning activities in the context of real-world applications of science in the lower grades. Similar calls for improving science education are reverberated in the United States (National Academies of Sciences, Engineering, and Medicine, 2022), emphasizing problem-solving and informed decision-making. However, in this age of information dominated by the internet reforming science teaching and learning in schools remains a challenge.

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The internet is an ideal platform for developing multimedia anchors that introduce students to nanotechnology in elementary science education and promote their informed decision-making in nanotechnology lessons. The content, figures, sound, and video information that can be developed and made available online enable the user to access, manipulate, and interact with science concepts irrespective of their location or environment. Internet-based science learning modules take advantage of a network of internally and externally associated platforms to represent a collection of thoughts for students to investigate. In this paper, an application of web-supported multimedia on concepts of nanotechnology for elementary science education that have been developed using a problem-based learning (PBL) approach (Kumar, 2021, 2015; Kumar and Yurick, 2018) is reviewed. In addition to describing the content of the online learning module, this paper presents the affordances of this medium for nanotechnology and associated recommendations for teaching.

One approach to reforming science education is empowering K-12 students to solve complex real-world problems and make informed decisions through PBL. Decision-making is a key aspect of PBL because it heightens critical thinking by requiring students to learn about and weigh all options before arriving at a decision. Student-centered outcomes of PBL include critical thinking, active learning, and flexible reflections (Huang, 2002) with resources such as loosely structured learning cases developed on a multimedia platform for student-centered, small-group cooperative learning (Cognition and Technology Group at Vanderbilt, CGTV, 1997; Huang, 2002; Tamrin and Desnita, 2023).

What is nanotechnology?

According to the National Nanotechnology Initiative (n.d.), nanotechnology deals with matter at the nanoscale of one billionth of a meter. The prefix "nano" means one billionth in terms of the International System of Units (Figure 1). The figure demonstrates the comparable size of the nanoscale by showcasing the width of a strand of human hair at 80,000 to 100,000 nanometers, the diameter of a strand of human DNA at 2.5 nanometers, the diameter of a single gold atom at 3 nanometers, and the thickness of a single sheet of paper at 100,000 nanometers. At the nanoscale, matter exhibits unusual chemical, physical, and biological properties and showcases unusual quantum effects. When compared to bulk-sized materials, nanomaterials have different magnetic properties, are better conductors of heat, and have enhanced interaction with light in ways that better display color changes with structural changes. By working with matter at the nanoscale, scientists could "fine-tune" a material that holds a particular property of interest. For example, sunscreen containing nanoscale zinc oxide is colorless and therefore more desirable to users than regular sunscreen containing bulk-size zinc oxide, which is usually white in color. In tandem with its several benefits, learning about nanotechnology can also elucidate to students some of the health risks that nanoscale materials purport, such as that their use in skin products can trigger mutation because matter at the nanoscale is small in size enough to enter the human cell.

Challenges in student performance and instruction in science

Scores from the National Assessment of Educational Progress science assessment show decreases in the science knowledge of a nationally representative sample of fourth graders in 2019 as compared to 2015 in the areas of life science and earth and space sciences, and no gains since 2015 in the areas of physical science (The Nation's Report Card, 2019). Challenges in science knowledge, performance, and interest continue to linger onwards from elementary grades, with low numbers of enrollees in undergraduate science, technology, engineering, and mathematics (STEM) subjects (Obi and Obi, 2019), 25% of 15-22-year-old students shifting away from STEM topics in their area of study (Freeman *et al.,* 2019), and substantial drop-out rates of college students majoring in STEM (Kennedy *et al*., 2018). Reasons for these patterns have been correlated with students' increased feelings of disinterest or boredom with science because of their difficulty to relate concepts to their everyday lives (Shirazi, 2017).

Amongst a range of issues in schools that obstruct students' science interest, learning, and performance, ineffective science instructional practices may be a source (Reardon, 2018). Moreover, investigations into students' critical thinking skills show that students have difficulties explaining their answers, justifying decisions with evidence-based rationale, and thinking critically during the learning process (Aktamiş and Yenice, 2010). Research highlights the need for science instruction that encourages students' reflection, open-ended exploration, and integration of science, technology, engineering, and mathematics with arts and culture, and emphasizes real-world application of the science content in lieu of traditional lecture-based approaches (DeHaan, 2005; National Research Council, 2011; Liritzis, 2024; Bountis, 2025). For students to be able to affiliate science concepts with practical applications in society (e.g., water cleanliness, food storage, pathogen exposure) and to think critically about these issues, science instruction must prioritize community-connected, experiential approaches (Zuryanty *et al*., 2019). Within these approaches, science teachers can expose students to real-world issues and create space for student discussion and brainstorming that leads to critical thinking, the formulation of arguments, and informed decision-making (Christenson *et al*., 2014).

Cultivating students' critical thinking skills is particularly crucial in the study of nanotechnology and nanomaterials, where, beyond an understanding of nano characteristics, size, and measurement, students need to be primed to consider their benefits and risks to health and the environment (Moor and Weckert, 2004). The study of nanoscience can be construed as a multidisciplinary field of learning that incorporates aspects of economics and sociology because of its proximity to and use in everyday materials (Christine and Hayden, 2008; Laherto, 2011). Since nanomaterial prevalence and usage is estimated to continue increasing in industry and society, knowledge of nanoscience is important for science students (Sebastian and Gimenez, 2016). Moreover, students' exposure to these topics at elementary grade levels can be particularly apt for supporting their developing critical thinking skills (Zuranty *et al*., 2019). For example, teachers can use a problem-oriented approach that invites students to express and form opinions about social situations or controversial issues that stem from nanotechnology use (Feierabend and Eilks, 2011). These types of instructional approaches, which stimulate students' critical and creative thinking and argumentation, have the potential to increase students' interest and understanding of science concepts (Christenson *et al*., 2014) and their likelihood to select STEM topics in their future studies.

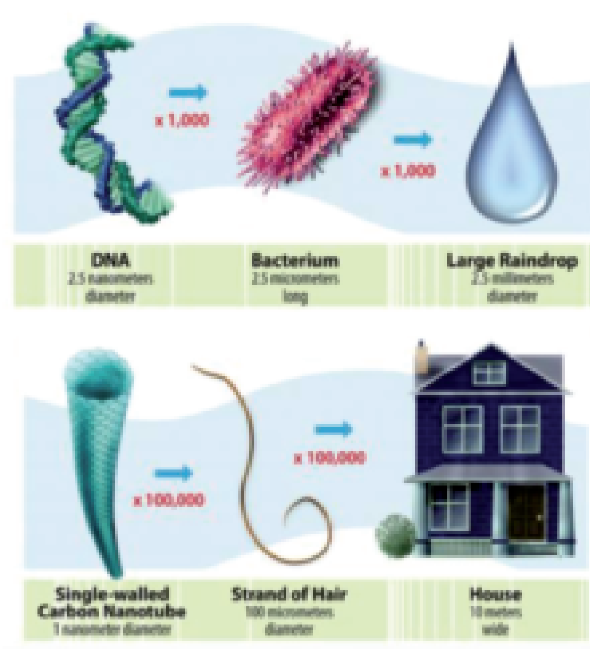

Figure 1. Scale of nano. Courtesy of United States National Nanotechnology Initiative, National Nanotechnology Coordination Office.

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Use of multimedia platforms

Multimedia technology on the web has generated much interest in instruction thanks to helpful ways to represent knowledge structures in line with a few of the learning theories. A few of the advantages of interactive media include visual, dynamic, spatial, veridical representation of data, random access, and more noteworthy, user control (Cognition and Technology Group at Vanderbilt, CGTV, 1997; Kumar, 2010). For points of interest on how multimedia innovation has been utilized to broaden the setting of PBL, see *Problem-Based Learning in Nanotechnology* (Kumar, 2015), *The River of Life* (Kumar and Sherwood, 2007), and *Adventures of Jasper Woodbury* (CGTV, 1997). These multimedia applications moreover involve hands-on learning and give classroom teachers the adaptability to make fundamental adjustments based on their curricular needs. Web-supported multimedia has the possibility of enhancing students' knowledge building and may lead to more meaningful learning outcomes. Due to the enriched context of learning that web-supported multimedia provides and that positively impacts hippocampal functions, its use may offer more meaningful and diverse science learning opportunities for students (Collins, 2007; Sakon *et al*., 2014). Moreover, developments in neuroscience and associated brain-based learning show an association between the critical role of context and learning (Funa *et al*., 2024).

Web-supported multimedia platforms allow for numerous creative approaches to enhance the context of learning, such as using stories or parables (The Zondervan Corporation, 1995-2010). A parable is a method of instruction using allegorical illustrations that present human characters (e.g., the good Samaritan) and which is separate from fables, where animal characters and inanimate objects are used (e.g., Aesop's Fables; Oxford University Press, 2016). John Dewey's (1933) experiential learning is another creative approach that suggests that students take up knowledge more readily when information is organized and contextualized within a real-life experience that matches their capabilities and readiness. The use of case studies, proposed by Charles Gragg (1940), is yet another creative approach that allows students to learn about a contextualized dilemma told with characters and dramatization. The case study is particularly democratic and interactive as a teaching approach because it positions students to learn about the issues and consider approaches for solving the problem. A note should be made that augmenting the context of science learning is not limited to the use of multimedia applications. Liritzis (2024) proposed integrating science with arts, and Bountis (2025) proposed taking advantage of the science of complexity to make science more interdisciplinary and meaningful to learners, and these approaches can be implemented through carefully developed web-supported multimedia instructional platforms.

Among these techniques, multimedia platforms enable the recreation of authentic episodes that can enrich the context of problem-based learning (CGTV, 1997; Kumar, 2010, 2015) thanks to unprecedented developments of the internet that now offer a variety of multimedia, electronic communication technologies, and artificial intelligence affordances. Information-rich contexts, such as those proffered in online mediums, can be fundamental for developing enhanced contexts to improve problem-based learning in science education that better engage students. Frequently alluded to as «macro-contexts,» information-rich contexts encourage the active construction of knowledge by learners and contrast with «micro-contexts" in ways that previous iterations of conventional educational technology applications failed (CGTV, 1997; Jin and Bridges, 2014). Especially for the purposes of PBL, which seeks to integrate real-world problem situations into classrooms, multimedia platforms allow for such topics to be presented in a realistic and interesting fashion.

One early and foundational example of multimedia-based PBL applications is Sherwood's (1980) *Golden Statuette,* which is an uncopyrighted experimental work that sheds light on how an enriched context may be developed to bolster science learning experiences. The episode was developed with the intention of providing a real-world PBL setting for introducing the concepts of volume by displacement and density. In the episode, a man spray paints an old, lead statuette in gold in hopes of fooling a shop owner about its worth. The man hands the statuette to the shop owner, explaining that the antique was given to his grandfather by a Middle Eastern potentate in exchange for a portable radio and that he needs to sell the valuable memento to obtain money for his mother's surgery. To assess its value, the shop owner uses the displacement method to determine the mass and volume of the statuette. When the calculated density emerges as that of lead at 11.35 gm/cc, the shop owner offers the startled man 20 cents, showcasing how applications of science helped the shop owner to avoid the man's attempts to fool him. When exposed to the *Golden Statuette* episode and engaging in hands-on activities involving volume and density calculations by displacement, undergraduate science education students expressed a greater appreciation for science as they were able to see its association to societal applications in an authentic context (Kumar and Hofwolt, 2002).

Description of the PBL nanotechnology module

Following the style and objectives of Sherwood's *Golden Statuette*, Kumar (2011, 2015) developed an online PBL module entitled *Catching the Rays* that concerns informed consumer decision-making and selection between sunscreens containing nanoparticles (e.g., nano-scale size Zinc Oxide) and those containing regular particles (e.g., regular size Zinc Oxide). Featuring a five-phase learning cycle (Figure 2), the STAR Legacy Learning Cycle (Schwartz *et al*., 1999), the *Catching the Rays* module involves a narrator who navigates a teacher and students through the module, offering timely cues to research, brainstorm, reflect,

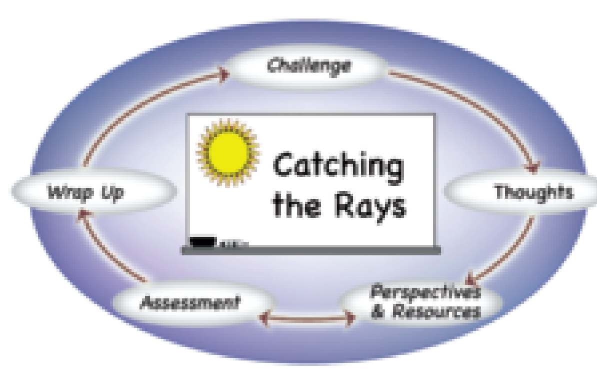

Figure 2. Modified STAR legacy learning cycle.

and test students' ideas concerning nano scale matter in sunscreen. In the "Challenge" phase, the teacher challenges students to make an informed consumer decision between using sunscreen containing nanoparticles or regular sunscreen.

During the "Thoughts" phase, the teacher introduces questions for students to consider, such as "What are nanoparticles?" and "How does sunscreen protect us from UV rays?" and guides students to pause the module and complete an Initial Thoughts organizer. In the "Perspectives and Resources" phase, the narrator invites students to conduct a search on the internet to develop a conceptual understanding of sunscreens, nanoparticles, and nanotechnology. During the "Assessment" phase, students are asked to reflect on their conceptual understanding developed during the "Perspectives and Resources" step by responding to the set of questions posed in the initial "Thoughts" phase. through assessing by trial and field testing and providing feedback and refining strategies. During the "Wrap Up" phase, the teacher invites students to prepare their presentation, select a suitable forum for presentation, and share their informed decisions on sunscreen selection based on the scientific evidence from both their Internet research and sunscreen UV bead research and support their decision.

In studies conducted on the impact of the "Catching the Rays" web-supported module, findings show that elementary school students (n=46) increased in their conceptual understanding and attitude towards science before and after engaging in the module (Kumar and Yurick, 2018). Based on the assessment of the quality of science learning, which evaluates students' scientific conceptual understanding, attitude towards science, and perception of science in society, students showed significantly higher understandings, attitudes, and perceptions in these three areas as related to their comprehension of nanoparticles. Data collected from post-evaluation interviews with these students suggested that students "have an accurate perception that nanotechnology comes with risks and benefits to society" (Kumar and Yurick, 2018) and "have an accurate perception that nanotechnology is governed by society's needs and that nanotechnology is used to help solve society's problems" (Kumar and Yurick, 2018). A retrospective analysis of the post-interview data for student decision-making processes in the *Catching the Rays* module showed most decisions by students were based on risks and benefits (e.g., damages to health, transparent sunscreens) and an understanding of nano properties (e.g., scale/size) (Kumar, 2011; Kumar and Yurick, 2018; Kumar, 2021). Students also discussed their increased knowledge of improved safety (e.g., impact on health), an understanding of the hands-on nature of science, a general feeling of science as "fun," a need to follow steps in scientific methods, society's needs, solutions to society's problems, the need to consult alternative perspectives, and science work ethic. See Table 1 for the questions and sample student responses and emerging themes for SCU, ATA, and PSS (Kumar, 2021).

Discussion

According to the National Academies of Sciences, Engineering, and Medicine (2022), science education in the elementary school years seems to influence the formation of lasting attitudes toward science and the development of scientific literacy in students well into their adulthood. Science at the elementary grades is critical to provide the scaffolding necessary to enhance the quality of science learning experiences. Elementary schools play a vital role in improving the quality of student learning in science disciplines and the pipeline to a competitive scientific workforce. The Florida Science Standards call for developing K-12 students informed decision-making skills and underscore the need for students to engage in scientific investigation involving data collection, data analysis, and evidence-based informed decision-making. The web-supported multimedia outlined in this paper augmented the context of PBL and provided a theory-based learning cycle to engage elementary students in solving a progressively student-centered consumer decision-making challenge. A brief discussion of the learning cycle and how the web-supported multimedia in PBL and informed decisions could be implemented in elementary science education.

Like the web-supported PBL module presented above, previous research has also found promising effects of other types of multimedia-based PBL applications. Aspects of the *Catching the Rays* module incorporated socio-critical approaches (e.g., the "Perspectives and Resources" phase) and problem-oriented approaches (e.g., the "Challenge" phase), both of which have been

Table 1. Sample themes emerging from responses to interview questions in the quality of science learning categories SCU, ATS and PSS.

Emerging theme: Nano properties
Question prompt (SCU): What did your energy bead activity teach you about sunscreens containing nanoparticles and regular sunscreen?
Student response: "…nanoparticles [sunscreens] are clear … and they protect better. Regular sunscreen scatter are white and bulky…" (LG student); "The nano energy bead activity taught me nano protects better because it absorbs and it is clear. The regular sunscreen scatters and it's white" (MG student).
Emerging theme: Risks and benefits
Question prompt (SCU): Is the nanotechnology in sunscreen risk free? Explain (SCU).
Student response: "It may get into the bloodstream" (LTNG student); "It might affect the problem they have with their skin." (MG student).
Emerging theme: Solves society's problems
Question prompt (PSS): Do you think there is a relationship between sunscreen manufacturers, nanotechnology and people? Explain (PSS).
Student response: "Yes, there is a connection because the manufactures since they need products to keep people[']s skin to getting tanner and cancer they made nano and that relates to people to help them and keep them safe" (LG student).
Emerging theme: Hands-on
Question prompt (ATS): How do you feel about science compared to other school subjects? Explain using class examples.
Sample student response(s): "…you can actually conduct experiment… It's fun like when you do projects on say when you do projects on UV beads like we did in this lesson" (MG student); "...involves more experiments..." (LTNG student).

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shown to increase students' confidence in learning nanoscience concepts and applications as well as developing their critical thinking capacities (Rahmawati *et al*., 2020). Like findings in Zuryanty *et al*.'s (2019) study on the effectiveness of PBL on elementary students' critical thinking, the problem-based approach of the *Catching the Rays* module is likely to have contributed to increases in students' scientific conceptual understanding. When multimedia encourages students to construct the meaning of concepts and make connections (e.g., in a Legacy Cycle format) as opposed to memorizing facts, students are likely to develop a deeper understanding of the science concepts and be able to transfer that knowledge to novel problems (Cordray *et al*., 2009). Beyond the success of Catching the Rays in deepening students' science conceptual understanding, the module also provides instructional design support for teachers that ensures students are exposed to and practice application-based scientific methods for society-relevant science (Klein and Harris, 2007).

While the application of web-supported anchors dealing with nanotechnology in PBL is promising to promote engaging science education, the technology platform itself does not substitute the promotion of meaningful teaching and learning. Science instruction requires teachers to be knowledgeable about the physical and chemical sciences, and particularly the underlying important science concepts concerning nanoscale materials, to use such information to draw the attention of students (Lin *et al*., 2015). Unusual magnetic, electrical, optical, and chemical properties exhibited by materials at the nanometer scale because of quantum effects are counterintuitive enough to catch the attention of learners at any age level and engage them in exploring science. For example, regular zinc oxide appears white because it scatters most of the light waves interacting with it, while nano zinc oxide is small enough to allow most light waves to pass around it; hence, for one reason, sunscreens with nano zinc oxides appear colorless. This counterintuitive phenomenon provides an opportunity to gain the attention of learners, especially in the elementary grades, to think about the science and associated concepts and principles they learn through observable properties (Maulana *et al*., 2022). However, teachers need to be aware of and informed of these phenomena and how to incorporate them in interesting, appealing ways for student consumption.

Recommendations for teaching

There are several recommendations that can be made for teaching web-supported PBL and informed decision-making in nanotechnology in elementary science education. Throughout the sunscreen selection research process, the teacher can reinforce the design of the module by taking an active approach to supplement and facilitate its directions. The teacher can encourage students to take into consideration a variety of perspectives, such as consulting reference sources of basic information and providing guidance as students conduct their own hands-on laboratory-based research. Along with the additional resources in the *Catching the Rays* module to facilitate more hands-on research activities (e.g., to conduct sunscreen experiments using UV-detecting beads), teachers can supplement by finding related activities (from reliable sources) by searching popular content platforms such as YouTube. After completing the sunscreen testing activity with UV beads, students could engage in additional research using the Internet and visiting local sunscreen stores with parental supervision. Some of the research activities could include comparing brands, prices, SPF ratings, active ingredients, inactive ingredients, and product reviews in terms of health and consumer support/complaints. This could take place during the assessment phase of the learning cycle, which might overlap with perspectives and resources and be reported at the wrap-up phase.

Another supplementation to the *Catching the Rays* modules is having elementary students engage in a coloring activity as part of the assessment step of the learning cycle. Once students come up with their scientific reasons for the differences in the appearance of sunscreens with nano-sized particles and sunscreens with regular-sized particles, they could be invited to engage in this coloring activity. As noted earlier, regular sunscreens containing regular-sized zinc oxide appear white because the zinc oxide scatters most of the light waves interacting with it. In sunscreens containing nano-sized zinc oxide, the size of the zinc oxide is small enough to allow most light waves to pass around it. Students could use coloring to illustrate these two conditions of light waves interacting with regular and nano-sized zinc oxide particles. With creativity, the coloring activity could be made a meaningful, funfilled, and colorful activity by integrating other related concepts and principles.

Teaching methods and student learning styles vary considerably within and across science disciplines, grade levels, and classrooms, and it is recommended that teachers make classroom-specific adjustments to PBL supported with web-based anchors. Plumley (2019) pointed out that less than 53% of elementary school science classes offer hands-on learning experiences, though 93% of elementary school teachers agree that when instruction is connected to students' everyday lives, they learn the best. The web-supported PBL module provides real-world connections because of its design involving the Legacy Learning Cycle and video anchors and seems to promote decision-making skills involving modern topics, such as nanotechnology. Developing PBL modules in nanotechnology anchored in multimedia that is designed with established cognitive theories of learning (e.g., anchored instruction) is a win-win situation, providing scaffolding for teachers and students and a non-invasive means to build better student attitude in science subjects.

AI applications for web-supported multimedia

Given recent expansions of artificial intelligence (AI) software and use, its application in web-supported multimedia anchored educational systems should be explored (Kumar, 1995), particularly its potential for scaffolding instruction and learning. Integrating AI can assist students to gather background data when comparing sunscreens containing regular zinc oxide and nanosized zinc oxide, as well as to identify sources that indicate chemical properties, physical properties, and related health-related information of nanomaterials. Teachers can create a scenario where students compare their sunscreen activity results against AI-generated results. With ChatGPT, the role of artificial intelligence in anchored instruction, problem-solving, and decisionmaking remains a promising area for research and development. In this context, improving the quality of student learning in science remains a pedagogical challenge for K-12 science educators.

Often, instructional materials developed by third parties might not fit well with the individual teaching styles of teachers. Teachers should feel encouraged to explore and use other effective ways of teaching PBL, developing instructional materials that reflect their own real-world contexts alongside educational technology platforms. If the teacher is developing multimedia anchors and identifying the context of PBL in nanotechnology, it is important to ensure that the context is incorporated into the web-supported multimedia and suitable for student viewing at the appropriate grade level. The context should contain information needed to gain student interest and attention in nanotechnology and must be in a language of communication familiar to and/or popular with students. Moreover, it is recommended that the science topics illustrated in the context fall within a topic of instruction in the school curricula. The teacher should be able to identify the science, technology, engineering, or mathematics concepts embedded in the contexts, how these align with the science standards in use that govern the school's curriculum and develop associated pedagogical skills that are meaningful and engaging.

Conclusions

Research has clarified beyond a doubt that a one-size-fits-all approach to science education is not effective. While web-supported PBL in nanotechnology is not the only way to engage students in problem solving, this platform and module design help to enlarge the context of science teaching and learning by connecting classroom science to real-world applications. Carefully developed web-supported multimedia anchors are excellent support resources for engaging elementary students in hands-on science activities, developing problem-solving approaches, and enhancing decision-making skills in advanced topics such as nanotechnology. These platforms offer support to teachers who are looking to increase problem-based learning approaches that spark students' interest and attention, and which studies show increase science understanding and critical thinking skills.

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