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Understanding Functional Materials at School

Johannes Claußnitzer and Jürgen Paul*

This review explores effective strategies for teaching nanoscience and nanotechnology in schools. It identifies typical challenges as key obstacles to learning, such as students' difficulties in understanding scale, applying physical laws across different orders of magnitude, and working with powers of ten. Media-influenced biases, limited curriculum integration, and motivational issues further complicate teaching. To address these challenges, the review emphasizes the importance of linking nanoscience to core concepts in chemistry education like structure-property relationships, supported by multiple levels of representation. Inquiry-based learning is presented as a central approach to enhance student engagement and scientific understanding. By incorporating real-world contexts, hands-on experimentation, and science communication projects, educators can foster curiosity and critical thinking. The review also highlights various successful teaching examples, including classroom and out-of-school activities, digital tools, and interdisciplinary collaborations. A central conclusion is that teachers play a pivotal role as multipliers in both science education and science communication. Therefore, profound teacher training and professional development are essential to prepare students for participation in a technology-driven society.

1. Introduction

Advanced functional materials are crucial for many current and future technologies, including various fields such as electronics, photovoltaics, nanotechnology, and biomaterials. The associated research is developing rapidly, which also reflects the need for progress and success of these modern technologies. Some widely cited reviews summarize recent advances in these areas, e.g., battery development,[1] nanotechnology in medicine,[2,3] or zwitterionic biomaterials in engineering applications.[4] In general, the success of a technology always depends on two fundamental factors: The technology must function properly, and the technology must be accepted by human society.[5] For new technologies to work properly, appropriate research is essential. Societal acceptance requires both public trust in science and research and a basic understanding and ability to utilize the resulting technologies. This is why science communication and science education are key to the success of new inventions. They promote public acceptance and understanding. And this, in turn, is also a key to the funding of future research by state and public institutions.[6] In addition, a high-quality science education at school generates the necessary young talents for scientific research and engineering.[7] This review thus highlights typical challenges and promising perspectives for teaching, communicating, and understanding functional materials in schools, with a focus on nanoscience and nanotechnology.

J. Claußnitzer, J. Paul
Department of Biology and Chemistry Education
University of Bayreuth
Universitätsstr. 30, 95447 Bayreuth, Germany
E-mail: johannes.claussnitzer@uni-bayreuth.de

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2. Typical Challenges When Teaching Nanoscience

To analyze learning processes, we combine constructivism[8] and a revised conceptual change approach[9,10] that incorporates a situated perspective of learning.[11] We consider students to be individual learners who actively and self-regulatedly construct knowledge based on their pre-existing conceptions. These conceptions typically derived from everyday experiences may either facilitate or hinder learning.[12] The learning process cannot be fully controlled by external factors but can be initiated and supported by learning environments. We therefore understand conceptual change as the reconstruction of conceptions,[13] in which conceptions can be further developed, transformed, or newly formed, depending on the context and the individual.

Accordingly, students often enter lessons about nanoscience and nanotechnology with diverse and sometimes inaccurate conceptions that significantly affect their learning process. A common misunderstanding concerns the scale itself: many students struggle to grasp just how small a nanometer is and may conflate the nanoscale with the micro-scale or the atomic level (**Figure** 1(1)).[14,15] Young learners (below 9th grade) often distinguish only one category for objects smaller than themselves (small), while experts distinguish five categories (small, very small, barely visible, many atoms, and atomic).[16] Some students interpret "nano" simply as "really small". Such conceptions easily lead students to ascribe familiar macroscopic properties – such as color, malleability, or gravitational dominance – directly to atoms and molecules.[17,18] Consequently, students may assume, for instance, that single gold atoms possess the same characteristic color and malleability as bulk gold. This is based on a

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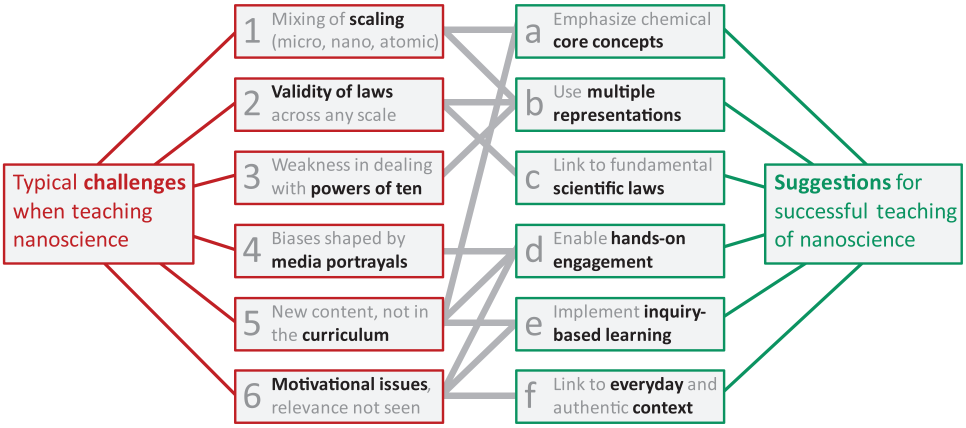

Figure 1. Challenges and suggested solutions for teaching nanoscience in schools. Grey lines indicate connections between challenges and proposed solutions.

frequent challenge in chemistry education when drawing conclusions about the properties of a substance from the structure of its particles, which is why we address this issue as a core concept separately in the next chapter.

A second, closely related challenge concerns students' tendency to generalize all laws of physics across every scale, mistakenly treating gravitational or classical mechanical principles as though they dominated interactions at the nanometric range (Figure 1 (2)).[19] In reality, electromagnetic forces are far more critical at extremely small dimensions, where quantum phenomena often supersede macroscopic rules. As a result, students can overestimate or underestimate the implications of nanoscale phenomena, failing to recognize that materials can acquire fundamentally different properties when particles become very small. Students typically do not acknowledge the unique quantum effects or the altered surface-to-volume ratios that give rise to novel behaviors at the nanoscale.[20,21] Students also find it difficult to identify precisely which fundamental forces – or which hybrid of physical, chemical, and biological concepts – are most relevant when explaining nanoscopic processes such as friction or light emission in an LED.[22,23]

Another key obstacle involves recognizing and assigning consistent numerical values to very small units or events. Although learners might label a virus or an atom as "tiny", accurately placing these objects in the correct order of magnitude proves problematic.[24] This weakness in working with powers of ten (Figure 1 (3)) leads to confusion not only with spatial dimensions but also with phenomena such as evaporation (involving molecular separation) or cellular division (involving the micrometric scale). Such misunderstandings highlight how difficult it is to help students visualize processes at both macro and nano scales.[25] The most sophisticated scale is the logarithmic scale. On this scale, the distance between objects does not reflect their subtractive size difference in reality, which makes it particularly difficult to understand.[26,27]

Beyond issues of scale, students often carry preconceptions shaped by media portrayals (Figure 1 (4)). For instance, they may associate nanotechnology primarily with futuristic or science-fiction scenarios, which can lead to an emphasis on sensational aspects (e.g., tiny robots, invisibility cloaks) rather than developing a grounded understanding of real-world applications.[28] In some cases, misconceptions involve the belief that nanotechnology is inherently dangerous, spurring fears disproportionate to the actual risks, or conflating risks from bulk chemicals with those of nanoparticles.[29,30] Conversely, some students perceive nanotechnology as universally beneficial "magic dust" that can solve global problems instantly, without appreciating the complexity of research, safety testing, and ethical considerations.[31]

In addition, several motivational issues can inhibit deeper engagement with nanoscience (Figure 1 (6)). Learners often compartmentalize classroom knowledge, treating nanotechnology as an exotic add-on rather than as an extension of fundamental physics, chemistry, and biology. Because nanoscience is deeply interdisciplinary, students need strong conceptual connections among these fields – a point, educators frequently underemphasize.[21,32,33] Furthermore, teachers themselves may receive limited formal preparation in nanoscience, making it challenging to integrate relevant content consistently.[34,35] Similarly, in some contexts, students show a lack of interest in integrating nanoscience into the formal curriculum (Figure 1 (5)). Although students generally acknowledge that nanotechnology drives cutting-edge developments in medicine, new functional materials, and digital devices,[36] they do not necessarily wish to study its basic principles during high school. This attitude may be partly due to a lack of prior knowledge or a perception that nanoscience and nanotechnology a purely specialized topics best addressed in specific extracurricular contexts, advanced university courses or professional settings.[37,38] Moreover, school teachers are faced with the problem that state-of-the-art nanotechnology experiments sometimes utilize methods of instrumental analysis that are not available in schools, such as scanning electron microscopy.[39] Occasionally, chemicals are used that cannot be obtained due to strict budget limitations or that students are not permitted to use in experiments for safety reasons. Besides the motivational issues, there are also problems with the equipment at schools.

To summarize, educators who want to introduce nanoscience and nanotechnology in schools must overcome several interrelated hurdles. Students' misconceptions regarding scale, matter, and natural laws intersect with numerical and representational challenges, while limited curricular resources, teacher preparedness, and varied student motivation add further complexity. Effective instruction will likely require a coordinated approach that uses hands-on demonstrations, interactive digital simulations, and deliberate discussions linking macro-level principles to nanoscale realities. By addressing both the cognitive and attitudinal barriers, chemistry education can help learners appreciate how nanoscience grows out of and reshapes classical ideas, thereby fostering a clearer, more integrated understanding of the smallest scales in our technological world.

3. Core Concepts in Chemistry Education

A key to conveying an understanding of functional materials in schools is to link current research, e.g., in nanotechnology, with core concepts of chemistry. Traditional classifications consider the properties of substances according to the groups to which the elements involved belong in the periodic table. In organic chemistry, other substance classes, such as alcohol or carbonyl compounds, are considered depending on the functional group. As there are always many important representatives of each substance class with historical, technical or social significance, these substance classifications are often presented very intensively in school lessons. This often leads to an abundance of details, which is detrimental to an in-depth consideration of the relationships and understanding.[40]

Accordingly, educational strategists, researchers in chemistry education, and curriculum creators seek to emphasize "Anchoring Concepts",[41] "Core Ideas",[42] or "Basic Concepts".[43] Those core concepts derived for chemistry education are very similar across countries, focusing on the concepts of 1) structure and properties of substances and their particles, 2) chemical reactions including kinetics and equilibrium, and 3) energy and thermodynamics. In line with the first core concept, many chemistry educators argue that the distinction between the level of substances and the level of their particles as well as deliberate switching between these levels are of central importance for a profound understanding of chemistry.[44–46] Correspondingly, students should learn to explain and derive the properties of the substance from the structure of its particles. The clear distinction between the levels is also intended to prevent students from believing, for instance, that single gold atoms possess the same characteristic color and malleability as bulk gold (see above). The systematic linking of macroscopic observations with submicroscopic structures and symbolic representations (according to Johnstone's triangle)[44] underpins representational competence,[47] which is particularly needed when teaching functional materials. Conversely, the teaching of functional materials, e.g., nanotechnology, can be superbly used to further deepen the understanding of the core concepts in chemistry. Thus, combining some fundamental challenges mentioned above with the importance of core concepts in chemistry education, two guidelines for teaching nanoscience can be deduced: 1) Emphasizing multiple representations of scale and 2) connecting to basic scientific principles and laws (Figure 1a,c).

An essential step is to make explicit the relationship between macro-, micro-, and nanoscales as well as the switch between experienceable macroscopic observations and modeling submicroscopic structures, using multiple external representations such as diagrams, scaled images, videos, and physical or virtual models (Figure 1b).[48] Students commonly conflate nano- with microdimensions, underestimating the magnitude of changes and the new phenomena that appear at the nanoscale.[24,25] By integrating representational aids – such as side-by-side illustrations of viruses, atoms, and molecules – teachers can help learners develop more accurate mental models. In addition, inviting students to compare different forms of media (e.g., animations, museum exhibits, or interactive simulations) fosters a deeper understanding of relative sizes.[22]

A second proposal is that nanoscience teaching should not assume students' mastery of fundamental physics, chemistry, and biology principles and their application to specific settings. Instead, instructors must explicitly address the limits of classical laws – for instance, gravitational force is negligible at the nanoscale, while electromagnetic effects become dominant (Figure 1c).[17] Teachers are therefore advised to design lessons that carefully contrast macroscale phenomena (e.g., friction or light emission) with their nanoscale underpinnings, incorporating tasks that prompt students to consider the different forces or quantum effects at play in the latter.[19] Providing short narrative or experimental demonstrations to illustrate, for instance, how light interacts with nanomaterials differently than with bulk substances, has been shown to clarify these distinctions.[21] In this way, bridging the macroscopic, microscopic, and nanoscale through core concepts of chemistry not only illuminates the fascinating chances and frontiers of functional materials but also sows the seeds of enduring scientific curiosity, empowering learners to comprehend and appreciate the elegant interplay between scale, structure, and properties that underlies our material world.

4. Relating Hands-On Engagement to Everyday Contexts

As described above (see Chapter 2), there are further challenges that typically arise when teaching nanoscience: the belief that nanotechnology is futuristic or dangerous, motivational issues, the lack of integration of nanoscience into the formal curriculum, and challenges with equipment. In order to meet these challenges constructively, it turned out to be beneficial to promote inquiry-based learning and hands-on engagement as well as to link nanotechnology with everyday contexts and authentic careers (Figure 1d–f; e.g.,).[49,50]

Inquiry-based learning represents a prominent domain of science education.[51] The term "inquiry" here spans three distinct perspectives: 1) scientists conducting investigations using scientific methods, 2) students engaging in active learning by performing inquiry tasks like scientists, and 3) teachers providing suitable learning environments and support. Regardless of the perspective, the inquiry process itself encompasses key components such as formulating scientifically oriented questions, drawing conclusions from evidence, and examining alternative explanations (e.g.,).[52–55] All of these components can come together in experimentation, a scientific procedure that generally, though not invariably, involves the following steps (see **Figure 2**): 1) generating a research question, 2) formulating a theory-based hypothesis, 3) designing an appropriate experiment, 4) conducting the experiment, 5) documenting observations and collecting data,

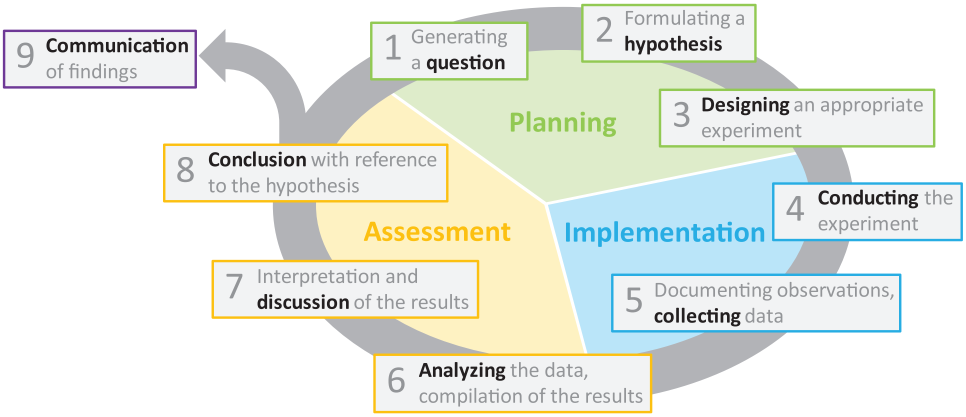

Figure 2. The research cycle with its typical steps of scientific inquiry during experimentation, in line with Pedaste et al.[57]

6) processing and analyzing the data, compilation of the results, 7) interpretation and discussion of the results, 8) conclusion with reference to the hypothesis, and 9) communication of the findings. Usually, the conclusions drawn raise new questions, which is why we refer to this procedure as the "cycle of research" representing the typical structure of scientific inquiry. Of course, we do not assert that this sequence is the only possible scientific procedure. Nevertheless, there is extensive national and international agreement on the importance of conveying such a fundamental understanding of scientific thinking and practice (e.g.,).[56]

In science lessons at school, experimentation has multifaceted functions to foster four major learning objective areas:[58] 1) learning science (acquiring content knowledge), 2) learning to do science (developing psychomotor and methodological skills), 3) learning about science (understanding the nature of scientific knowledge), 4) and learning to like science (nurturing affective and motivational aspects). Experiments can serve as, for instance, introductory, problem-solving, consolidation, or assessment tasks. Even the same experiment may be employed as an "entry" to spark curiosity or as a "confirmation" experiment to solidify conceptual understanding. Teachers must therefore carefully determine the didactic role of an experiment based on curricular aims and students' prior knowledge. The goal of "learning to do science" is to support and promote both the students' lab experience and skills of inquiry.[59,60] While the commonly used "cookbook" experiments, which typically only cover steps 4 to 6 of the research cycle (cf. Figure 2), can effectively introduce basic lab techniques, the rare authentic inquiry settings require learners to coordinate hypotheses, planning, observation, and interpretation.[61,62] These different levels of inquiry therefore not only differ in instructional aspects (structured, guided, open, or authentic inquiry), but also address different competencies.[63,64] Deeper learning and understanding can be achieved primarily through more authentic inquiry, in which students take over as many steps of the research cycle as possible.[65] Moreover, authentic inquiry can better pave the way for comprehending key aspects of the Nature of Science (NOS), such as the tentative nature of scientific knowledge and the creativity among scientists.[66–68] Finally, "learning to like science" underscores the motivational value of hands-on laboratory experiences. Successful experiments can generate enthusiasm, and apparent "failures" are valuable learning moments if handled constructively. Autonomy, experience of competence, and social relatedness are crucial to sustaining long-term interest.[69] Hence, by integrating student-oriented hands-on experiments, science teachers can promote comprehensive scientific literacy and a deeper appreciation for the subject.

For teaching nanoscience, hands-on engagement through experimentation is thus very well suited to increasing motivation for nanotechnology topics.[36] For example, small-scale experiments that demonstrate new and unique properties emerging at nanometric dimensions, like color changes in colloidal gold or shifts in reactivity, can help and engage students to see the sharp contrast between nanometric and everyday-size objects.[32,34] This practical focus also reinforces cross-disciplinary links to biology, physics, and engineering, since students perceive how nanoscopic concepts intersect with broader scientific and technological domains. When direct experimentation is not feasible, virtual laboratories and remote microscopy can still heighten awareness of what "nano" means.[70] Besides motivational aspects, student-oriented experimentation also solves two other challenges. Since it is a hands-on engagement, students deal directly with nanomaterials, which allows them to experience for themselves that nanotechnology is neither science fiction nor particularly dangerous. In addition, conducting experiments is embedded in the curriculum, enabling the teacher to link nanoscience to the formal curriculum twice – through experimentation as well as through the core concepts of chemistry (cf. chapter 3).

Equally vital is showing students how nanotechnology overlaps with their daily experiences and potential career paths. Relating to hands-on engagement, students can explore medical uses of nanoparticles for drug delivery,[49] and examine energy solutions involving nanoscale solar cells[71,72] or nanoparticles in sunscreen.[50] Collaborative projects, guest speakers from local industries, and problem-based scenarios can spark student curiosity by clarifying how nanotechnology offers career pathways beyond conventional chemistry or physics jobs.[37] By grounding nanoscience in tangible, hands-on exploration and everyday contexts, educators not only dispel misconceptions and kindle students' curiosity, but also enlighten the many real-world pathways where nanotechnology shapes and enriches our lives – ultimately cultivating both a profound scientific literacy and an enduring sense of wonder.

5. Examples of Promising Learning Opportunities

To provide exemplary ideas on how an understanding of functional materials can be taught in schools, this chapter compiles examples of hands-on experiments, science communication projects or other promising learning opportunities in the field of nanotechnology education. For this, we selected some publications that address typical challenges when teaching nanoscience or our suggestions derived above (see Figure 1). We also included some recent review studies that have, e.g., analyzed the distribution of articles in this field across the various journals or identified trends in nanoscience teaching.[73]

In a nanotechnology course for upper secondary chemistry classes, hands-on experiments with titanium dioxide (TiO_2) were conducted.[50] Titanium dioxide nanoparticles are among the most extensively studied nanomaterials due to their diverse properties.[74] Accordingly, they are incorporated into a wide range of products, covering sunscreen and other cosmetics, wood preservatives, optical brighteners for textiles, and food items, which also make the perfect connection to everyday life (Figure 1f). In the laboratory part of that course,[50] student experiments included the isolation and detection of titanium dioxide nanoparticles in everyday products, their characterization, and the investigation of their properties and current applications, such as photocatalytic activity or antimicrobial effects.

Learners are particularly motivated to engage with a specific topic when it affects their everyday reality, or it addresses a deeper meaning with a great impact. This is particularly true in the context of Education for Sustainable Development (ESD), which incorporates environmental as well as economic and social aspects. ESD is relevant here for at least two reasons. 1) Due to the complexity of sustainability issues and since the goals of ESD are often on an abstract level and the link between behavior and its consequences is far afield and therefore barely experienceable,[75] appropriate student-oriented hands-on experiments enable authentic experience and self-drawn conclusions. 2) Nanotechnology has the great potential to create a deep and meaningful link between inquiry, technology, and sustainable development. For example, experiments with gold nanoparticles can specifically explore the plasmonic properties of this nanotechnology in hands-on experiments.[76,77] Plasmonics may have a transformative impact on the way we will drive, manipulate, enhance, and monitor chemical processes in the future, which are fundamental for powering our society. There are many other exciting examples, where nanotechnology influences sustainability and vice versa, such as nanotechnology applications in fuels, medicine or sustainable agriculture.[2,3,78–81]

Another challenge can be tackled through such hands-on experiments: The media often take a critical view of nanotechnology, as safety concerns for both humans and the environment arise within the public (Figure 1 (4)).[82] To offer students a comprehensible and motivating learning opportunity for evaluating the toxicity of nanoparticles, particle size and size distribution of inorganic active ingredients (titanium dioxide or zinc oxide) of sunscreens can be investigated using dynamic light scattering.[83] With data from studies demonstrating the skin absorption of small, detectable quantities of certain-sized nanoparticles,[84,85] students can conduct their own toxicity assessments. However, this experiment requires cooperation between the school and university, since some of the employed methods, such as scanning electron microscopy, are not available at schools. Such collaborations can be implemented excellently with the help of student laboratories or student research centers as out-of-school learning environments at universities.[86] Thus, several student labs offer various programs and experimental settings about nanotechnology (e.g.,).[87,88] The problem of a lack of equipment at school can therefore be circumvented through partnerships between schools and universities. Adapting experiments also sometimes lead to success: Gold nanoparticles can be synthesized using the method of laser ablation in liquid,[89] which requires a special laser and elemental gold. However, gold nanoparticles can also be synthesized in a Leidenfrost reactor, which only requires a simple heating plate.[90]

Further hands-on experiments on characteristics of nanomaterials can be carried out with school equipment, e.g., the investigation of the effect of zinc oxide and silver nanoparticles on yeast during alcoholic fermentation.[91] By measuring the carbon dioxide yield, in an inquiry-based setting, learners can estimate the toxicity of nanoparticles and evaluate their use in everyday products. In another experimental setting for schools, magnetic iron oxide nanoparticles were synthesized and stabilized using ammonium cations or polyvinyl alcohol to produce amazing materials such as safer aqueous ferrofluids, ferrogels, ferromagnetic inks, plastics, and nanopowders illustrating how versatile materials can be produced just by simple modifications.[92] Considering all these hands-on experiments, inquiry-based learning, where students go through as many steps of the research cycle as possible (Figure 2),[65,93] not only motivates students and fosters a better understanding of nanomaterials but also promotes a deeper understanding of scientific knowledge acquisition and thus a better connection of nanoscience to the curriculum (Figure 1(5e)).

Many experiments at school only focus on steps 4–6 of the research cycle (chapter 4, Figure 2). In addition to planning experiments (steps 1–3) and drawing conclusions from the data obtained (steps 7–8), the communication of findings is an important and vital part of science (step 9). This is why science communication projects are worthwhile for science education. In a "minds-on project", students learned, through concrete examples, how scientific reporting differs from non-scientific reporting.[6] As one goal of this project, students were taught to communicate a topic in a way that provides honest and interesting information to a non-expert audience. The subsequent audience survey revealed, e.g., that non-scientific listeners were particularly convinced by content that highlighted future applications of nanotechnology and focused less on technical aspects. Science communication projects are also able to integrate different institutions. A collaboration between a scientific institute and a theater resulted in a public workshop that combined science communication with hands-on experiments.[15] The workshop addressed environmental issues due to the biological interactions of plastic nanoparticles.

Besides a closer understanding of the research cycle (Figure 2), some specific skills are essential for scientists and therefore also for generating future scientists, such as critical thinking, problem-solving strategies, and creativity.[67,94] Translating undergraduate research in nanotechnology, renewable energy, and sustainability into lesson plans at schools and engaging in outreach to diverse populations promotes equity in science education and encourages underrepresented groups to seek careers in a scientific field.[95] Furthermore, such outreach activities lead to a positive impact on local communities.

Finally, some examples are given of the explicit integration of chemical core concepts and the use of multiple representations to overcome scaling problems (Figure 1a,b). Innovations in chemistry occasionally provide equally innovative learning opportunities for chemistry lessons.[96] For instance, students typically assume that the surface of a lotus leaf must be smooth for a water droplet to run off. From a scientific point of view, however, it is a rough micro- and nanostructure that causes this effect. By introducing the core concept of structure and properties of substances and their particles (see Chapter 3), a suitable learning environment can be developed that integrates both perspectives in a constructive way.[43,97] In other settings, by using metallic nanoparticles, different color effects can be achieved depending on the particle size.[98–101] These color effects can be adequately explained using chemical core concepts. The platinum-catalyzed oxidation of hydrogen with oxygen can be used to show how the surface-to-volume ratio affects catalysis. Platinum nanoparticles have a significantly larger specific surface area relative to their mass and therefore accelerate the reaction considerably.[102]

In addition to diagrams, scaled images, and physical models (see Chapter 3), digital media can serve as versatile tools to provide multiple representations (Figure 1b), even if the corresponding real scientific method cannot be implemented at school. In a virtual reality lab, learners explore carbon allotropes and fullerenes by synthesizing them using the arc discharge method, analyzing their nanostructure with a transmission electron microscope, assembling molecular models, and 3D printing them.[103] Furthermore, digital technologies such as virtual reality (VR) make it easy to gamify learning content. For instance, in a VR scenario, learners assume the role of a forensic scientist who must solve a murder case.[104] Within this game, different levels of representations are transposed, e.g., the macroscopic level (pills lying around) and the submicroscopic level (the chemical composition of the pills). In other contexts, too, educational simulation games appear to be promising vehicles for making complex content experienceable.[75,105] Moreover, artificial intelligence can be used to teach the design of data visualizations, including multiple representations.[106] In summary, these various examples vividly demonstrate how hands-on experiments, science communication projects, and other innovative learning opportunities not only can promote a deeper understanding of nanotechnology by applying specific guidelines for successful teaching, but also empower students to engage critically, creatively, and collaboratively with the scientific world.

6. Conclusion

The advancement of modern technologies, such as nanomaterials and functional surfaces, relies not only on scientific breakthroughs, but also on public understanding and acceptance. This makes science communication and science education essential pillars of a technology-based society. This review therefore highlighted common challenges and promising approaches for effective teaching and promoting understanding of functional materials in school settings, with a particular focus on nanoscience and nanotechnology.

Students face several challenges. They frequently confuse micro-, nano-, and atomic scales, emphasizing the need for multiple representations and explicit comparisons to support accurate mental models of scale. Misconceptions can arise when learners incorrectly apply classical laws, such as gravity, to nanoscale phenomena where quantum and electromagnetic effects dominate, underscoring the necessity to contrast macro- and nanoscale principles in teaching. Difficulties in dealing with powers of ten and challenges in logarithmic thinking also hinder students' ability to grasp nanoscale dimensions. Media-influenced misconceptions or inaccurate perceptions – from exaggerated fears to unrealistic expectations – can distort students' understanding of nanotechnology, making critical media engagement and the integration of authentic context essential. The interdisciplinary nature of nanoscience often exceeds traditional curricular boundaries, requiring innovative teaching formats and collaboration with external institutions to ensure meaningful learning experiences. Without clear connections to everyday life or future career paths, students may perceive nanoscience as irrelevant or overly abstract, reinforcing the value of hands-on, student-centered, and context-rich learning opportunities.

To overcome these various challenges in science lessons, we provide some guidelines for successful teaching and a number of examples of concrete learning environments. Teaching nanoscience effectively requires linking to core concepts of chemistry, such as structure-property relationships. Students must learn to switch between macroscopic, submicroscopic, and symbolic levels to develop representational competence. Nanoscience can deepen these understandings by illustrating how novel properties emerge at small scales, thus reinforcing core ideas through real-world applications. Hands-on, inquiry-based learning fosters deeper understanding, motivation, and appreciation of science. By engaging in authentic experimentation – ideally covering all steps of the research cycle – students explore nanoscale phenomena in meaningful ways. This approach also counteracts fears and misconceptions, integrating nanotechnology into the curriculum in a compatible way while building competencies for scientific thinking and working. Numerous classroom and outreach examples demonstrate how nanotechnology can be made accessible. These include experiments with everyday products, student research projects, virtual labs, and science communication activities. Such formats promote creativity, critical thinking, and interdisciplinary understanding, while also making science relevant, inclusive, and engaging for diverse learners. This provides teachers with a comprehensive set of ideas and tools to enhance learning. However, this also requires correspondingly elaborate teacher training.

Ultimately, a science-oriented and technology-driven society depends on educators who can inspire, guide, and empower. Further improving teacher training and recognizing the central role of teachers as multipliers of knowledge is therefore a crucial investment in our collective scientific future. Good teachers are a key and indispensable factor in nurturing and developing good young talent.

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Conflict of Interest

The authors declare no conflict of interest.

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hands-on experimentation, inquiry-based learning, nanoscience, nanotechnology, science communication, science education, teaching guidelines

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Johannes Claußnitzer completed his studies in Chemical and Biological Engineering at FAU Erlangen-Nuremberg, Germany. He subsequently obtained his doctorate in Chemical Engineering from the University of Bayreuth. Following his completion of teacher training for vocational schools (specializing in laboratory and process technology), he served as a teacher before accepting his current position as Group Leader for Chemistry Education at the Department of Biology and Chemistry Education, University of Bayreuth. His current research focuses on Education for Sustainable Development, inquiry-based learning, and the integration of digital tools (e.g., extended reality and 3D printing) to connect Natural Sciences and Engineering teaching.

Jürgen Paul is a full professor and holds the chair of Biology and Chemistry Education at the University of Bayreuth in Germany. He studied Biology and Chemistry in Würzburg, Germany. After a research stay at the University of Arizona in Tucson, USA, he also taught biology and chemistry as a teacher at secondary schools. He then worked in science education and teacher training at the University of Bamberg, Germany. His current research focuses on education for sustainable development, inquiry-based learning, and the use of digital tools for teaching science.