

Review

Integrating real-world problems into chemistry curricula: Enhancing relevance and student engagement

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Abstract: Chemistry education plays a pivotal role in fostering scientific literacy and addressing global challenges. However, traditional curricula often fail to connect abstract concepts to real-world applications, leading to disengagement among students. This study examines how integrating real-world problems into chemistry education enhances student engagement and prepares them to address pressing global challenges. Grounded in constructivist, contextual, and situated learning theories, the paper presents actionable teaching strategies, including problem-based learning and case studies. These strategies contextualize abstract chemical principles within pressing global issues such as climate change, sustainable energy, and public health. The paper also addresses practical challenges in implementation, including resource limitations, curricular rigidity, and assessment complexities, and offers mitigation strategies such as leveraging digital tools and fostering industry partnerships. Empirical evidence highlights the effectiveness of these methods in improving conceptual understanding, critical thinking, and interdisciplinary collaboration. By aligning chemistry education with contemporary scientific practices and global needs, this study advocates for a transformative shift in pedagogy, ensuring students develop critical thinking, interdisciplinary skills, and the capacity to navigate complex global challenges.

Keywords: chemistry education; real-world problems; problem-based learning; student engagement; interdisciplinary education; global challenges; sustainable development

1. Introduction

Science education is undergoing a significant shift, with chemistry education leading the way in this pedagogical transformation. As global challenges become increasingly complex and interconnected, traditional paradigms of scientific instruction are being fundamentally reexamined [1]. Chemistry, a discipline intrinsically tied to addressing critical global issues—ranging from climate change and sustainable energy to healthcare advancements and environmental preservation—necessitates a radical reimagining of how scientific knowledge is taught, understood, and applied [1–3].

Chemistry is often referred to as “the central science” because of its integral role in connecting the physical sciences with life sciences and applied fields such as engineering, medicine, and environmental science [4]. Despite its importance, a significant challenge persists in chemistry education: students frequently struggle to see its relevance to real-world applications, leading to disengagement and a lack of enthusiasm for the subject [5]. This disconnect is particularly concerning in an era when global challenges—such as climate change, energy sustainability, water scarcity, and health crises—demand chemical solutions [5,6]. The question arises: How can

educators effectively bridge the gap between theoretical chemistry concepts and their real-world implications?

Contemporary chemistry education stands at a critical juncture. The conventional instructional model, heavily grounded in reductionist methodologies that emphasize rote memorization and abstract theoretical constructs, is increasingly misaligned with the interdisciplinary and applied nature of modern scientific practice [7]. This paradigm often frames chemistry as a fragmented collection of theoretical principles, isolated laboratory techniques, and decontextualized mathematical representations. Such an approach fails to capture the dynamic, problem-solving essence of the discipline and contributes to declining student motivation, curiosity, and deeper conceptual understanding [7,8]. For instance, many students perceive stoichiometry or thermodynamics as abstract exercises [9–11], disconnected from tangible applications such as sustainable manufacturing or renewable energy systems [12–15].

The implications of this educational disconnect are profound. Studies have consistently documented a decline in student engagement with chemistry, particularly at the secondary and tertiary levels [16–20]. Global scientific literacy surveys highlighted that many students do not perceive chemistry as a relevant or engaging field [21–24]. This perception gap represents more than a pedagogical challenge—it threatens the development of a scientifically literate society capable of tackling the pressing challenges of our time.

One promising approach to addressing this issue is the integration of real-world problems into chemistry curricula. By embedding real-life scenarios, case studies, and problem-solving activities into instruction, educators can help students connect abstract concepts to tangible applications, fostering deeper learning and long-term retention [25–28]. Real-world problem integration, for example, through the incorporation of research embodied by the rich literature [29–31], not only enhances the perceived relevance of chemistry but also equips students with the skills necessary to tackle interdisciplinary challenges in their future careers.

Emerging research emphasizes the transformative potential of contextual and problem-based learning (PBL) approaches [32,33]. These pedagogies situate scientific knowledge within authentic, meaningful contexts, fostering the application of complex conceptual frameworks to real-world scenarios. For instance, engaging students in challenges such as designing sustainable polymers or analyzing biochemical pathways in disease contexts allows them to see the relevance of chemistry while developing higher-order thinking skills. Additionally, collaborative research experiences and interdisciplinary integration encourage active learning and inquiry-driven exploration, moving beyond passive knowledge transmission [30,31]. The urgency of this educational transformation transcends academic concerns; it is vital for preparing a new generation of scientific practitioners capable of navigating the complexities of an interconnected world [34,35]. Systemic thinking, interdisciplinary collaboration, and applied chemical problem-solving are now essential competencies for addressing multifaceted global challenges [4,12], from mitigating climate change to advancing personalized medicine.

This paper critically examines the theoretical underpinnings, practical strategies, and empirical evidence supporting a contextual, problem-oriented approach to chemistry education. By evaluating current instructional paradigms and proposing

innovative pedagogical frameworks, we aim to contribute to a comprehensive understanding of how chemistry education can be strategically redesigned to align with the demands of contemporary scientific practice. Embracing these changes is not just an option but an imperative for fostering a scientifically literate and innovative society. Furthermore, this paper aims to address the gap between abstract chemical concepts and their real-world applications by proposing pedagogical strategies grounded in contemporary learning theories. The scientific contribution lies in synthesizing these strategies into a cohesive framework applicable across various educational systems. The work described herein primarily addresses the integration of real-world problems in secondary and tertiary-level chemistry education, focusing on these levels due to their alignment with the cognitive development of learners and the curricular flexibility typically available. However, many strategies discussed, such as contextual learning and problem-based approaches, are adaptable to other educational contexts, including primary education and informal learning environments, where foundational scientific literacy can also be nurtured. Practically, the paper provides actionable teaching methods, such as problem-based learning and case studies, to foster student engagement and interdisciplinary skills essential for addressing global challenges.

2. Theoretical foundations

Table 1. Theoretical frameworks and teaching methods supporting real-world problem integration in chemistry education.

Theoretical Framework	Core Principle	Application in Chemistry Education	Example Activities
Constructivist Learning Theory	Knowledge is constructed through active engagement with the environment.	Students investigate real-life phenomena by designing experiments and analyzing outcomes.	Exploring catalysts in industrial processes: students compare reaction rates with and without catalysts.
Contextual Learning Theory	Learning is most effective when connected to meaningful, real-world contexts.	Embedding abstract chemical principles into practical applications relevant to global challenges.	Using fuel cells to teach electrochemistry by calculating energy efficiencies of different systems.
Situated Learning Perspective	Knowledge is acquired within authentic, real-life practices.	Replicating professional practices in laboratory or fieldwork environments to provide context for learning.	Conducting environmental testing: students measure pollutants in local water samples and analyze findings.
Problem-Based Learning (PBL)	Engages students in solving complex, open-ended problems.	Encouraging collaborative approaches to solving interdisciplinary challenges, mirroring professional scientific practice.	Designing biodegradable plastics: students evaluate chemical synthesis routes and compare environmental impacts.

The integration of real-world problems into chemistry curricula is grounded in several well-established learning theories and teaching methodologies that emphasize the active, contextual, and social nature of learning. **Table 1** provides an overview of these theoretical frameworks and teaching strategies, illustrating how their core principles align with practical applications in chemistry education. These examples highlight the transformative potential of contextual and problem-based learning in fostering deeper understanding and skill development. Early exposure to these approaches is crucial, as it helps students build a strong foundation in applying theoretical knowledge to practical challenges [36,37]. Starting from introductory courses, embedding real-world contexts not only enhances student engagement but

also fosters a mindset oriented toward problem-solving and interdisciplinary thinking—skills essential for addressing global scientific challenges.

2.1. Constructivist learning theories

Constructivist theories emphasize that learners build knowledge through active engagement with their environment, integrating new information with prior experiences. This approach is especially effective in fostering deep learning, as it encourages students to explore and make sense of concepts rather than passively receiving information [38,39]. One pedagogical strategy that aligns closely with constructivism is Problem-Based Learning (PBL). In PBL, students are presented with complex, real-world problems that do not have a predefined solution. Through collaborative efforts, they research, analyze, and apply knowledge to find solutions, which promotes the development of critical thinking, problem-solving, and teamwork skills [40,41].

In the context of chemistry education, PBL can bridge the gap between abstract chemical concepts and real-world applications. For example, in a PBL chemistry course, students might be tasked with designing an eco-friendly plastic alternative. This would require them to understand the chemistry of polymers, thermodynamics, and environmental impacts. Such a project not only makes chemistry more relevant but also encourages students to apply their theoretical knowledge to practical, interdisciplinary problems [42]. Additionally, PBL fosters skills that are crucial for future careers in chemistry and related fields, such as the ability to collaborate with peers, think critically about complex issues, and communicate scientific findings effectively [43]. By introducing PBL early in the chemistry curriculum, educators can shift from traditional, teacher-centered instruction to a more student-centered approach, where learners actively construct their understanding in the context of meaningful, real-world challenges. This method has been shown to increase engagement, improve retention, and enhance the application of knowledge in novel situations [44]. Moreover, PBL encourages the development of transferable skills that students can carry forward into their professional lives, including research, decision-making, and ethical considerations in scientific practice [45–47].

2.2. Contextual learning theory

Contextual learning theory emphasizes that knowledge acquisition is most effective when learning is situated in meaningful contexts that relate to students' real-life experiences and potential future applications [48]. This approach is grounded in the idea that learning becomes more engaging and relevant when students can directly connect what they are learning to real-world problems. In the context of chemistry education, contextual learning fosters a deeper understanding by linking abstract chemical principles to global issues such as climate change, sustainable energy, and advancements in medical technologies. By applying contextual learning early in the chemistry curriculum, educators can help students recognize the practical applications of theoretical concepts. For example, discussing the chemical principles behind renewable energy sources, like solar or wind energy, can not only teach fundamental topics in thermodynamics and reaction kinetics but also highlight their importance in

solving the global energy crisis [49,50]. Similarly, understanding the chemical processes involved in drug synthesis or the development of sustainable materials for industrial applications can make chemistry lessons more tangible and relevant to students' future careers [51].

Furthermore, when students encounter real-world contexts in their learning experiences, they are more likely to feel motivated and engaged. The connection between content and its impact on global challenges can increase their interest in the subject, leading to greater participation and improved long-term retention [52]. For instance, projects focusing on water purification or carbon capture technologies can deepen students' understanding of environmental chemistry while simultaneously encouraging them to think critically about real-world solutions. Incorporating contextual learning not only enhances cognitive engagement but also fosters skills in problem-solving, critical thinking, and interdisciplinary collaboration, all of which are essential for future scientists. This approach reflects the growing need for education to produce graduates who are not only knowledgeable in their respective fields but are also equipped to address the multifaceted challenges of a rapidly changing world [53]. Thus, contextual learning aligns chemistry education with global needs, enhancing both the relevance and the impact of the discipline.

2.3. Situated learning perspective

The situated learning perspective, developed by Lave and Wenger [54], emphasizes that learning is fundamentally social and context-dependent, thriving in environments that simulate real-world application. This approach suggests that students gain deeper understanding and retention when actively engaged in authentic tasks within communities of practice. In chemistry education, this can be applied through experiential learning activities that replicate professional scenarios, such as environmental testing or pharmaceutical synthesis [55].

For example, a situated learning activity might involve students conducting water quality analyses to identify pollutants, mirroring environmental monitoring practices. Similarly, designing and testing a drug synthesis pathway in an organic chemistry class provides hands-on exposure to pharmaceutical development. Such tasks not only enhance content understanding but also foster interdisciplinary collaboration, critical thinking, and ethical reasoning—skills essential in modern scientific and industrial settings [56]. By embedding learning in real-world contexts, this approach prepares students to navigate complex challenges while reinforcing the relevance of chemistry to societal needs. Research indicates that situated learning significantly improves engagement and skill acquisition, aligning educational outcomes with the demands of professional scientific practice [57]. This underscores the importance of integrating authentic, context-rich activities early in chemistry curricula.

Together, these theoretical frameworks emphasize the importance of integrating real-world problems into chemistry education from the earliest stages. This approach not only supports deeper conceptual understanding but also prepares students to navigate complex, interdisciplinary challenges throughout their academic and professional careers.

3. Strategies for integration

To effectively bridge the gap between abstract chemistry concepts and real-world applications, a range of targeted strategies can be employed. These strategies should address a specific aspect of integration while highlighting practical approaches and pedagogical benefits.

3.1. Contextualizing abstract concepts

One foundational strategy is to anchor theoretical chemical principles in real-world contexts, making them more relatable and meaningful to students [58]. For example, teaching gas laws and thermodynamics through the behavior of greenhouse gases provides a tangible link to climate change science. Similarly, principles of green chemistry and renewable energy [59] can be framed within the context of Sustainable Development Goals (SDGs), such as SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action). By contextualizing abstract concepts in this way, students not only gain a deeper understanding of the material but also appreciate the broader societal relevance of chemistry in solving global challenges.

Implementation Example:

- **Greenhouse Gas Behavior:** Students calculate the relationship between pressure, volume, and temperature for atmospheric gases, applying the Ideal Gas Law to model how greenhouse gases like CO₂ behave under different atmospheric conditions. This activity includes using real-world datasets, such as NASA's atmospheric measurements, to analyze trends in greenhouse gas concentrations over decades. Students also create visualizations using software like Excel to interpret their findings. In educational systems with limited access to computational tools, manual calculations and graphing on paper can be utilized as alternatives, showcasing adaptability to different contexts.
- **Renewable Energy Systems:** Students conduct hands-on experiments to measure voltage and current output from various battery chemistries (e.g., lithium-ion, nickel-metal hydride) using readily available lab kits. They also design a comparative analysis of battery efficiencies, longevity, and environmental impacts, culminating in a presentation of their findings. To address disparities across educational systems, schools with advanced facilities might incorporate computer simulations of electrochemical reactions, while under-resourced systems can focus on basic experiments, such as assembling saltwater batteries or using lemon cells as proxies for renewable energy applications.

Connecting abstract chemical concepts to real-world challenges enhances student engagement and learning by demonstrating the practical relevance of these topics. **Table 2** showcases some representative examples of chemistry topics paired with real-world problems and suggested activities, offering a structured approach to making lessons more meaningful and impactful.

Table 2. Representative examples of real-world challenges integrated into chemistry topics.

Chemistry Topic	Real-World Challenge	Learning Activity	Expected Outcome
Acid-Base Chemistry	Addressing ocean acidification	Students calculate pH shifts in seawater due to CO ₂ absorption and discuss implications for marine ecosystems.	Understanding the chemical and environmental impact of acid-base reactions.
Thermodynamics	Optimizing energy efficiency in renewable systems	Investigate enthalpy and Gibbs free energy in battery or fuel cell reactions, comparing technologies.	Applying thermodynamic principles to improve renewable energy technologies.
Organic Chemistry	Designing sustainable polymers	Synthesize biodegradable polymers from renewable sources and analyze their properties.	Connecting organic chemistry to sustainability and material science.
Environmental Chemistry	Mitigating water pollution	Analyze contaminants in water samples and propose chemical treatment methods.	Gaining practical skills in environmental analysis and pollution control.
Analytical Chemistry	Ensuring food safety	Test for pesticide residues or contaminants in food using chromatography techniques.	Learning how analytical chemistry protects public health.

3.2. Case studies and problem-based learning (PBL)

Case studies derived from real-world scenarios and problem-based learning modules are particularly effective for engaging students in critical thinking and scientific inquiry [60]. In pharmaceutical chemistry, for instance, students can analyze the synthesis of drugs while addressing ethical concerns, cost-efficiency, and environmental impacts. Environmental chemistry offers similar opportunities; a case study on water pollution might involve identifying contaminants, understanding their chemical behavior, and proposing remediation strategies [61].

PBL extends these activities by requiring students to collaboratively address open-ended problems, mimicking professional scientific practice [62,63]. This active, inquiry-driven approach helps develop critical skills such as teamwork, creativity, and evidence-based decision-making.

Implementation Example:

- **Pharmaceutical Chemistry:** Students design a hypothetical drug for a specific medical condition, outlining synthesis routes, key reagents, and reaction conditions while incorporating green chemistry principles. They analyze regulatory frameworks (e.g., FDA guidelines) and assess production sustainability, including environmental impacts. Advanced systems might use molecular modeling tools, while less-resourced settings can rely on case studies or theoretical planning. Teams present their findings through reports and oral pitches simulating regulatory approval or investor meetings.
- **Water Pollution Case Study:** Students collect and analyze local water samples to measure pH, turbidity, and contaminant levels (e.g., nitrates, heavy metals). They assess pollutant sources based on land use and propose remediation strategies, such as filtration or bioremediation. Advanced systems may use spectrophotometry or GIS mapping, while others can focus on manual testing and theoretical solutions. Students present recommendations to local stakeholders, emphasizing cost-effective and sustainable methods.

3.3. Community-engaged projects

Community-based learning integrates chemistry education with civic engagement, allowing students to apply their knowledge to real-life problems that

benefit local communities [64,65]. For example, students might participate in water quality testing in underserved areas, using their findings to advocate for improved environmental policies. Alternatively, they could design low-cost biodegradable materials to address the issue of plastic waste. These projects not only reinforce technical knowledge but also instill social responsibility, showing students how chemistry can contribute to societal progress.

Implementation Example:

- **Water Quality Testing:** Students partner with local municipalities to assess water contamination by testing parameters such as pH, turbidity, and heavy metals. They propose chemical treatment methods, like neutralization or filtration, based on their findings. Advanced systems may include spectrophotometric analysis, while resource-limited settings focus on accessible tools like pH strips and simple filtration experiments. Students share results with community leaders to guide policy or practical interventions.
- **Biodegradable Materials:** Students design and prototype biodegradable packaging materials using renewable resources, such as plant starches or cellulose. They test chemical properties like tensile strength and degradation rates in lab settings. Advanced setups may include mechanical and thermal analysis tools, while simpler environments focus on basic physical and chemical tests. Findings are presented with comparisons to traditional plastics, emphasizing sustainability benefits.

3.4. Collaboration with industry

Partnerships with industry provide students with invaluable insights into the practical applications of chemistry in professional settings. Collaborating with local manufacturing firms, for instance, allows students to address real-world challenges, such as optimizing waste management processes or creating sustainable industrial products [66,67]. Such exposure not only demonstrates the relevance of their learning but also equips students with skills and experiences that enhance their career readiness.

Implementation Example:

- **Waste Management Challenges:** Students collaborate with a factory to identify sources of hazardous waste and propose chemical solutions to minimize production. Activities may include analyzing waste composition, optimizing reaction pathways, or designing neutralization processes. Advanced systems might employ industrial chemistry software for modeling, while resource-limited setups focus on basic lab simulations. Findings are shared with factory representatives, emphasizing cost-effective and sustainable waste reduction.
- **Agricultural Chemistry:** Students work with agricultural companies to develop eco-friendly fertilizers using locally sourced materials. They test fertilizer efficacy through plant growth experiments and analyze environmental impacts, such as nutrient runoff. Advanced systems may include soil analysis using spectrometers, while simpler settings utilize manual testing methods. Results are presented to stakeholders, highlighting both productivity and environmental sustainability.

3.5. Environmental chemistry challenges

Focusing on environmental challenges is a compelling way to integrate real-world problems into chemistry education. Hands-on projects, such as exploring carbon capture technologies or analyzing local water quality, enable students to apply chemical principles to address pressing ecological issues [68,69]. These activities highlight the role of chemistry in sustainability and empower students to develop innovative solutions to global environmental problems.

Implementation Example:

- **Carbon Capture:** Students experiment with chemical absorbents, such as sodium hydroxide or amine solutions, to capture CO₂ under varying conditions of temperature and concentration. Efficiency is measured using gas collection setups or titration methods. Advanced systems might include real-time sensors, while simpler setups focus on basic chemical principles. Results are discussed in the context of industrial carbon capture technologies and their environmental applications.
- **Water Quality Analysis:** Students conduct fieldwork to collect water samples and test for heavy metal contamination using methods like precipitation reactions or colorimetric assays. Advanced systems may employ atomic absorption spectroscopy, while resource-limited settings use test kits or simple reagents. Findings are linked to local environmental policies, with students presenting actionable recommendations for mitigating pollution.

3.6. Pharmaceutical and medical applications

The intersection of chemistry and healthcare provides a rich context for real-world problem integration. Students can engage in drug design projects, simulating molecular modeling exercises to explore the chemical basis of pharmaceutical interventions. Similarly, biochemical problem-solving activities might involve analyzing the chemical mechanisms underlying disease processes and proposing potential treatments [70,71]. These approaches connect chemistry to tangible outcomes in healthcare, fostering both content mastery and interdisciplinary understanding.

Implementation Example:

- **Drug Design:** Students simulate a research project to design a new antibiotic, focusing on molecular interactions and resistance mechanisms. They use computational tools (if available) to model drug-receptor binding and propose synthesis pathways. Simpler settings can focus on theoretical approaches and literature reviews. Results are presented as research proposals, emphasizing the drug's potential impact on public health.
- **Disease Chemistry:** Students analyze case studies on metabolic disorders, such as diabetes or phenylketonuria, exploring the underlying chemical pathways and proposing biochemical treatments. Advanced systems may involve modeling enzyme-substrate interactions, while others focus on theoretical analyses and discussion. Students present findings, highlighting the connection between chemical principles and medical solutions.

3.7. Sustainable materials and industrial chemistry

Sustainable innovation in materials and industrial processes offers another avenue for integrating real-world challenges into chemistry education. Green chemistry initiatives, such as designing biodegradable plastics or renewable energy storage systems, allow students to explore the chemical principles driving sustainable development [72–74]. Industrial case studies further illustrate how chemistry can optimize resource efficiency and minimize environmental impact.

Implementation Example:

- **Biodegradable Plastics:** Students design and test polymers from renewable resources, comparing their properties (strength, flexibility, degradation rate) to conventional plastics. They synthesize bioplastics in the lab, conducting tests like tensile strength and biodegradability. Simpler settings may rely on simulations and literature review. Results are presented as sustainability assessments, highlighting environmental impacts.
- **Energy Storage Solutions:** Students investigate the chemistry of next-generation batteries using materials like lithium or sodium-based electrodes. They assemble battery prototypes, test charge/discharge cycles, and compare energy efficiency with traditional batteries. In resource-limited settings, students may use theoretical models and simulations. Findings are presented as proposals for improving renewable energy storage.

Overall, by employing these strategies, chemistry educators can create dynamic, relevant learning environments that bridge theoretical knowledge with practical applications. While the examples provided are non-exhaustive and intended only as illustrative samples, they highlight the potential for integrating real-world contexts into chemistry education. This list can be extended or adapted based on the specific context and available resources, enabling educators to further enhance student engagement, deepen understanding, and better prepare learners to address the complex challenges of a rapidly changing world.

3.8. Integration across education systems

The adoption of these strategies can differ significantly depending on the resources available and the level of flexibility within different educational systems. In resource-limited settings, where access to advanced equipment and materials may be restricted, virtual simulations, online platforms, or low-cost DIY experiments are often prioritized to engage students and provide hands-on learning opportunities. These approaches enable students to explore complex scientific concepts without the need for expensive lab materials. On the other hand, well-funded institutions with access to specialized equipment, funding, and industry partnerships can implement more resource-intensive projects, such as field-based research, real-world case studies, or collaborations with companies working on cutting-edge technologies. These initiatives not only provide students with practical experience but also create pathways for future career opportunities.

Educators must be mindful of the unique constraints and opportunities within their educational contexts when adopting these strategies. The goal remains consistent across systems: to enhance the relevance and engagement of the learning experience,

fostering students' critical thinking and problem-solving skills. By tailoring approaches to the resources available while focusing on the core learning objectives, educators can create impactful learning environments that are inclusive, accessible, and forward-thinking.

3.9. Link to the sustainable development goals

The integration of real-world problems into chemistry education plays a vital role in advancing the Sustainable Development Goals (SDGs) proposed by the UN General Assembly. By aligning educational strategies with global sustainability efforts, educators can enhance the relevance of science education while fostering a deeper sense of responsibility in students toward solving critical issues such as climate change, energy access, and environmental sustainability. For example, incorporating topics such as renewable energy systems directly supports SDG 7 (Affordable and Clean Energy), providing students with the knowledge and skills needed to engage with the transition toward clean energy technologies. Similarly, addressing the chemistry of greenhouse gases and climate change connects to SDG 13 (Climate Action), enabling students to understand the scientific principles underlying global climate challenges and encouraging them to become advocates for effective climate solutions.

Moreover, these strategies contribute to SDG 4 (Quality Education) by promoting inclusive, equitable, and high-quality education. In both resource-limited and well-funded educational settings, there are opportunities to foster critical thinking, innovation, and engagement with global challenges. For example, in resource-limited settings, virtual labs and low-cost experiments can provide access to high-quality learning experiences, ensuring that even students in less affluent areas can engage with key scientific concepts related to sustainability.

Educators must consider how their teaching strategies can be adapted to the context of their educational systems while maintaining a clear focus on these global goals. The integration of SDGs into chemistry education ensures that students not only gain scientific knowledge but also develop a strong sense of global citizenship, ready to contribute to the ongoing efforts to achieve a sustainable future.

4. Benefits of real-world problem integration

Integrating real-world problems into chemistry education offers transformative benefits that extend beyond content mastery, enhancing both student engagement and skill development while addressing the interdisciplinary demands of contemporary scientific practice.

4.1. Enhanced student engagement

One of the most immediate benefits of real-world problem integration is its ability to increase student motivation and interest. When chemistry lessons are tied to relevant societal and personal issues, students are more likely to find the subject meaningful and engaging. For instance, connecting chemical principles to pressing challenges such as climate change, healthcare advancements, or sustainable development captures students' attention and fosters intrinsic motivation. Empirical evidence supports this

claim [75–79]: studies reveal that students show greater enthusiasm and sustained interest when they see direct applications of chemistry in solving real-world problems.

4.2. Development of transferable skills

Incorporating real-world problems into the curriculum also facilitates the development of critical transferable skills, including critical thinking, collaboration, communication, and problem-solving. For example, engaging students in a project to design an eco-friendly product not only sharpens their scientific reasoning but also develops entrepreneurial and teamwork skills. These abilities are crucial for success in professional and interdisciplinary settings, where chemists must navigate complex challenges and work collaboratively across fields. By integrating authentic problems into instruction, students gain hands-on experience in applying chemical concepts to practical scenarios, bridging the gap between theory and practice.

4.3. Preparation for interdisciplinary challenges

The global challenges of the 21st century—such as mitigating climate change, managing sustainable resources, or addressing health crises—demand interdisciplinary approaches. Chemistry, often referred to as “the central science,” lies at the core of these efforts, requiring professionals who can collaborate across traditional disciplinary boundaries. Integrating real-world problems into the curriculum prepares students for these collaborative roles by exposing them to interdisciplinary problem-solving early in their education. This approach equips them with the ability to synthesize knowledge from multiple domains, fostering adaptability and innovation in tackling complex scientific issues.

5. Empirical evidence and impact

A range of studies has underscored the advantages of problem-based learning (PBL) and real-world problem integration in chemistry education [25,42]. For example, a study by Aidoo in 2018 [80] explored the impact of a problem-based curriculum on student learning outcomes. Their research found a general increase in students’ conceptual understanding of chemistry after participating in problem-based activities. This significant improvement highlights the capacity of real-world problems to enhance students’ ability to grasp complex chemical concepts, particularly when they are applied in authentic contexts. Additionally, students demonstrated a marked increase in motivation, which is a key indicator of academic engagement, alongside a greater interest in pursuing scientific careers, revealing that students in PBL environments exhibited enhanced critical thinking and problem-solving skills, which are essential for success in both academic and professional settings.

Similarly, studies focusing on interdisciplinary curricula designed around real-world challenges in chemistry showed that such curricula not only improved students’ scientific literacy but also deepened their understanding of the broader societal implications of chemical research [81–84]. These students showed a stronger sense of the interconnectedness of science and society, which is crucial for addressing global challenges like climate change, resource management, and public health. Furthermore, students exhibited higher retention rates of complex scientific concepts. This is

particularly significant given the tendency for students to struggle with abstract theoretical concepts in traditional chemistry instruction, which often fails to establish clear connections to real-world applications. By contextualizing chemistry education within tangible, real-life scenarios, students are more likely to retain and apply knowledge in both academic and professional settings.

In addition to the cognitive benefits, studies have highlighted the development of essential transferable skills. For instance, research by Hmelo-Silver [33,44] on problem-based learning in science education found that students who participated in real-world problem-solving activities exhibited greater improvement in skills such as collaboration, communication, and critical thinking. These skills are highly valued in professional scientific settings, where teamwork and interdisciplinary communication are critical for addressing complex global challenges. Such findings are supported by empirical evidence from industry surveys, which indicate that employers in STEM fields [34] prioritize candidates who can work collaboratively, think critically, and communicate effectively across disciplines. By embedding these skills into chemistry curricula through real-world problem integration, educators can better prepare students for the demands of the modern workforce.

Moreover, studies on service-learning projects, where students apply chemical knowledge to solve community issues, show that such experiences enhance students' sense of social responsibility and provide a more holistic understanding of the role of science in society [64,65,67]. For example, service-learning projects focused on water quality, waste management, and sustainable agriculture not only reinforce students' chemical knowledge but also enable them to directly contribute to solving real-world problems. These projects have been shown to improve students' problem-solving abilities while fostering a sense of empowerment and civic engagement. The impact of these projects extends beyond academic learning, shaping students' perspectives on the ethical, social, and environmental dimensions of scientific practice.

Quantitative empirical studies have consistently demonstrated the effectiveness of integrating real-world problems into chemistry education, particularly in enhancing student learning outcomes and engagement. Sristy and co-workers [5] reported substantial improvements in student achievement scores and a deeper appreciation for chemistry's relevance when real-world contexts and application-based activities were incorporated into general chemistry courses. The work of Aidoo [80] highlighted that problem-based learning approaches led to an increase in conceptual understanding compared to traditional instructional methods, reinforcing the value of active, context-driven pedagogy in fostering student comprehension and engagement. Problem-based learning has also been shown to cultivate critical skills essential for interdisciplinary challenges. Hmelo-Silver [33,44] provided evidence of improved problem-solving, teamwork, and critical thinking abilities among students participating in problem-oriented learning environments, skills that are indispensable for addressing complex global issues. Similarly, Mahaffy and co-workers [4,13] demonstrated that systems-thinking frameworks enhanced students' ability to integrate and apply chemical concepts in broader interdisciplinary contexts, as reflected in their superior performance on assessments requiring contextual application. In secondary-level chemistry, inquiry-based lessons using particulate-level models, as described by Kimberlin and Yeziarski [9], improved students' understanding of stoichiometry by

linking abstract concepts to tangible phenomena. This underscores the role of contextual and inquiry-driven approaches in facilitating mastery of traditionally challenging topics.

The growing body of research collectively affirms that integrating real-world problems into chemistry education is not only effective in improving students' scientific understanding but also plays a critical role in the development of broader competencies necessary for future scientific and professional success. By contextualizing chemistry instruction within authentic, interdisciplinary challenges, educators can create dynamic learning environments that foster both intellectual and personal growth, ultimately contributing to the preparation of a new generation of chemists equipped to address the complex problems of the 21st century.

6. Challenges and mitigation strategies in real-world problem integration

Integrating real-world problems into chemistry education presents several challenges that require thoughtful consideration and strategic solutions. These challenges range from resource limitations to the complexity of assessment and the constraints of rigid curricula. This section explores these challenges and proposes various mitigation strategies to ensure the effective integration of real-world problem scenarios.

6.1. Resource constraints

One of the primary barriers to implementing real-world problem scenarios is the need for resources, such as laboratory equipment, chemicals, or access to fieldwork opportunities. These resources may be financially burdensome, especially in underfunded institutions or regions with limited infrastructure. However, there are several cost-effective alternatives that educators can adopt to overcome this challenge.

For instance, low-cost DIY experiments [85,86] can be designed to simulate real-world chemical processes without requiring expensive equipment. A good example is using household materials to demonstrate concepts like pH, acidity, or simple chemical reactions. Virtual simulations [85] also provide an accessible way for students to experience hands-on learning, particularly in fields like organic chemistry or environmental science, where field experiments might be impractical. Platforms such as PhET Interactive Simulations offer virtual labs on a variety of topics, allowing students to engage with chemical principles in a controlled, digitally simulated environment.

6.2. Curricular rigidity

Many chemistry programs follow standardized curricula, which can be inflexible and slow to adapt to emerging trends or real-world issues. The integration of real-world problems often necessitates substantial changes to established curricular structures, which can be met with resistance from faculty and accreditation bodies [36,37].

To address this, faculty advocacy and collaboration with curriculum committees are crucial in aligning real-world problem integration with program objectives. For

example, professors can work with curriculum committees to incorporate topics like sustainable chemistry or green chemistry within existing modules. Collaborative efforts with industry stakeholders, such as environmental organizations or local businesses, can also help ensure that curriculum changes reflect the latest scientific developments and societal needs while maintaining compliance with accreditation standards.

6.3. Assessment complexity

Assessing students' engagement with real-world problems requires moving beyond traditional testing methods. Traditional exams often fail to capture the depth of learning associated with PBL, where students engage in critical thinking, collaboration, and real-world problem-solving [87].

To address this, instructors can develop rubrics for evaluating projects, presentations, and reflective writing, which offer more comprehensive assessments of students' understanding and skills. For example, a rubric assessing a student's participation in a project-based learning experience might include criteria for creativity, application of scientific concepts, teamwork, and communication. This allows for a more nuanced evaluation of students' abilities to solve complex, interdisciplinary problems.

Case Example: Sustainable Plastics Initiative

A case example of how to overcome these challenges can be seen in a university-level polymer chemistry course, where students were tasked with designing and synthesizing a biodegradable polymer. The project involved several real-world problem-solving components:

- **Literature Review:** Students conducted extensive research into existing biodegradable materials, exploring their properties and applications.
- **Design and Synthesis:** Students developed a synthetic pathway for creating a novel biodegradable polymer, applying principles of organic chemistry and materials science.
- **Environmental Impact Assessment:** Students analyzed the potential environmental benefits of their polymer compared to traditional plastics, incorporating sustainability considerations into their designs.

This project culminated in a presentation to local stakeholders, including representatives from environmental organizations and industries. By integrating real-world challenges into the learning process, this initiative not only reinforced the principles of polymer chemistry but also helped students understand the importance of chemistry in solving global sustainability challenges.

6.4. Pedagogical challenges

The curriculum design complexity of developing integrated problem-based curricula is another significant challenge [88]. Creating a curriculum that aligns with real-world problems requires significant instructional redesign, particularly in terms of pacing, content delivery, and assessment. Educators must move beyond traditional lecture-based methods and create more interactive, problem-solving environments [89] that encourage student engagement and deeper learning [90].

Additionally, traditional assessment methodologies may not adequately capture the nuanced learning outcomes of contextual learning approaches. For example, students who work on interdisciplinary projects might demonstrate scientific literacy, creativity, and collaborative skills that traditional tests fail to measure. Developing appropriate assessment strategies—such as portfolios or project-based assessments—can help capture these broader learning outcomes.

6.5. Technological considerations

Digital technologies offer additional opportunities to enhance real-world problem integration:

- Virtual laboratory simulations [85] allow students to conduct experiments in a controlled, digital environment, providing authentic experiences without the need for physical lab setups.
- Data analysis platforms can help students engage with real-world data sets, allowing them to analyze chemical reactions, environmental data, or materials properties in a way that mirrors professional scientific work.
- Collaborative online problem-solving environments enable students to work together on complex issues, breaking down geographical and institutional barriers. Platforms like Google Scholar, ResearchGate, and online collaboration tools such as Slack or Microsoft Teams can facilitate real-time collaboration and information sharing between students, industry professionals, and researchers.

6.6. Recommended implementation strategies

To mitigate these challenges, several implementation strategies are recommended:

- **Interdisciplinary Collaboration:** Encouraging partnerships between chemistry departments, industry professionals, and environmental organizations can help create real-world problem scenarios that are both relevant and feasible. This collaborative approach can also provide students with access to resources and expertise that may not be available within the classroom.
- **Faculty Development:** Providing robust professional development opportunities for educators is essential for successfully implementing real-world problem-based learning. Training in areas such as curriculum redesign, project-based learning strategies, and assessment techniques will ensure that instructors are equipped to handle the complexities of this pedagogical shift.
- **Flexible Curriculum Frameworks:** Creating modular curriculum components that can be adapted to local contexts and emerging scientific challenges is a critical strategy. These flexible frameworks allow educators to introduce contemporary issues, such as climate change or sustainable energy, while maintaining the integrity of the core chemistry curriculum.

Incorporating real-world problems into an introductory chemistry curriculum provides students with early exposure to the practical applications of the discipline. **Table 3** outlines how real-world challenges can be integrated into specific chemistry topics, accompanied by activities and expected learning outcomes. This

comprehensive guide serves as a resource for educators aiming to create engaging and relevant instructional experiences.

Table 3. Integration of real-world problems in an introductory chemistry curriculum.

Topic	Real-World Problem/Context	Proposed Activity	Learning Outcome
Measurements and Units	Precision and accuracy in pharmaceutical dosages	Students calculate dosages for medications, emphasizing the importance of accuracy and significant figures.	Understanding the role of precision in real-world chemistry applications.
Atomic Structure	Radiation in medical imaging	Investigate isotopes used in PET scans, focusing on their properties and roles in diagnostics.	Recognizing the significance of isotopes in healthcare.
Chemical Bonding	Material properties for sustainable construction	Analyze the structure and bonding in materials used in green building technologies.	Relating bonding to the properties of materials in practical applications.
Stoichiometry	Minimizing waste in chemical production	Calculate reactants and products to optimize yield and minimize waste in a hypothetical industrial process.	Applying stoichiometry to address environmental and industrial efficiency challenges.
States of Matter	Impact of greenhouse gases on the atmosphere	Use gas laws to model atmospheric changes due to varying greenhouse gas concentrations.	Applying theoretical models to explain real-world climate phenomena.
Thermochemistry	Improving energy efficiency in appliances	Analyze energy transfers in common household appliances and propose improvements.	Relating thermochemistry to everyday energy use and conservation.
Acids and Bases	Neutralizing acidic soil for better agricultural yields	Design experiments to determine the amount of lime required to neutralize soil samples.	Applying acid-base concepts to agricultural challenges.
Chemical Kinetics	Decomposing pollutants in the environment	Investigate reaction rates of pollutant decomposition under different conditions.	Understanding the importance of reaction rates in environmental science.
Chemical Equilibrium	Industrial ammonia production via the Haber process	Model equilibrium conditions in the Haber process and evaluate factors affecting ammonia yield.	Applying equilibrium concepts to real-world industrial chemistry.

While the challenges of implementing real-world problem scenarios in chemistry education are significant, they can be overcome with strategic planning, collaboration, and the creative use of technology. By addressing resource constraints, overcoming curricular rigidity, and developing effective assessment methods, educators can foster a dynamic learning environment that prepares students to meet the interdisciplinary challenges of the 21st century. The integration of real-world problems not only enhances student engagement but also deepens their understanding of chemistry's role in addressing global issues.

7. Conclusion and future direction

The integration of real-world problems into chemistry curricula marks a critical advancement in scientific education, providing students with the opportunity to bridge the gap between theoretical knowledge and practical application. By connecting abstract concepts to tangible, real-world challenges, this pedagogical strategy not only enhances the relevance of chemistry but also transforms it from a theoretical discipline into a dynamic, engaging field of inquiry. Students are better equipped to understand the direct impact of chemistry on global issues such as climate change, sustainable energy, and public health, thus fostering deeper engagement and motivation.

Beyond increasing student engagement, the integration of real-world problems also plays a pivotal role in preparing students for the complex interdisciplinary challenges of the 21st century. As global issues become increasingly interconnected,

it is essential that future scientists, policymakers, and informed citizens possess the skills to navigate these challenges. By embracing contextual learning, chemistry education can cultivate a scientifically literate population capable of tackling pressing global issues with an informed and innovative approach.

However, as educators continue to explore innovative ways to incorporate real-world problems, future research should focus on assessing the long-term impact of such curricula on students' academic achievements and professional careers. Specifically, studies should examine how engagement with real-world problems influences career readiness, scientific literacy, and students' ability to collaborate across disciplines. Additionally, research can explore the efficacy of various instructional strategies, such as problem-based learning, case studies, and interdisciplinary collaborations, in fostering the skills necessary for future scientists to address the evolving challenges of the modern world.

In summary, integrating real-world problems into chemistry education offers immense potential to prepare students not only for careers in science but also for the broader societal role they will play in addressing global challenges. As scientific boundaries blur and interdisciplinary approaches gain prominence, chemistry education must evolve to reflect these changes, ensuring that students are equipped with both the technical knowledge and the problem-solving abilities necessary for success in an increasingly complex and interconnected world.

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