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Promoting Systems Thinking Using Project- and Problem-Based Learning

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Supporting Information

ABSTRACT: With a growing number of global challenges related to the environment, water, public health, and energy, there is an imminent need to teach chemistry in the context of its interconnectedness with other systems. Project- and problem-based learning are student-centered learning approaches which offer educators the opportunity to engage learners in solving complex real-world problems. By choosing a globally relevant project/problem and requiring students to utilize scientific methods to solve the problem, both problem-based learning and project-based learning are excellent strategies for educators to teach chemistry using a systems approach. This review summarizes key research studies which utilize project- and problem-based learning in the context of enabling learners to confront global problems and the wide applicability of these approaches to systems thinking.

KEYWORDS: *Curriculum, Collaborative/Cooperative Learning, Inquiry-Based/Discovery Learning, Systems Thinking*

INTRODUCTION

Over the past few years there has been an increasing emphasis to reorient chemistry education via a systems thinking approach with the ultimate goal of empowering students with tools and skills necessary to address important 21st century challenges.[1] The systems thinking approach seeks to extend student learning beyond chemical concepts and theories to develop an understanding of interconnections among physical, biological, and environmental systems. Understanding the interdisciplinary and connective nature of these systems is crucial to solving several global problems.

The imminent need for curriculum reform in chemistry curricula is well-documented in the literature.[2−4,1] General chemistry classes taken by students preparing for careers related to life sciences and engineering have been described as "a disjointed trot through a host of unrelated topics".[5] With a growing number of global challenges related to the environment, water, public health, energy, and disease, chemistry education, particularly at the undergraduate level, must be modified such that chemistry is taught in the context of global problems in order to equip students for an informed citizenry and enable them to work toward a sustainable future. In this context, systems thinking encourages educators to teach chemistry in relation to its interconnectedness with other disciplines with a specific emphasis on global challenges and sustainability.[6] Orgill et al.[7] provide a good definition of systems thinking as the ability to "visualize the interconnections and relationships between parts of a system". Systems thinking attributes (STA) based on previous work[8,9] and pertinent to the current discussion are summarized below:

1. Students acquire the ability to identify components of a system and processes within the system.[10,11]
2. Students develop the ability to identify dynamic relationships within the system.[12]
3. Students are able to identify relationships among system components.
4. Students learn to organize the systems' components and processes within a framework of relationships.[13]
5. Students develop the ability to understand the cyclic nature of the system.[14]
6. Students develop the ability to make generalizations.
7. Students understand the hidden dimensions of the system.[15]
8. Students learn to think temporally, retrospect, collaborate, and make predictions.[10,16]

System thinking skills[17] described in the literature include "forest thinking" (understanding the behavior of the system as a whole), "closed-loop thinking" (considering the effect of system-relevant variables on each other), and "system-as-cause thinking" (evaluating internal causes of the system's behavior). "Operational thinking" (identify variables which influence a system's behavior and its changes), "quantitative thinking", "scientific thinking", and "dynamic thinking" are other important skills described in the literature.[7] In general, pedagogies which support systems thinking rely on applying scientific principles to solve real-world problems and prepare students for collaborative interdisciplinary work. Context-based learning relying on systems thinking[18] has been implemented to provide "rich content" in general chemistry

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courses.[19] While context-rich pedagogies can help promote systems thinking,[7] they are not synonymous with systems thinking.

By choosing a globally relevant project/problem and requiring students to utilize scientific methods to solve the problem, both problem-based learning and project-based learning have the potential to align with systems thinking.

PROJECT-BASED LEARNING AND PROBLEM-BASED LEARNING

Project-based learning (PjBL) and problem-based learning (PBL) are student-centered learning strategies which aim at fostering deeper learning through active exploration of real-world problems. Both PjBL and PBL are pedagogical approaches which solidify many of the underlying concepts of systems thinking and can be used by educators in the classroom to teach chemistry in the context of global events. The focus of this review is to summarize some key research studies which utilize PjBL and PBL design in the context of enabling learners to confront global problems and the wide applicability of these approaches to systems thinking. PjBL and PBL design principles are briefly reviewed in the next section.

Project-Based Learning

Project-based learning (PjBL) is an inquiry-based learning model where teachers act as facilitators guiding students through an extended inquiry process which includes working collaboratively to develop a product, testing a prototype/plan, and reflecting on the entire experience.[20]

Several books and review articles (Hall,[21] Palmer,[22] Bennett,[23] Starobin,[24] and Zhang[25]) have summarized the positive effects of PjBL. Multiple research studies reiterate that PjBL allows students to develop and hone important technical and life skills as they collaborate with peers to develop their project. Krauss[26] and McComas identified important skills that students learn while engaged in PjBL, which included collaboration, effective communication, and interpersonal skills such as cooperation and teamwork.[27]

A number of books and research papers outline key principles of PjBL.[28−30] While the design strategy in PjBL is geared toward use in K−12, this can be easily adapted in a higher education setting. The design principles discussed below are a summary of many PjBL designs proposed in the literature.[31,32] Design principles have been linked to applicable systems thinking skills (STH) described in the literature.[17]

(a) Driving/challenge question: The essence of project-based learning is the driving question which serves to shape and drive student activities. Driving question(s) should be open-ended and realistic, with many solutions and multiple methods for reaching solutions.

(b) Use of scientific practices: In order to solve the challenging question, students should be encouraged to construct hypotheses, identify variables, brainstorm, and engage in problem-solving. The project must be student-driven (STH: scientific thinking, operational thinking).

(c) Sustained inquiry, assessment, and feedback: Students engage with in-depth inquiry by focusing on internal and external factors, designing and carrying out experiments with appropriate controls. Students are often exposed to unforeseen challenges as they progress through the project (this aspect mimics real-world problems which are unscripted, complex, and multidisciplinary) (STH, quantitative thinking, system-as-cause thinking, closed-loop thinking).

(d) Utilize learning technology scaffolds: PjBL requires students to access and use technology (scientific search engines, for example) to support the process of inquiry. Since many of these tools are used by researchers and scientists, a PjBL experience can serve as good training for success in the workplace.

(e) Final product: A unique feature of all PjBL modules is a final product. Students may present their final product to members of the community, class, or university or draft a written report.

Problem-Based Learning (PBL)

The use of authentic problems in the classroom is not a recent concept; many educationalists like Dewey[33] have emphasized that learning requires active involvement of the student and that the process of learning should not be a mere assimilation of knowledge and information. He suggested using real-world problems in the classroom and providing students with the resources to solve the problem. While the idea of using authentic problems to learn was innovative, it was not until the late 1960s that the idea received renewed interest and eventually led to the incorporation of PBL in medical education.[34] PBL has also found its way into a number of other disciplines such as architecture, law, engineering, and social work.[35]

PBL is characterized by student-centered learning which occurs in small groups where teachers act as facilitators when students tackle real-world and challenging problems which become the foci and provide stimuli for learning. Students acquire new knowledge and information through self-directed learning and learning in groups.[36] Like PjBL, PBL allows educators to connect chemistry with real-world contexts and enables learners to solve complex problems and become independent learners.

Project-Based Learning vs Problem-Based Learning

While project-based and problem-based learning are both considered to be inquiry-based approaches, there is some disagreement in the literature as to whether PjBL and PBL are similar or very different approaches. A review by Thomas[37] rationalized that the essential components of problem-based learning align with some of the PjBL criteria. Other authors[38−40] have argued that PjBL is not synonymous with PBL. Both problem-based learning and project-based learning are referred to as "PBL", which adds to the confusion. In this review, PjBL refers to project-based learning; problem-based learning is abbreviated as PBL.

ALIGNMENT BETWEEN SYSTEMS THINKING AND PjBL/PBL PEDAGOGY

Both PjBL and PBL pedagogies are reviewed in this paper, since they both contribute to the systems thinking approach by allowing educators to design real-world problems and projects based on global challenges and engage learners in interdisciplinary learning, thereby empowering them to use the gained knowledge to solve global problems of the 21st century. Both PjBL and PBL develop a range of transferrable skills such as critical thinking that can be applied in other complex environments beyond chemistry alone. The alignment among systems thinking, PjBL, and PBL is elucidated in Table 1. This review summarizes recent studies in chemistry education which

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Table 1. Project-Based Learning and Problem-Based Learning and Their Applicability to Systems Thinking

Relevant Systems Thinking Attributes	Alignment with Problem-Based Learning (PBL)	Alignment with Project-Based Learning (PjBL)
Teaching and learning chemistry in contexts relevant to society. Equip students with skills to confront global challenges.	**Learning through authentic problems.** Design problems which are focused on relevant societal and environmental needs.	**Driving question.** The driving question which sets the tone for the project can be designed around relevant global problems. The driving question can potentially be designed to allow students to gain insight into the role of chemistry in helping to meet the emergent challenges of multiple unfolding global crises.
Visualizing the interconnections and relationships between different parts in the system and with surroundings	**Sustained inquiry and skills development.** During the course of PBL, students engage in interdisciplinary inquiry focused on real-world problems comparable to the actual collaboration that takes place in interdisciplinary research.	**Sustained inquiry.** Students engage in the process of inquiry to recognize the interaction, connectedness of physical and biological systems.
Engaging in quantitative and scientific thinking, closed-loop thinking, forest thinking, dynamic thinking, and system-as-cause thinking	**Development of problem-solving skills.** Problems can serve as the vehicle for developing many problem-solving and critical thinking skills. PBL enables students to acquire unique skills to become independent and lifelong learners	**Use of scientific practices.** Projects serve as a vehicle for students to acquire essential 21st century competencies essential for career readiness. These 21st century skills align with system thinking skills.
Involves collaboration and democratic participation.	**Self-directed learning.** Learning is student-centered and occurs in small peer groups where students engage in problem-solving in a collaborative manner.	**Student voice and choice.** Students engage in learning by collaborating with peers on the project, develop interpersonal skills and learn to work effectively in a group.

have utilized PjBL and PBL as tools to educate students on global issues and sustainability, thereby enabling the incorporation of a systems approach into teaching and learning. While applications of PjBL and PBL in several disciplines in chemistry have been reported, the alignment to systems thinking is evident in introductory chemistry, general chemistry, analytical chemistry, environmental chemistry, forensic chemistry, instrumental chemistry, and biochemistry. PjBL and PBL approaches used in organic chemistry or inorganic chemistry are not part of the review. Studies involving K−12 demographics are also not discussed here.

Use of PjBL in Undergraduate Courses and Laboratories To Promote Systems Thinking

The versatility of PjBL allows educators to design open-ended multiweek projects where the driving question can be designed by instructor or student.[41] By designing open-ended PjBL projects which focus on global issues, educators have the opportunity to engage students in realistic projects. This, in turn, allows students to encounter and resolve conflicts, provides opportunities for collaboration, and empowers them to address future problems. In this context, analytical and environmental chemistry laboratories offer excellent opportunities for engaging students in relevant global problems.

Monitoring water quality in the 21st century is a growing challenge due to the increased use of chemicals and existing challenges with potability. The importance of water quality can be taught using a systems approach. The instructor can (1) talk about access to pure drinking water as a global problem and how humans interact with/influence the water cycle[42] and (2) enable students to connect water quality to pollutants and consider the role of the environment[43] in this problem. A systems thinking approach would ask students to consider that water quality is determined by environmental factors, quantity, and type of pollutants which can be liquids, solids, and dissolved substances or particulates (*operational thinking*). Students can be asked to analyze the effect of a number of compounds/ions, nitrates, nitrites, phosphates, ammonia, and ammonium, on the quality of water. Students can measure the concentration of nutrients to understand their impact on water quality (*quantitative thinking*). As an example, research has shown that the ratio of nitrogen/phosphorus can have an impact on the occurrence of algal blooms.[44] A change in concentration of various nutrients will affect quality of water (*system-as-cause thinking*). Water quality also depends on physical parameters, climate, and rainfall (*dynamic thinking*) and is impacted by temperature and amount of dissolved oxygen. Students can deduce, through experimentation, that the amount of dissolved oxygen in water decreases as temperature increases (*closed-loop thinking*). Water quality can be influenced by the presence of wetlands, which enhance water quality by acting as filters, and removing pollutants (*forest thinking*).

Many of the relevant physical and chemical parameters described above to ascertain water quality have been utilized by educators in separate PjBL modules. Several papers report the use of PjBL to introduce water quality as a global issue in analytical,[45,46] introductory,[47] and environmental chemistry laboratories.[48−50] Collaboration with community members and relevant federal institutes has been used as a strategy to highlight the importance of water quality to students.[45]

Dick et al.[51] developed a PjBL for quantifying pesticides using EPA approved methods. Students learned to analyze and

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quantify the effect of extensive use of dichlorodiphenyltrichloroethane (DDT) in the San Joaquin valley prior to its ban in 1972. Students researched and developed methods to quantify the concentration of DDT and its environmental degradation products (dichlorodiphenyldichloroethane [DDD] and dichlorodiphenyldichloroethylene [DDE]). Many of the tasks associated with this PjBL module can complement systems approach as summarized in Table 1 (Supporting Information). By designing PjBL around important laboratory skills, educators have been able to enhance training and employability for students in chemical and environmental associate degree programs.[50]

Use of project-based service-learning methods have been reported where service learning is used to provide greater context to the problem being investigated. A PjBL described below[52] based on bottled water can be linked to the systems approach; relevant STA attributes are indicated in parentheses.

In this PjBL experience, students design and carry out experiments to determine "if bottled water is worth buying" and if bottled water is superior to tap water (driving question in PjBL). To answer the driving question, students must be able to identify factors which decide the quality of bottled water (STA attribute 1). Students had to consider contradicting results which report that minerals in bottled water have medicinal and therapeutic effects[53] and other studies which suggest that components in bottled water interfere with endocrine activity[54] (STA attribute 2). Using inductively coupled plasma mass spectrometry (ICPMS), students analyzed samples from different sources: natural spring water, distilled water, municipal tap water, and well water (sustained enquiry in PjBL; STA attributes 3, 4). Results obtained by students indicated that untreated municipal tap water and untreated well water have higher concentration of Na compared to bottled water samples. In addition, bottled water samples have a lower concentration of Mg compared to municipal tap and well water samples (STA attribute 7). Students also concluded that use of a reverse osmosis system reduced concentration of mineral elements (STA attribute 6). Results from experiments indicated that the major difference between samples was dependent on hardness and taste (STA attribute 8; authenticity in PjBL). Students presented their results in the form of a poster presentation (public product in PjBL).

With the growing number of pollutants, PjBL projects educating students on different types of pollutants and analytical methods for quantifying pollutant concentrations have been reported. Draper[55] developed a PjBL-based service-learning experience by choosing driving questions which have a strong impact on the community such as assessment of particulate matter in soil and gasoline contamination in soil.

Educators have also used PjBL to teach instrumental methods[56] in analytical chemistry in the context of their use in the pharmaceutical industry. Robinson used a relevant problem, the deaths of some patients who received an anticoagulant drug heparin, to teach students about the importance of purification methods in drug manufacture. The project is authentic with a relevant driving question: Can microplate-based protein assays be used to test for protein impurities? Students work to test the efficacy of a protein assay to determine the presence of oversulfated chondroitin sulfate which mimics heparin but is an allergen for some patients, resulting in their death.

PjBL has also been used to engage students in interdisciplinary learning. Kahl[57] described an interdisciplinary project involving chemistry and engineering students working together to compare performance and effectiveness of smartphone paper spectrophotometers and traditional spectrophotometers. PjBL in combination with process-oriented guided learning inquiry (POGIL) has been used in a chemistry course taken by predominantly nonscience majors.[58]

Use of PBL in Undergraduate Courses and Laboratories to Promote Systems Thinking

Due to a larger number of publications which report use of PBL, work on PBL is summarized in three separate subsections: use of PBL in analytical and environmental chemistry, use of PBL in instrumental analysis, use of PBL in general and introductory chemistry, and use of PBL in biochemistry classes.

Use of PBL in Analytical and Environmental Chemistry

Several studies have shown that students who engage in problem-solving are able to think critically and recognize and solve complex real-world problems.[59,60] PBL, hence, aligns well with many of the key elements of the systems thinking approach by allowing students to work on critical problems which will play a key role in the 21st century. Systems thinking emphasizes the need to provide students with requisite knowledge and skills that will help them contribute to sustainable development. A key part of sustainability is educating students on the principles and importance of green chemistry, circular economy, recycling, and life cycle analysis.

Overton et al.[61] describe the development and implementation of a PBL activity on sustainable development for undergraduate chemistry students in the freshman year. The dynamic PBL activity teaches students about the importance of sustainability and the unifying role of chemistry in developing renewable energy sources, recycling, and atom economy. Students were asked to assist and advise a company on efficient use of energy and technology in four different scenarios, each with a defined budget. The first scenario required students to advise on the design of a sustainable village with 60% of the raw materials sourced locally while minimizing the environmental impact of construction. Students have to think critically, balancing requirements and costs while minimizing the impact on the environment. The second scenario required students to design a self-sustaining graduate school in a mountain environment. This activity required students to focus on the use of renewable energy, minimize waste, and pay attention to the nature of building materials used. The third scenario required students to analyze cost of producing biodiesel and bioethanol to power a fleet of buses. Students had to evaluate the feasibility of construction of a bioethanol fermentation plant and biodiesel processing plant, and evaluate costs of reactants, fuel mixtures, production, and implementation. The final scenario required students to help a university become greener which involved consideration of many issues including recycling, energy use, and waste management. Evaluations from students indicated that a majority of the learners appreciated and understood the importance of sustainable development and the role of chemistry. It is worthwhile pointing out that this activity aligns very well with system thinking attributes described by Mahaffy et al.[6] The PBL resource described provides social contexts for learning while directing learning toward meeting the societal and environmental needs of the future.

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Students in analytical chemistry classes can experience the interconnectedness of systems if analytical techniques and instrumental analysis courses are offered in the relevant context of global problems. PBL has been used extensively in analytical chemistry[62] and by faculty to design laboratories and research projects[63] which require students to use analytical techniques to solve real-world problems in forensics,[64,65] and to quantify pollutants[66] and pesticides.[67]

Environmental chemistry covers a range of topics within the discipline of chemistry, from toxicology to legislation and from chemical processes that occur in aquatic and atmospheric systems to the effects of human activity on them. Many of the key environmental problems rely on use of instrumental methods for quantification. By virtue of its inherent interdisciplinary nature, this field offers educators exciting opportunities to engage students in PBL projects. Ramos et al.[68] developed an environmental analysis lab where students used geographic information system (GIS) in conjunction with an atomic absorption spectrometer to monitor sediment accumulation and map lead concentrations in a local pond. Use of GIS allowed students to extend beyond chemical analysis, explore land management issues, and discuss erosion and the importance of wetlands. Jansson et al.[69] have designed a PBL activity that links the structure of pollutants to their transformation in the environment. The course introduces students to methodologies for risk assessment of hazardous compounds in the environment. Teaching exercises and activities around sustainable development and green chemistry using PBL have also been reported.[70,71] Water quality related projects[72] in the environmental chemistry laboratories have also been reported. Kegley et al.[73] have developed modules where students learn chemistry in the context of key environmental problems such as lead contamination, pesticides in fruits and vegetables, concentrations of polychlorinated biphenyls in sediments, and health risks of hair dyes.

Use of PBL in Instrumental Analysis

Several common instrumental techniques have been presented to students in the context of their use in various applications such as the use of GC−MS for determining the amount of cocaine on US currency,[74] and the use of Raman spectroscopy[75] and surface-enhanced Raman scattering[76] for identifying art forgeries and art conservation. Advances in atomic spectroscopy were utilized to develop a PBL lab to detect and quantify lead and arsenic in the soil[77] and for the simultaneous determination of cadmium and lead[78] in contaminated water. Vera et al.[79] report the development of an instrumental analysis lab integrating recycling concepts. Students learn to utilize instrumental methods such as thermogravimetric analysis to evaluate conversion of calcium carbonate (derived from eggshells) to quick lime. Students learn the concept of a "zero waste economy" that uses waste as raw material for manufacture of new products. Williams et al.[80] have developed an instrumental analysis lab involving e-cigarettes. Students learn to use various instrumental techniques such as atomic absorption, HPLC, and mass spectrometry to analyze constituents of e-cigarettes and measure nicotine concentrations.

Jensen[81] developed an analytical chemistry curriculum based on instrumental analysis with a final PBL component. In the PBL module, students designed their own problem statement and were encouraged to incorporate knowledge from other science courses to reaffirm the multidisciplinary nature of chemical analysis.

Instrumental analysis courses which integrate student-driven research projects allow students to explore projects which are of interest and importance to them. Authors[82] report that many students chose to explore projects of relevance to the society and community such as analysis of soil samples from a junkyard for heavy metals and hydrocarbons. Students also chose projects which could engage learners in other disciplines such as determination of barium leaching from ceramic glazes. This allowed students to collaborate with the learners and faculty in the art department.

Zivikovic et al.[83] describe the use of NMR as a tool for quantitative analysis of over-the-counter painkiller drugs. Students were able to use their knowledge of NMR instrumentation to analyze tablet formulations containing painkillers. Learners are able to understand and appreciate the use of NMR beyond chemistry for application in life sciences. In a related application, students learned to use NMR as a quality control tool to help a hypothetical citrus fruit manufacturer.[84]

Many disciplines such as forensic science and pharmacy require competency in more than one science discipline. Using PBL, educators have enabled students to understand the interconnectedness of chemistry with physical and biological sciences. Interdisciplinary procedures are often used to solve crimes,[85] and PBL around the forensic sciences has been developed.[86] Medicinal-chemistry-based laboratory activities have been designed to teach students instrumental analysis as it applies to quality control and analysis of an active pharmaceutical ingredient.[87]

While exposure of students to modern methods of instrumental analysis is important, students do not often understand the inner working of instruments and "view many instruments as black box". This ultimately limits their ability to utilize the instrument to minimize errors and maximize performance. Several papers[88,89] integrated instrument design principles to enable students to produce UV−vis spectrophotometers. This experience enables students to gain an in-depth understanding about the science and technology behind these commonly used laboratory instruments.

Use of PBL in General and Introductory Chemistry Lectures and Laboratories

Introductory chemistry courses are taken by a large number of students from varied disciplines. Hence, incorporating a systems thinking approach in the introductory setting enables teachers to reach a broader segment of students.[90,91] Students in these introductory classes will perceive chemistry to be a unifying science if scientific topics are presented to them through the lens of global problems.[92] Since many of the students in these introductory classes may not take more chemistry courses, it is important to provide this cohort of students with the capability to address socioeconomic, ethical, and environmental issues.

PBL has been used in introductory classes to teach fundamental chemical principles using the principles and practice of green chemistry;[93] PBL has been used to teach students about radioactive waste disposal.[94] This four-week group activity teaches students about low level radioactive waste (LLRW) and enables students to see connections between science, law, and ethics and the underlying role of chemistry in decision making processes. Students work

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together in groups to make a policy decision about disposal of LLRW by using information cards provided to them and gathering information on their own. The PBL helps students realize the interdisciplinary nature of physical and biological sciences by integrating concepts such as biological effects of radiation, risk analysis, biological half-life, and ethics. It equips students with knowledge for making informed decisions on LLRW in their communities. Student evaluations indicated that the PBL exercise served as an excellent vehicle for students to learn about radiation. PBL projects based on removal of copper from soil using phytoremediation[95] and determination of pesticides in drinking water[96] have been reported. An interesting PBL demonstrating the application of a self-heating mechanism has been incorporated in the introductory chemistry class. Core concepts have been taught through a PBL in the context of its application.[97] Chemical concepts have been taught in the general chemistry laboratory in the context of environmental remediation and pharmaceuticals in the environment.[98]

Use of PBL in Biochemistry Classes

PBL has been used in biochemistry classes[99,100] to link metabolic pathways to inherited diseases[101] and to link food chemistry to chemical reactions. Sol–gel chemistry has been used to prepare inorganic materials templated on biological templates showing students the interlink between chemistry and biology[102]

CONCLUSIONS AND FUTURE DIRECTIONS

It is now well-accepted that interdisciplinary approaches to research are required to solve problems at both global and local levels. Young chemists seeking to enter the workforce must possess experience working in interdisciplinary projects and acquire analytical and experimental skills necessary to solve emerging problems.[90] By choosing a globally relevant project/problem and requiring students to utilize scientific methods to solve the problem, both problem-based learning and project-based learning are excellent strategies for educators to teach chemistry using a systems approach. In this context, a systems approach to teaching can serve as an excellent tool for educators. This review does not suggest that traditional approaches should be replaced with a systems thinking approach. Instead, a systems approach in chemistry education and research can complement other approaches.[103]

PBL and PjBL approaches mimic challenges students will experience in real-life and can showcase the interconnectedness between systems. Hence, both these approaches have the ability to connect to systems thinking in a profound manner. Multiple studies reiterate that PBL and PjBL play a pivotal role in promoting student engagement in the classroom and long-term positive benefits in their professional careers.[104,105] The use of PBL in undergraduate chemistry lectures and laboratories can hence be a rewarding experience for both students and the instructor.

However, critics have also pointed out that implementation of PBL and PjBL can be costly, time-consuming (for both students and instructor), and dependent on expensive resources that may not always be available at all universities across the world. Educators also report that students who do not have the necessary academic preparation may find the PBL exercise overwhelming.[106]

Hence, more effort is needed to develop PjBL/PBL approaches which can be completed in a shorter duration of time using cheaper and readily available materials which will enable their widespread use. Mini-PBL projects[107] may be a good starting point to develop modules with greater relevancy to the student population. In introductory classes, more efforts are needed to shift the focus from rote memorization to problem-based learning around key global issues.[108,109]

With an increasing number of educators adopting project- and problem-based learning strategies into the teaching pedagogy, there is a real opportunity to develop these strategies in the context of systems thinking with the ultimate goal of empowering our future citizens to meet the challenges of the upcoming century.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.9b00358.

Exemplar of PjBL module and its alignment with system thinking attributes (PDF, DOCX)

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Notes

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