INTERDISCIPLINARY APPROACHES TO CHEMISTRY EDUCATION

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ABSTRACT

This paper describes the application of a framework for K-12 integrated STEM to the teaching and learning of high school chemistry. The paper draws on a detailed conceptual framework for K-12 integrated STEM education that includes seven characteristics: (a) focus on real-world problems, (b) centrality of engineering, (c) context integration, (d) content integration, (e) STEM practices, (f) twenty-first century skills, and (g) informing students about STEM careers. Examples relevant to high school chemistry are used to illustrate each characteristic and its role in improving chemistry education. *[African Journal of Chemical Education—AJCE 13(2), June 2023]*

INTRODUCTION

Over the past decade, K-12 science education across the world has been shaped by policies that aim to address concerns about the increasing needs of the STEM workforce [1]. These policies are based on the premise that continued progress and prosperity depends on the development of the future generation of STEM professionals [2]. The development of a robust STEM workforce is essential for African economies to be competitive in the global market, create jobs, and improve economic outcomes. However, within the African continent, less than 25% of students in higher education pursue a STEM-related degree [3]. This issue is compounded by the significant under-representation of women in STEM [4]. For example, in most Sub-Saharan African countries, less than 30% of engineering graduate from institutions of higher education are women [5]. This is problematic not only in terms of the number of students entering the STEM fields, but also because the unique contributions and perspectives of women are absent from the development of solutions to real-world problems. New approaches to K-12 science education are needed to motivate students, particularly women, to pursue STEM careers.

Changes to K-12 science education also need to address the ever-changing world in which we live and to support the development of solutions to the critical challenges facing humanity, such as sustainability, climate change, health, and the environment [6-7]. To quote Albert Einstein, “the significant problems we face today cannot be solved at the same level of thinking we were at when we created them." These problems are inherently complex and multidisciplinary in nature and require new and creative thinking to develop possible solutions. As such, the future STEM workforce not only needs strong STEM content knowledge and skills, but also strong twenty-first century skills (e.g., critical thinking, communication, collaboration, and creativity) [8-9]. Indeed, more than half of today's Kindergarteners will end up working in jobs that do not currently exist [10]. It is no longer enough for students to simply learn scientific content, rather students should be involved in knowledge construction and the application of scientific content and twenty-first century skills to analyze, evaluate, and create possible solutions to real-world problems [11].

In response to these calls for improving K-12 science education to address current and future STEM workforce needs, there is a global push for integrated STEM (science, technology, engineering, and mathematics) approaches to science teaching and learning [12 – 15]. Research shows that teaching approaches which integrate disciplinary STEM content can greatly improve student learning [16-19] and improve student interest in science and engineering [20 – 22]. However, this research has predominantly been conducted at the elementary and middle school levels, with limited attention to high school chemistry settings [23]. In this paper, integrated STEM approaches to K-12 science learning are described with a focus on applications in chemistry classrooms.

LITERATURE REVIEW

Despite the proliferation of integrated STEM in the literature, no single accepted definition of integrated STEM instruction exists. Common across all definitions is that learning should be contextualized within a real-world problem [7, 24 - 25]. However, debate remains about whether integrated STEM requires integration across all four of the STEM disciplines [26 – 27] or more common within the literature the integration of at least two of the STEM disciplines [6]. For example, Moore and colleagues defined integrated STEM education as “an effort to combine some or all of the four disciplines of science, technology, engineering, and mathematics into one class, unit, or lesson that is based on connections between the subjects and real-world problems” (p. 38) [28]. Similarly, Kelley and Knowles defined integrated STEM as “the approach to teaching the STEM content of two or more STEM domains, bound by STEM practices within an authentic context for the purpose of connecting these subjects to enhance student learning” (p. 3) [24].

In addition, researchers and educational practitioners do not agree on what integrated STEM looks like in practice [6]. However, there is growing consensus on the central characteristics of integrated STEM education: (a) centrality of engineering design, (b) driven by authentic problems, (c) context integration, (d) content integration, (e) STEM practices, (f) 21st century skills, and (g) informing students about STEM careers [29].

Focus on Real-world Problems

Proponents of integrated STEM education argue that using real-world problems as a context for learning provides motivation for learning STEM [24, 30]. However, the nature of the real-world problem needs to attend to students' interests and lived experiences [30 - 32], as well as the context of the educational setting. For example, Fomunyam argues that "elements of Africa's ideologies, concepts and culture have to be incorporated into the engineering curriculum for easier assimilation and practical application" (p. 2429) [33].

Unfortunately, integrated STEM classroom activities tend to focus on the technical aspects of engineering related to the design of "things", such as designing cars and rockets [34], which perpetuate male dominance in STEM and negatively impact girls' interest in STEM careers [35]. Girls are motivated by projects with a communal goal orientation that highlight how STEM can improve the human condition related to societal issues such as health and the environment [35 - 37]. Thus, an approach grounded in care and empathy that engages students in considering the societal implications, as well as technical considerations, of their design solutions is an important consideration [34, 38].

Specific to chemistry classrooms, Gilbert notes that the traditional chemistry instruction lacks relevance for students because of its focus on isolated facts [39]. Researchers are turning to contextualizing chemistry instruction within real-world problems to promote student learning. For example, Fortus and colleagues used the context of developing environmentally friendly batteries to help students develop electrochemistry concepts [40]. Apedoe and colelagues used the context of designing heating and systems to promote learning about atomic interactions, reactions, and energy [41]. Hadinugrahaningsih and colleagues designed a curriculum to promote the learning of concepts related to acids and bases using the context of aquariums and hydroponics [42]. Burrows and colleagues explored gains in student learning using a unit that used the development of biodiesel as a context for learning [43]. A common thread across these examples is the use of sustainability and the environment to contextualize student learning, contexts that have the potential to motivate female students and help to diversify the STEM fields.

Centrality of Engineering

Engineering is a systematic and iterative approach to designing solutions to real-world problems [15]. Given the expectation of integrated STEM, that students should be engaged in developing solutions to the real-world problem, design or engineering practices are highly relevant [7, 15 - 16]. The limited body of research in chemistry education shows that “situating learning chemistry in an authentic practice, like design, meaningfully connects chemistry content and practices around a shared practical purpose” [44]. The integration of design practices in chemistry education has been found to promote students’ understanding of chemistry concepts [40 – 41, 45] and problem-solving skills [46].

Context Integration

The real-world problem or engineering design challenge used to contextualize learning should engage learners in applying and expanding their knowledge of the STEM disciplines [16, 30]. Specific content learning objectives need to be aligned with the needs of the real-world problem to promote students' application of STEM content knowledge toward generating possible designs and making evidence-based decisions. Without this explicit integration between the real-world problem and content learning goals, students will resort to tinkering (a form of trial and error), limiting the learning of scientific concepts [47 – 49]. Thus, integrated STEM activities should provide students with opportunities to apply developmentally appropriate mathematics or science content within the context of solving engineering problems [15, 50 - 51].

As a chemistry example, Apedoe and colleagues designed a high school STEM unit where students were challenged to design a heating or cooling system that uses chemical energy to meet a personal need in their own life [41]. Central to the unit were learning goals related to specific chemistry concepts: atomic interactions, reactions, and energy changes. These concepts were selected as they are conceptually important to understanding chemistry, included in state and district science standards, and relevant in designing possible solution to their personal heating or cooling problem. Thus, the unit included specific lesson targeting the central chemistry concepts. For example, students explored the concept that "energy transfers from particles with high kinetic energy to particles with lower kinetic energy through collisions" and applied this to the design of the container for their heating or cooling system. Through this approach, the design challenge creates a need-to-know and motivation to learn the chemistry concepts [40, 52 - 53].

Content Integration

Integrated STEM approaches can improve students' learning of scientific concepts [16 – 19], however students' have trouble in recognizing the ways in which different content areas support and complement each other [7, 54]. Although teachers may understand the connections across the different content areas, students often struggle to make these connections on their own [55 – 56]. Therefore, teachers need to help students to recognize these connections and make them explicit for students [24, 54].

For example, it is difficult to imagine teaching and learning chemistry without engaging in mathematical practices. However, chemistry teaching has traditionally over-emphasized the symbolic level, which includes the use of mathematical equations [57] and the connections between mathematical representations and scientific concepts are not transparent to students [49]. Students are expected to interpret the mathematical and scientific meaning represented by an equation [58 – 59], however, students rely on algorithmic procedures without making connections between the mathematical equation and the scientific phenomenon [60]. However, when instructors explicitly integrated science and mathematics through blended sensemaking, students' scientific and mathematical knowledge is activated which improves students' quantitative problem solving [61 – 63].

STEM Practices

Engaging students in STEM practices is a common component of definitions of integrated STEM education [6, 24]. The range of STEM practices in which students should engage is vast, however, the nature of integrated STEM is focused on engaging students in generating, evaluating, and iteratively improving design solutions. Thus, a prominent practice is the expectation that students "justify design choices and science explanations with sound reasoning and evidence" [40]. Siverling and colleagues refer to the practice of justifying design decisions as evidence-based reasoning, arguing that students should be explicitly engaged in evidence-based reasoning throughout the design process [64]. Evidence-based reasoning requires students to make claims about their designs and design decisions that are supported by both evidence and reasoning [65].

Specific to chemistry education, Stammes and colleagues argue that improving students' reasoning in chemistry is a valuable goal of design in chemistry education [66]. However, students tend to focus on pragmatic reasoning such at cost and materials, rather than using scientific concepts to justify and explain their design choices [67 – 68], thus students need to be encouraged to reason when designing [40, 69]. The design cycle used by Apedoe and colleagues includes a step that calls for students to generate reasons [41]. For example, when designing their heating and cooling system, students generated reasons for why different materials did not allow for sufficient transfer of energy and the teacher helped students to understand how thermal conductivity had important implications for their design. As another example, researchers engaged students in designing environmentally safe batteries and students had to provide chemical justifications for their choice of electrodes and electrolytes [40].

21st Century Skills

The skills needed for students to thrive and succeed in today's world, and more specifically the STEM workforce, include knowledge construction, real-world problem solving, skilled communication, collaboration, use of information and communication technology for learning, creativity, and collaboration [11, 70]. While demographic projections show decreases in the workforce in developed countries in Europe, North America, and East Asia, the workforce will increase in sub-Saharan Africa [71 - 72]. A policy focus within developing countries on 21st century and STEM skills has the potential to stimulate the national economies and development in these countries [72]. For example, the Kenyan government prioritized of 21st Century Skills in their Vision 2030, with the Ministry of Education, Science and Technology focusing on equipping citizens with 21st Century Skills required for the modern economy [73]. As another example, Egypt has focused on the development of STEM schools as central to re-envisioning education in Egypt (Egypt vision 2030). The mission of these schools is to foster the development of socially responsible leaders who are equipped with the knowledge and 21st century skills to address the grand challenges of Egypt [74].

Integrated STEM instruction provides a rich environment to support the development of 21st century skills [48, 75]. Real-world problems and engineering design challenges are complex with multiple possible solution paths, thus requiring that students engage in critical thinking, drawing on their STEM content knowledge to propose possible design solutions. The lack of a single correct solution when engaging in the engineering design also promotes creativity and the potential of transformative and innovative design solutions [76 – 77]. Specific to chemistry education, Ah-nam and Osman reported on a STEM intervention where students designed digital games to help their peers to learn chemistry concepts that was successful in improving students' chemistry knowledge and 21st century skills [78]. In another example, Hadinugrahaningsih and colleagues showed that their STEM approach to teaching acids and bases was successful in developing students' **critical and creative thinking, problem-solving skills, collaboration and argumentation skills, leadership and responsibility, information, and literacy skills [42].**

Promoting STEM Careers

Given the policy goal of promoting future participation in STEM careers, integrated STEM education should expose students to details about STEM careers [79 – 80]. One strategy is for students to engage in the authentic work of STEM professionals as they participate in STEM activities [81 – 82]. Engagement in chemistry practices is important in preparing students to use chemical knowledge to make decisions as scientifically literate citizens, and for potentially continuing a career in chemistry [59]. However, debate remains about whether implicit modeling of STEM professions by engaging students in hands-on STEM activities leads to durable and robust understandings about the work of engineers and other STEM professionals [83]. Whereas explicit discussion of STEM professions can help students to understand specific career opportunities and align these professions with their interests [81 – 82].

Students typically have limited understanding of chemistry-related careers, seeing teaching and laboratory research as the only options [84]. A variety of career-focused interventions have been reported at the undergraduate and graduate levels [85 – 88], however less attention has been placed on addressing chemistry careers at the K-12 level. Burrows and colleagues embedded career connections into their biodiesel curriculum but did not report on the impact on students' career interests [43]. Conversely, Apedoe and colleagues reported on the positive impact of their STEM approach to teaching chemistry on students' interest in engineering careers rather than chemistry-related careers [41].

Rather than focusing explicitly on careers, K-12 chemistry education has focused on helping students to see chemistry as relevant outside of school [89]. Indeed, research suggests that chemistry instruction should include real-world contextual issues to promote interest in chemistry [90 – 91].

More research is needed to better understand the role of instruction about STEM careers in K-12 chemistry instruction.

DISCUSSION

Each of the seven characteristics of quality integrated STEM education has important implications chemistry education both globally and specifically in Africa. At the highest level, chemistry education needs to be driven by real-world problems to motivate students to persist in the pursuit of STEM careers. Careful consideration is critical in selecting the context for an integrated STEM lesson, as research shows motivation for female students is driven by topics that promote positive societal impact, such as sustainability and healthcare [35 - 37]. Such topics are rich contexts for teaching chemistry concepts as demonstrated in the chemistry education literature [40 - 43].

While the integrated STEM framework described here [29], calls for engaging students in engineering practices and the contextualization of the real-world problem as an engineering design challenge, this may not be appropriate in the African context. The focus on engineering is relevant to countries that call for the integration of engineering into K-12 science standards [12 – 15]. Some of the examples within the chemistry education draw on engineering and design-based approaches [35 – 37], whereas others provide a real-world scenario to contextualize a chemistry lab without a heavy emphasis on engineering [92]. Attention to selecting real-world problems and related engineering design challenges that promote positive STEM identities for students that are under-represented in STEM not only addresses reported workforce needs but brings new perspectives and approaches to how STEM content and practices are applied in the real-world [29].

Regardless of whether the real-world problem is framed as an engineering design challenge, it is critical that the context is aligned with specific chemistry learning objectives. The context could be used to reactivate prior knowledge, or the lessons would include the explicit teaching of the relevant chemistry content. In other words, quality integrated STEM units should include lessons designed to explicitly teach relevant chemistry content as described in the chemistry education literature [40 - 43]. However, given that students rarely make connections between disciplines spontaneously [56], it is critical that teachers use specific pedagogical approaches, such as evidence-based reasoning [64 – 65], to help make these connections explicit. Strong teacher facilitation and questioning is needed to help students recognize the connections across the disciplines [29].

Most critical to the integrated STEM approaches to teaching science is the use of student-centered pedagogies that engage students in STEM practices and 21st century skills. However, the educational structure in Africa does not lend itself to such approaches and the current skills taught do not align themselves with the needs of the future workforce [93]. Indeed, pedagogical change is constrained by issues such as class size, hierarchical school structures, and examination requirements [94]. There is an urgent need to improve teacher recruitment, teacher preparation, and curriculum upgrades to promote integrated STEM approaches and improve educational outcomes in African nations [93 – 94]. Some hopefully cases of systemic change exist that could be used as the groundwork for other countries. For example, in Rwanda has promoted STEM education across K-12 and university levels, implementing new curriculum STEM and ICT (Information and Computer Technologies) integrated curriculum [95].

The integrated STEM framework described in this paper provides guidance on teacher practices to improve chemistry education. Teachers and researchers can use these characteristics of integrated STEM education as a grassroots effort to improve the teaching and learning of chemistry for specific topics in support of the necessary larger systemic changes needed within the education system itself.

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