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Equity-Oriented Conceptual Framework for K-12 STEM Literacy

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REVIEW

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Equity-Oriented Conceptual Framework for K-12 STEM literacy

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Abstract

We introduce a conceptual framework of K-12 STEM literacy that rightfully and intentionally positions each and every student, particularly minoritized groups, as belonging in STEM. In order to conceptualize the equity-based framework of STEM literacy, we conducted a systematic review of literature related to STEM literacy, which includes empirical studies that contribute to STEM literacy. The literature on the siloed literacies within STEM (i.e., science, technology, engineering, and mathematics literacy) also contributed to formulate the necessity of and what it means to develop STEM literacy. The Equity-Oriented STEM Literacy Framework illuminates the complexities of disrupting the status quo and rightfully transforming integrated STEM education in ways that provide equitable opportunities and access to all learners. The Equity-Oriented STEM Literacy Framework is a research-based, equity and access-focused framework that will guide research, inform practice, and provide a lens for the field that will ensure each and every student, especially minoritized students, develop, and are developing STEM literacy.

Keywords: STEM Literacy, Equity, Conceptual framework, Informal learning, Formal learning, STEM education

Introduction

Integrated K-12 Science, Technology, Engineering, and Mathematics (STEM) makes STEM subjects more meaningful (NRC, 2011), increases students' engagement and interest (Cotabish et al., 2013; Moore, Guzey, & Brown, 2014), and raises student achievement (Barker & Ansorge, 2007; Becker & Park, 2011; Dickerson et al., 2014; Rehmat, 2015; Sullivan, 2008; Venville et al., 2000). Given the importance of these outcomes of integrated STEM, it is imperative that each and every student has access to integrated STEM learning experiences, especially minoritized students in STEM and the STEM disciplines. For the purpose of this paper, minoritized students in STEM are Blacks, Latinx, Native Americans, students with dis(abilities), students in poverty, girls, trans, and non-binary students. Unfortunately, minoritized students have been marginalized in STEM and within the STEM fields. In 2015, minoritized individuals comprised approximately 38% of the population in the USA (Anderson, 2015), but only made up about 12.7% of the total STEM workforce (Aish et al., 2018). Thus, it is imperative to disrupt the systems of oppression that are evident in our society to provide each and every student, including minoritized individuals, access to high-quality STEM experiences to develop STEM literacy, which is a critical asset needed by all in today's world. STEM literacy refers to the integration of STEM disciplines and the tools and knowledge necessary to apply STEM concepts to solve complex problems (Balka, 2011). Through every student gaining access to high-quality STEM learning experiences, we can begin to develop a society where all students are STEM literate (Mohr-Schroeder et al., 2020). The purpose of this paper is to introduce a conceptual framework of STEM literacy that rightfully and intentionally positions each and every student, particularly minoritized groups, as belonging in STEM.

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Review of literature

In order to conceptualize an equity-based framework of K-12 STEM literacy, we conducted a systematic review of literature related to STEM literacy, which includes empirical studies that contribute to STEM literacy as well as our own empirical work in STEM literacy (e.g., Cavalcanti & Mohr-Schroeder, 2019; Clark et al., 2015; Jackson & Mohr-Schroeder, 2018; Maiorca et al., 2020; Mohr-Schroeder et al., 2014; Mohr-Schroeder et al., 2017; Mohr-Schroeder et al., 2018; Nurlaely et al., 2017; Roberts et al., 2018; Tati et al., 2017). For this systematic literature review, we reviewed literature from 2009 to present. Using the keywords "STEM literacy", "integrated STEM literacy", and "STEM or STEAM conceptual frameworks" we reviewed 115 articles, books, and reports in totality. We limited the search to empirical studies, conceptual and research-informed practice-oriented articles, book chapters, syntheses, and reports that focused on STEM literacy within an integrated STEM context within K-12 education. We define integrated STEM as the integration of two or more content areas of STEM (i.e., science, technology, engineering, or mathematics). More specifically, integrated STEM learning consists of addressing real-world problems that engage students in disciplinary big ideas and skills in at least two of the four content areas in a student-centered, collaborative environment (Moore et al., 2020; Roehrig et al., 2021). While there were numerous blog and news-media publications regarding STEM literacy from 2009 to present, we intentionally decided not to include them in this systematic review as we wanted to focus on research-based evidence of STEM literacy. In the subsequent sections, we discuss the foundations of the equity-based STEM literacy conceptual framework based on our systematic literature review, and then we present the framework and situate it within the results of the systematic review and our prior empirical research.

STEM literacy

STEM literacy in grades K-12 is essential for each and every student because it promotes and fosters in students innovative thinking, collaboration, creativity, problem solving and critical thinking, and communication skills (Mohr-Schroeder et al., 2020), which are necessary components to live a productive life in the 21st century. STEM literacy is not a conglomeration of the four silos that comprise STEM; that is, it is not a laundry list of components of scientific literacy, technological literacy, engineering literacy, and mathematical or quantitative literacy. But the literature on the siloed literacies play a pivotal role on how STEM literacy is configured. For example, according to the American Association for the Advancement of Science (AAAS) (1989), science literacy is multi-faceted and interdependent on mathematics, technology and the social sciences. AAAS further describes scientific literacy as "being familiar with the natural world and respecting its unity; being aware of some of the important ways in which mathematics, technology, and the sciences depend upon one another...and being able to use scientific knowledge and ways of thinking for personal and social purposes" (p. 20). The National Research Council (2012) builds on the concept of science literacy by describing it as the appreciation of "the beauty and wonder of science; possess sufficient knowledge of science and engineering to engage in public discussions on related issues; are careful consumers of scientific and technological information related to their everyday" (NRC, 2012, p. 1).

The National Academy of Sciences (2014) defines technology as the product of science and engineering, and further states that humans create technology and technological devices to meet the needs and desires. The International Technology Education Association (2007) views technology as a means to extend the abilities of humans, a compilation of knowledge and processes that helps us satisfy the wants and needs of humans in our society. Bybee (2010) suggests that technology heavily influences our daily lives, and few people truly understand it. Being technologically literate is essential in participating in society, enhancing education of other subject areas and vital for individuals to gain and maintain employment.

Mathematical literacy has been defined in many different ways and is dependent on the goals of mathematics education (Tout, 2000). According to the National Academy of Sciences (2014), mathematics is the study of relationships and patterns among quantities, numbers, and space. In K-12 education, mathematics focuses on numbers and arithmetic, algebra, functions, geometry, ratios and proportional relationships, and statistics and probability. Kaiser and Willander (2005) proposed that mathematical literacy has four levels: illiterate, nominal, functional, and conceptual and procedural. For Kaiser and Willander, the ultimate goal of mathematical literacy was students' ability to use mathematics in their personal, private lives outside of the mathematics classroom. In their study, they found few students had conceptual and procedural literacy and were unable to relate mathematics to the real world.

While engineering literacy has not been globally defined, we view engineering as both a process of solving problems and a body of knowledge (NRC, 2012) and as the application of mathematics, science, and technology. Engineering is a vital tool for integrating science, technology, and mathematics (English, 2016; Grubbs & Strimel, 2016; Moore, Glancy, et al., 2014).

The literature on the siloed literacies within STEM (i.e., science, technology, engineering, and mathematics literacy) help formulate the necessity of and what it means to develop STEM literacy. It is important that each and every student develop STEM literacy—with the ability to take the literacy from the individual disciplines and integrate it to solve problems that will arise in their everyday personal and professional lives, regardless of whether or not they pursue a STEM career (Mohr-Schroeder et al., 2020). STEM literacy is the ability to apply concepts from science, technology, engineering, and mathematics to solve problems that cannot be solved using a single discipline. The literature on STEM literacy includes multiple definitions that serve to inform how we think about students and their developing STEM literacy. For example, Bybee (2010) defines STEM literacy as using abilities, conceptual knowledge, and skills to problem-solve STEM-related social, personal, and more global issues in society. Zollman (2012) extends this definition and includes cognitive, affective, and psychomotor domains. The National Governer's Association (2007) refers to STEM literacy as an individual's ability to apply his or her understanding of how the world works within and across four interrelated domains adopting an integrated focus. Similarly, the National Research Council (2011) describes STEM literacy as "...the knowledge and understanding of scientific and mathematical concepts and processes required for personal decision making, participation in civic and cultural affairs, and economic productivity for all students" (p. 5). In this paper, we specifically draw on Mohr-Schroeder et al.'s (2020) definition of STEM literacy: "STEM Literacy is the dynamic process and ability to apply, question, collaborate, appreciate, engage, persist, and understand the utility of STEM concepts and skills to provide solutions for STEM-related personal, societal, and global challenges that cannot be solved using a single discipline" (p. 33).

Much of the reform efforts in STEM education have been largely geared to preparing a STEM-literate workforce to maintain global competitiveness in our rapidly changing society (e.g., Committee on STEM Education National Science and Technology Council, 2013; Kennedy & Odell, 2014; National Science Board, 2015). While this focus is critical, our focus on STEM literacy expands beyond this overarching notion and particularly seeks to include groups that have been historically underrepresented in STEM, who continue to remain at risk of disengaging (e.g., Beasley & Fischer, 2012; Morgan et al., 2016; Museus et al., 2011). STEM policy reports (such as Committee on STEM Education of the National Science & Technology Council, 2018; National Research Council, 2011; U.S. Department of Education, 2016) highlight the importance of fostering STEM literacy in each and every student, from all backgrounds, so they have access to and are empowered to develop foundational knowledge in STEM, no matter whether or not they pursue a STEM career (see Bush, 2019 for review of policy reports). Further, national standards documents such as the Next Generation Science Standards (NGSS Lead States, 2013) and the Common Core State Standards for Mathematics (NGA Center & CCSSO, 2010) have taken a practice-based approach calling for the integration of STEM disciplines in ways that enacts STEM literacy and its subcomponents (e.g., scientific literacy, quantitative literacy, statistical literacy, technological literacy, etc.).

STEM frameworks

It is clear from the literature that integrated STEM education is established as a field in education (Johnson et al., 2020; Moore et al., 2020; Roehrig et al., 2021). Teaching integrated STEM K-12 has been found to be a more effective teaching pedagogy when compared with individually teaching the siloed disciplines (Becker & Park, 2011; Venville et al., 2000). Becker and Park (2011) described that through the integration of the disciplines, the theory learned in science and mathematics can be bridged with the practical applications of engineering and technology. Furthermore, McCright (2012) argued inquiry-based project learning, one of the tenets of STEM education, not only developed quantitative and scientific literacies but also 21st century competencies necessary to be successful in the STEM workforce.

In the literature, numerous frameworks within STEM education exist. Table 1 showcases a sample of such frameworks (not intended to be an exhaustive list). In the table, we included four STEAM education frameworks as it was found that some of the most recent frameworks in the literature were inclusive of the arts. A review of the STEM and STEAM education frameworks revealed that some focused generally on the integration of the disciplines (e.g., Bybee, 2010; Honey et al., 2014; Kelley & Knowles, 2016; Tan et al., 2019; Yakman, 2011; Yata et al., 2020), several focused on preparation of teachers and workforce development (Lee & Nason, 2012; Reider et al., 2016), two focused on a teaching model (Falloon et al., 2020; Quigley et al., 2017), one on equity and access broadly (Bush & Cook, 2019), and one specifically on students with disabilities (Hwang & Taylor, 2016).

While STEM (and STEAM) education frameworks exist and support for developing students' STEM literacy exists, a conceptual framework of STEM literacy with equity explicitly positioned at the forefront, does not yet appear to exist, although there is one general equity-focused STEAM education framework, as well as a specific STEAM education framework focused on students with disabilities. As further explained below, this critical inclusion of equity within STEM literacy provides unique contributions that other STEM education and

Table 1 Sample STEM and STEAM education frameworks

Framework name	Brief description
STEM	
A Framework for Model STEM Units (Bybee, 2010)	A framework that centers around the context of problems that need STEM to solve them. STEM competencies are the learning outcomes
A STEM Literacy Development Framework for STEM Education (Falloon et al., 2020)	A framework that maps connections across different characteristics of K-12 STEM education, to highlight different approaches to STEM curriculum planning and teaching
STEM Integration in K-12 Education: Status, Prospects, and Agenda for Research (Honey et al., 2014)	Integrated STEM education framework organized into four components: Goals, Outcomes, Nature and Scope of Integration, and Implementation
Situated STEM Learning (Kelley & Knowles, 2016)	Integrated STEM education framework organized as a pulley system, with the pulley connecting common practices across disciplines, and a rope representing a community of practice
A Framework for Reforming Preparation of STEM Teachers (Lee & Nason, 2012)	A framework focused on reforming the preparation of STEM teachers organized by three principles and eight strategies
ITEST STEM Workforce Education Helix (Reider et al., 2016)	A framework organized as a helix to illustrate the relationship between STEM content development activities, STEM career development activities, teacher professional development, partnerships, and cultural context
The STEM Quartet Instructional Framework (Tan et al., 2019)	A framework showing the level of connection among the STEM disciplines, with six steps (i.e., identify problem, understand problem, formulate solution, implement solution, review solution, new problem) around the circumference of the visual
Relationship Between the Engineering Design Process and Science, Technology, and Mathematics (Yata et al., 2020)	A framework that serves to promote interdisciplinary STEM education recognizing the uniqueness and similarities of each STEM discipline, considering how each science, technology, and mathematics are needed in engineering
STEAM	
Interdisciplinary Approach to STEAM Education for Students with Disabilities (Hwang & Taylor, 2016)	A framework focused on a real-world context/authentic problem, the integration of the STEAM disciplines, and generalizability
Equitable STEAM Education (Bush & Cook, 2019)	A framework that describes the key ingredients for equitable STEAM education as: providing access to each and every student, implementing reform practices in mathematics and science teaching, and exploring meaningful and authentic problems through STEAM.
STEAM: A Framework for Teaching Across the Disciplines (Yakman, 2011)	A framework organized as a pyramid with content specific at the base, then discipline specific, multidisciplinary, integrative, and then life-long holistic at the top of the pyramid
STEAM Teaching Model (Quigley et al., 2017)	A framework organized by two domains (i.e., instructional content and learning context) and six dimensions (i.e., problem-based delivery, discipline integration, problem-solving skills, instructional approaches, assessment practices, and equitable participation)

STEM literacy frameworks do not address. Equity within STEM literacy is grounded and central in students' sense of belonging in the STEM community, STEM identity development, seeing the utility and application of STEM, and the role empathy exemplifies in doing integrated STEM. The purpose of this paper is to provide a research-based, equity and access focused, STEM literacy framework to the field to guide research, inform practice, and to provide a lens for the field that ensures each and every student, especially minoritized students, develop and are developing STEM literacy.

Conceptualization of the Equity-Oriented STEM Literacy Framework

Given the support for developing students' STEM literacy, schools and districts as well as informal learning settings and networks (e.g., Blackley & Howell, 2015; Kennedy & Odell, 2014; Mohr-Schroeder et al., 2015; Sanders, 2008) are moving forward with K-12 STEM initiatives that deserve clarity on how best to empower each and every student through STEM learning experiences, which influences their development of STEM literacy. Many factors influence the development, or lack thereof, of an individual's STEM literacy. These include the priority in- and out-of-school learning opportunities, who is believed to belong in STEM, our long-standing and deeply-rooted cultural stereotypes centered around STEM, and how we define integrated STEM and STEM literacy (described in Mohr-Schroeder et al., 2020). We want to throw caution to avoid using the phrase—a "STEM literate" individual. Our work has revealed that STEM literacy is a continuum and there is never an "end." In the same way we have and pursue lifelong learning, we are continuously in pursuit of lifelong STEM literacy. In the subsequent sections, we provide clarity and focus to the field regarding STEM literacy by conceptualizing an equity-oriented STEM Literacy Framework.

The Equity-Oriented STEM Literacy Framework (Fig. 1) provides general guidance for researchers and educators to ensure equity is integral within each component of STEM literacy. Equity must be a centralized component of STEM literacy. If it is not, students, especially minoritized students, may be unintentionally or intentionally excluded from STEM learning experiences, thereby hindering their STEM literacy development. We draw on Gutiérrez's (2009) conception of equity, which goes beyond the traditional confines of access and achievement to include emphasis on power and identity. Although access and achievement are important components of equity, providing access and focusing on achievement does not sufficiently provide marginalized populations the tools they need (Gutiérrez, 2009). But access and opportunity are critical components to enter and engage in integrated STEM learning experiences. Consequently, the underlying premise of the framework describes how opportunity and access contribute to the importance of STEM literacy, and conversely, the implications of STEM literacy and its impact on opportunity and access. The other two components of equity, identity and power, focus on how individuals see themselves as a member of the community and how they use their understanding to change the world. In essence, each and every student needs access to high-quality STEM learning experiences that affirm their identities as important members of the STEM community who are working to make the world a better place.

The Equity-Oriented STEM Literacy Framework goes beyond platitudes of "diversity, equity, and inclusion", and the traditional focus on access by illuminating the complexities of disrupting the status quo and rightfully transforming integrated STEM education in ways that provide equitable opportunities and access to all learners. This will only be accomplished through employing strategies to break down real and perceived barriers for students belonging to the STEM conversation, particularly with minoritized populations in STEM. Each component of the Equity-Oriented STEM Literacy Framework is further delineated in the subsequent sections.

Systems of oppression and privilege

In today's society, individuals, both young and old, are affected by oppression and privilege. The systems of oppression and privilege have become institutionalized in our society through the forms of racism, classism, sexism, ableism, and other -isms that manifest in today's society. Minoritized students have been historically excluded from STEM learning and engagement in STEM careers. Bian et al. (2018) argue a brilliance bias exists against girls in STEM fields as they are less likely to be considered "really, really smart" in relation to boys. Ford et al. (2019) suggest this brilliance bias can be present as early as elementary school, discouraging girls from pursuing STEM interests at young ages, making it difficult to spark their interest in STEM opportunities later in their academic careers. Similarly, Schunk and Meece (2006) argue cultural stereotypes portray minoritized groups as less academic and skilled than white men, specifically when it comes to the STEM disciplines. The pervasiveness of colorblind ideology in teaching and policy documents continue to ignore the systems of oppression and privilege that negatively impact minoritized students (Basile & Lopez, 2015; Bonilla-Silva, 2006).

It is not only necessary to be aware of the systems of oppression and privilege that are prevalent in today's society (e.g., racism, sexism, classism, and ableism), it is imperative we also acknowledge privilege and oppression are not "figments" of peoples' imagination (Stinson & Spencer, 2013) and disrupt these systems if we want each and every student to develop and increase their STEM literacy. The primary way to disrupt and continue to disrupt the systems of oppression is to provide access and opportunity to students, including minoritized students to high-quality integrated STEM learning experiences. The specific components to be addressed include dispositions, STEM identity development, empowerment, critical thinking and problem solving, utility and application, and empathy. However, these cannot be addressed without first working to provide opportunity and access to high-quality STEM/STEAM learning experiences.

Opportunity and access

The quality of the STEM learning experiences in which students have access matters. Each and every student needs and deserves access to the highest-quality integrated STEM learning experiences where students apply the content and practices of the disciplines to solve authentic problems in ways that are rigorous and maintain the integrity of grade-level standards (Bush & Cook, 2019; NCSM & NCTM, 2018). Access to and engaging in authentic learning experiences promote literacy among students (Israel et al., 2013). Moreover, inquiry approaches within authentic learning provide opportunities for authentic meaning-making and encourage successful STEM affiliation (Ballenger, 2005), as well as level differences in performance through careful alignment of hands-on activities and purposeful discourse strategies that elicit and honor student thinking (Palincsar et al., 2000). Further, STEM instruction can be inclusive of the incorporation of other disciplines, such as the Arts to make STEAM or computer science to make STEM+C. It is not really about the acronym, it is about access to high-quality learning experiences (Bush & Cook, 2019). Thus, the Equity-Oriented STEM Literacy

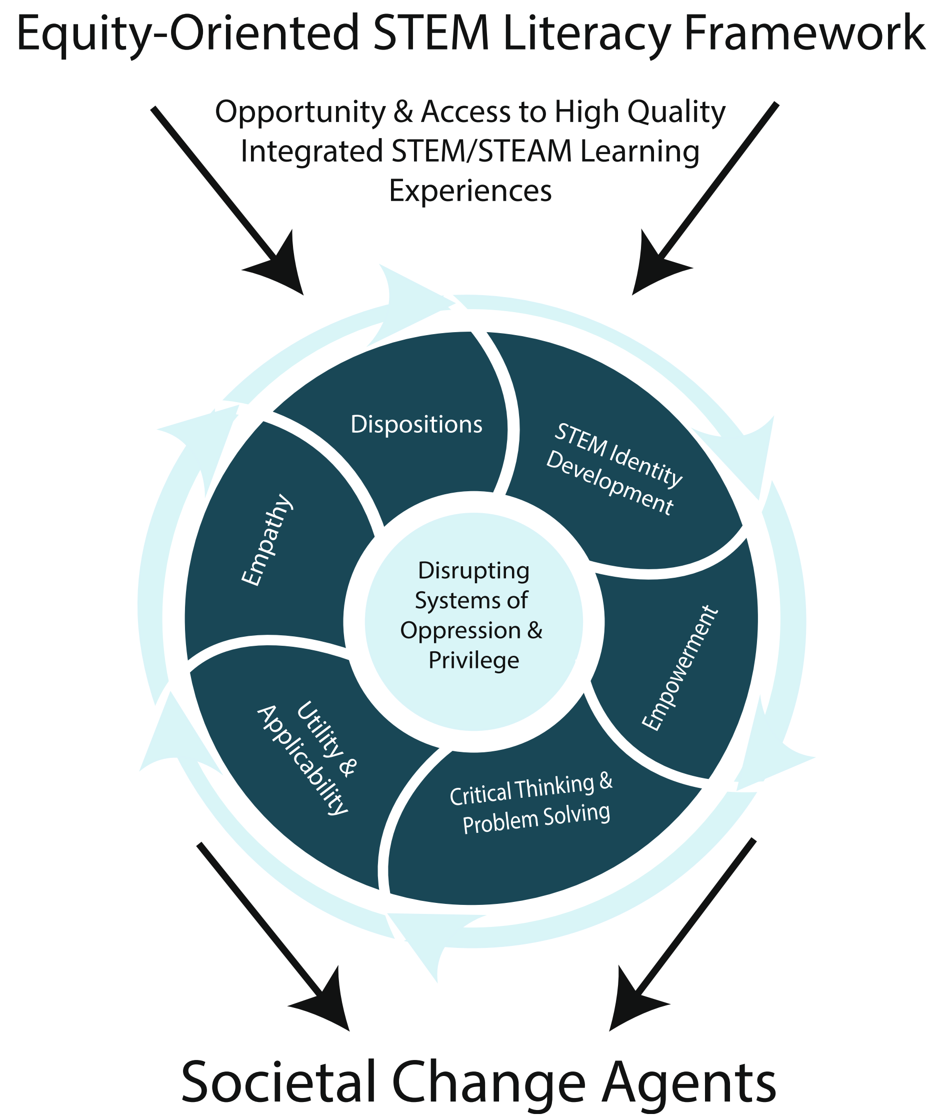

Fig. 1 Equity-Oriented STEM Literacy Framework

Framework can apply to variations of integrated STEM (e.g., STEAM, STEM+C, STEM+M, STREAM, etc.). As the number of STEM careers continues to increase, the ability to develop STEM literacy is directly affecting students' interests in STEM-related disciplines, which are often determined by the way students interact with science and mathematics, making access to varying opportunities distinctly important and necessary (Cavalcanti, 2017; Maiorca et al., 2020; Roberts et al., 2018).

Importantly, K-12 students should have opportunity and access to STEM in both formal and informal learning environments. The access to science and mathematics courses in formal learning environments often directly affects a student's interest in STEM. According to Jong et al. (2020), access to advanced STEM courses in high school is a prominent factor in the decision to major in a STEM-related discipline. In fact, minoritized students weigh success in twelfth grade mathematics heavily when deciding to pursue a future in STEM or other STEM-integrated disciplines (Jong et al., 2020; Wang, 2013). However, access to formal STEM classes is significantly skewed to the advantage of white, affluent students, and frequently leaves minoritized students behind. The fixation on standardized test scores often prevents schools which are heavily populated with minoritized students from accessing the funding required to institute more formal STEM opportunities (Bell et al., 2009; Chambers, 2009; Meyers et al., 2013). Ultimately, this kind of limited perspective places the blame on students, as though it is their fault for not being "smart enough" or "interested enough" in STEM, rather than focusing on the need to take a closer look at the deeply rooted and systemic barriers to their participation in STEM (Jong et al., 2020; Museus et al., 2011), which significantly diminishes access to advanced formal science and mathematics opportunities, in turn directly affecting the likelihood of further pursuit of STEM-related disciplines.

Informal STEM learning environments provide opportunities for students, especially minoritized students, to engage in STEM learning experiences that are not generally afforded to them in formal STEM environments (Barton et al., 2016; Roberts et al., 2018). Informal STEM learning environments include camps, museums, after-school programs, and other environments where students have the option to attend, and assessments within these environments, if any, have little to no consequences (Cavalcanti, 2017). Having the opportunity to engage in informal STEM learning experiences during the summer counters the effects of learning loss that disproportionately affects minoritized students. Informal STEM learning environments provide access for students to engage in authentic learning experiences that bridges their formal and informal learning (Meredith, 2010; Popovic & Lederman, 2015; Roberts et al., 2018), which support their initial and continuous development of STEM literacy. With STEM opportunities and experiences equally accessible to all, society will be much better able to address problems that must be examined through an integrated approach which will enable the development of solutions that are innovative (Mohr-Schroeder et al., 2020).

Critical thinking/utility and applicability

At the core of nearly all STEM experiences, especially those centered on increasing STEM literacy, is the use of critical thinking and problem-solving skills. While critical thinking and problem-solving skills have long been hallmarks within the STEM disciplines (e.g., NCTM process standards), we see a re-emergence of their focus within the last 10 years with the standards for mathematical practice (CCSSO, 2010) and the science and engineering practices (NGSS Lead States, 2013).

STEM learning environments provide rich learning experiences in which students have the opportunity to apply their critical thinking skills to solve complex problems. Applied further, students get to visualize and see the utility and applicability of the solutions to the complex problems. Utility and applicability address the extent that students recognize STEM as it relates to the real world and the skills associated with STEM areas that are useful to address real-world issues (e.g., STEM as worthwhile). In our prior work, we focused our STEM learning experiences on the utilization of the standards of mathematical practice and the science and engineering practices (e.g., Mohr-Schroeder et al., 2014). In doing this, we were able to focus on the immersion of the students in the experiences, rather than a traditional “sit and get” model. In this way, students, especially minoritized students, were able to see the utility and applicability of their work. Further, we found that students then had the desire to apply their knowledge and curiosity further, beyond the experience. Students valued STEM in their personal lives and valued it as a tool for addressing societal needs.

Empathy

A student’s ability to mentally identify themselves with and fully comprehend another person can be described as empathy (Brown, 1996; Cohen, 2001; Cooper, 2011), which importantly focuses on “feeling with” and not just “feeling for.” Through our research (e.g., Bush et al., 2020; Bush & Cook, 2019; Edelen, Bush, et al., 2020; Maiorca et al., 2020; McCurdy et al., 2020), we have found that specifically developing empathy in students as they explore an inquiry under investigation can serve as a potential bridge for students who have encountered real or perceived barriers to STEM. Such barriers could be lack of access to meaningful STEM inquiries or students not seeing others who look like them doing STEM. However, empathy can serve as a gateway to students seeing themselves as needing to play a role in helping to find a solution to the problem under investigation. Empathy brings humanization and care into the STEM equation. Positioning empathy as a key access point to STEM potentially makes learning experiences more meaningful to students, thus helping them to identify and experience the impact of STEM in both their lives and the lives of others (McGee & Bentley, 2017; Sun, 2017). For example, in one study, we found that not all integrated STEAM inquiries are of equal quality, and the ones that engaged students in empathetic problem solving provided the most transformative learning experiences for students (Bush et al., 2020). In another study, we found that empathy has real potential to impact students’ interest in STEM careers (Maiorca et al., 2020). Some examples of empathy-driven inquiries we have empowered students through include designing a coat for a kind giant living in harsh weather (Kaiser et al., 2018; Owen et al., 2018), exploring tiny homes as a solution for homelessness (Edelen, Simpson, & Bush, 2020, 2021), and designing a prosthetic for a local kindergartener in need (Bush et al., 2016; Cook et al., 2015). When considering our initial findings surrounding the role of empathy, the aspect of empathy importantly fits within multiple components of our framework including Utility and Applicability of STEM, and ultimately Societal Change Agents.

STEM dispositions

Productive STEM dispositions include seeing STEM as "sensible, useful, and worthwhile" (Kilpatrick et al., 2001, p. 116). We operationalize productive STEM dispositions to include one's attitude toward, interest in, and motivation in STEM. It is important students have opportunities to explore STEM in the classroom or in informal learning environments so their interest, engagement, and achievement in STEM grows (National Academy of Engineering and National Research Council, 2014). Previous studies have shown that positive attitudes toward content is a key factor in increasing achievement in that content area (Simpson & Oliver, 1990). Therefore, quality STEM learning experiences that promote positive dispositions toward STEM are important in supporting student achievement in STEM. Furthermore, the dispositions students form toward STEM in middle school impact the science and mathematics courses they complete in high school (Liu et al., 2011; Misiti et al., 1991) and the careers they choose to pursue (Choi & Chang, 2011; Nugent et al., 2015).

There are a variety of ways to provide early exposure to STEM through both informal and formal learning environments. Previous research has shown that STEM dispositions vary by type of STEM experiences. For example, Christensen et al. (2015) studied the STEM dispositions of three different groups of secondary students: (1) those who participated in Middle Schoolers Out to Save the World in which students study energy during formal classroom instruction, measure energy consumption of devices at home and at school, and discuss how their community can reduce the amount of carbon dioxide that the community produces, (2) those who participated in the Communication, Science, Technology, Engineering, and Mathematics program, an after-school program that culminates in an end-of-the-year STEM competition where students engage in a variety of challenges, and (3) those who attended the Texas Academy of Mathematics and Science, a program at University of North Texas for high school juniors and seniors who are interested in STEM where they complete 2 years of college coursework. The findings of the research showed that hands-on, real-world, active learning STEM activities appeared to promote positive STEM dispositions and a greater interest in STEM careers. However, Communication, Science, Technology, Engineering, and Mathematics and Texas Academy of Mathematics and Science students who self-selected into the STEM experiences showed highly positive STEM dispositions, higher than the dispositions of the Middle Schoolers Out to Save the World students who had to participate in the school-based program.

Informal STEM learning programs, such as Communication, Science, Technology, Engineering, and Mathematics, can be an ideal environment to increase productive STEM dispositions (Nugent et al., 2015). These types of environments have the capability of engaging students in in-depth study of STEM subjects through active learning and exploration without the constraints of a formal school structure (i.e., class periods, required assessments). Previous research has shown informal STEM learning environments can have a positive impact on youths' disposition toward STEM (Campbell et al., 2012; Chittum et al., 2017; Christensen et al., 2015; Gilliam et al., 2017), understanding of STEM concepts and careers (Adams et al., 2014; Campbell et al., 2012), attitudes toward pursuing a STEM career (Campbell et al., 2012; Chittum et al., 2017), and self-efficacy in STEM disciplines (Adams et al., 2014; Chittum et al., 2017). It is particularly important that minoritized students have opportunities to participate in informal STEM learning programs since they often attend schools with inadequate resources for science education (Rahm, 2008).

Campbell et al. (2012) investigated how an informal STEM learning experience supported minoritized students' motivation and interest in STEM. Secondary students who participated in the Mathematics, Engineering, Science Achievement program and competition in which they write a technical paper, prepare an academic display, conduct a scientific presentation, and construct a device to meet a particular challenge, participated in the study. Approximately three fourths of the participants were students of color. The results indicated that the Mathematics, Engineering, Science Achievement program and competition positively impacted the students' STEM learning, their productive STEM dispositions, and their interest in pursuing a career in STEM.

Research also shows formal STEM learning programs that occur during classroom instruction time influence students' dispositions toward STEM. One study investigated whether the implementation of an engineering design-based science curriculum improves student learning and students' attitudes toward STEM (Guzey et al., 2016). Three middle school life science teachers developed an engineering design-based unit that aligned with the Next Generation Science Standards in which students design a solution to an authentic, real-world problem and engage in a variety of hands-on science activities. Students who engaged in the unit completed a survey before and after the unit that assessed their attitudes toward STEM. The results of the study suggest that students' attitudes toward STEM significantly increased because of their participation in the unit (Guzey et al., 2016).

Knezek et al. (2013) also investigated the impact of a project-based learning STEM unit on students' STEM content knowledge as well as their dispositions toward STEM, including their perceptions of STEM subjects and STEM careers. The study utilized Middle Schoolers Out to Save the World project activities, discussed earlier, which were designed to pique middle school students' interest in STEM by engaging them in hands-on activities and solving real-world problems. The inquiry-based, project-based learning activities were designed to encourage students to question, think critically, and solve authentic problems to reach a common project goal. The STEM Semantics Survey was used to measure interest in STEM subjects and STEM careers. Analysis of the data indicates that STEM dispositions became more positive, interest in STEM careers increased, and students became more aware of opportunities (e.g., school programs, clubs, groups, etc.) that allow them to engage in building and designing things after participating in the Middle Schoolers Out to Save the World activities (Knezek et al., 2013).

Coleman and colleagues have investigated what motivated Black and Latinx students to engage in STEM and pursue STEM careers. Factors students mentioned that helped them persist is feeling an obligation to the Black and Latinx communities to break negative stereotypes about Black and Latinx students, having an intrinsic motivation to learn, understanding that STEM is a field that offers career and financial stability, and solving problems that better humanity (Coleman et al., 2018; Coleman & Ingram, 2015). In another study, Black male students explained they are motivated to engage in STEM because of their passion for STEM, the money that a stable STEM career can offer, their interest in solving problems that advance humanity, their desire to learn and discover new things, and their obligation to the Black community to break stigmas about Black males (Coleman, 2016). These findings provide insight into factors that support productive STEM dispositions. The importance of hands-on, real-world investigations of STEM concepts in building productive STEM dispositions is a common thread throughout these studies. Importantly, these studies also demonstrate that as students build productive STEM dispositions, they also build knowledge of and interest in STEM careers.

STEM identity development

Limited research has been conducted on integrated STEM identity development, especially in K-12 settings. Identity as a concept does not have a uniformly accepted definition in discipline specific literature (e.g., Hazari et al., 2020; Martin, 2000). Gee (2000) attempted to operationalize identity with an emphasis on a "kind of person" from four different perspectives. More recently, Vincent-Ruz and Schunn (2018) noted the difficulty of measuring science identity. The literature does offer several insights into what comprises identity. Broadly, we operationalize identity development as being *intersectional* (Capobianco et al., 2012; Carlone & Johnson, 2007; English-Clarke et al., 2012; Hazari et al., 2020; Martin, 2012; Zavala, 2014), being *influenced* by the community, parents, and peers (Berry III, 2008; Brown et al., 2005; Carlone & Johnson, 2007; Martin, 2000), and being related to seeing the *utility* and application of the subject matter (Capobianco et al., 2012; Martin, 2000).

Unfortunately, several barriers exist to forming positive STEM identities. Minoritized students are less likely to see themselves as scientists and mathematicians and feel like they do not belong in the STEM community (Coxon et al., 2018; Vincent-Ruz & Schunn, 2018). Therefore, our framework demands learning environments which affirm and encourage students' identities because they are critical in promoting positive STEM identities, particularly for minoritized populations (Jong et al., 2020). Promoting positive STEM identities extends to cultural and linguistic differences minoritized students bring to STEM learning experiences. Students' culture and native language must be attended to in STEM learning experiences (Jong et al., 2020; Savage et al., 2011), as valuing and using students' native language provides access to the learning environment (Zavala, 2014). With mathematics being the foundation of STEM (Bybee, 2010), students' early experiences in mathematics are critical to building positive mathematical identities (Berry III, 2008) which can also prevent mathematics from being a gatekeeper to more advanced STEM study (Martin et al., 2010). High-quality integrated STEM learning experiences central to this framework enable students to develop positive STEM identities as they see the utility and application of STEM in the world around them.

Empowerment

The instruction students receive and the education students experience in formal and informal STEM learning environments empower students and positively influence their long-term persistence (Fortus & Vedder-Weiss, 2014; Vedder-Weiss & Fortus, 2010). Several STEM learning experiences use an inquiry-based approach (Chittum et al., 2017; Guzey et al., 2016; Knezek et al., 2013) in which students take an active role in solving challenges by posing questions and engaging in problem solving to develop a solution. These real-world problems were hands-on, active, and engaging (Christensen et al., 2015; Gilliam et al., 2017; Guzey et al., 2016; Knezek et al., 2013), which may empower students to be a change agent in the world in which they live. Furthermore, the activities were interesting, enjoyable, and demonstrated the utility of STEM (Adams et al., 2014; Chittum et al., 2017). In one study, students were interviewed after participating in an after-school STEM program. Students reported feeling empowered because they had a choice over how to approach the content and how to design the device that would best meet the engineering challenge (Chittum et al., 2017). The students reported the program also provided a caring, supportive environment where they could participate (Chittum et al., 2017).

Studies highlighting characteristics of STEM learning environments have been shown to positively empower minoritized students in STEM. First, students report enjoying the social aspect of the STEM program they participated (Adams et al., 2014; Gilliam et al., 2017). Students reported the social interactions helped make the experience more enjoyable, increased their interest and motivation, and created a community in which everyone supported the learning and success of others (Gilliam et al., 2017). In one study, students explained that by working together in teams, they were able to appreciate each other's differences and the diversity of their team (Gilliam et al., 2017). In another study, the students valued the safe space the STEM learning experience created in which they no longer felt like outsiders due to their interest in STEM, but instead were excited about the opportunity to interact with like-minded peers (Adams et al., 2014). Through their participation, students gained confidence in their STEM abilities which helped them persist through challenges they faced while pursuing a STEM major in college (Adams et al., 2014).

To further empower and develop Black and Latinx students' positive dispositions toward STEM, curriculum and programs should include historical and current news and issues related to Black and Latinx communities so students understand societal issues that impact their communities and find the content meaningful and relevant (Coleman et al., 2018; Coleman & Ingram, 2015; Jackson et al., 2020; Jong et al., 2020). Incorporating culturally relevant pedagogy can show students STEM can be a part of their everyday lives, and not something that is challenging or atypical in the Black and Latinx communities (Coleman et al., 2018). Lastly, mentors and having exposure to STEM professionals may also empower minoritized students. Mentors and STEM professionals act as role models and help orient students to college and STEM careers (Gilliam et al., 2017). Previous research suggests that role models be relatable, that is, they have similar backgrounds, interests, and/or passions as the students (Aish et al., 2018). Aish et al. (2018) suggest that providing minoritized students with a more diverse pool of role models who represent similar backgrounds and paths to success in STEM may empower students to pursue and persist in STEM.

Societal change agents

As individuals develop and become more STEM literate, they simultaneously develop agency, which positions them to be change agents in society in which they live. Using the Equity-Oriented STEM Literacy Framework and attending to each component provide the needed space for students to see and use STEM as a tool to critique and understand society (as in Gutiérrez, 2009) and, in doing so, attend to students' perception of their capacity to act as a societal change agent using knowledge, skills, and dispositions associated with STEM areas. As societal change agents, students continue to work toward achieving personal goals by drawing on the components discussed previously in order to solve real-world issues and challenges in the community and at a broader level (Gutiérrez, 2009), thus disrupting the systems of oppression.

Research related to the development of Equity-Oriented STEM Literacy Framework

Prior work (e.g., Delaney, Cavalcanti, et al., 2017; Maiorca et al., 2020; Roberts et al., 2018; Roberts et al., 2019) has shown the See Blue See STEM informal STEM learning experience model to be effective in positively influencing the development of students' STEM literacy. Named a Top 5 model for Broadening Participation at the 2015 EPSCoR National Conference (Mohr-Schroeder, 2015), the See Blue See STEM informal learning experience model was designed to disrupt systems of privilege and oppression by providing opportunity and access to high-quality STEM learning experiences for middle school students from minoritized populations in STEM. In this example of applying the Equity-Oriented STEM Literacy Framework, the high-quality STEM learning experiences are facilitated by STEM experts in authentic STEM settings to build a community of practice (Kelley & Knowles, 2016). The See Blue See STEM model partners with faculty from Colleges of Education, Engineering, Arts and Sciences, Medicine, and STEM professionals from the community who share their expertise and their STEM work environments. These learning experiences vary from year to year so that repeat students participate in different activities. All students participate in robotics as a context to actively build, explore, inquire, and communicate their coding and problem-solving skills. In addition to robotics, students participate in different content sessions each day, such as completing an engineering design challenge with local engineers, exploring mathematical modeling with 3D pens or exploring biomedical science through DNA extraction. All of these activities require middle school students apply their knowledge of mathematics and science. The emphasis is not on specific content, but on the practices (e.g., Standards for Mathematical Practice, Science and Engineering Practices, and Technology and Engineering Practices).

By immersing students in this unique community of practice, they are empowered to see the utility and application of STEM while developing more positive STEM identities and dispositions (Delaney, Jackson, & Mohr-Schroeder, 2017; Maiorca et al., 2020; Roberts et al., 2018). Through their experiences in the informal STEM learning environment, students' perceptions of STEM broadened from a siloed view of traditional school subjects to a more integrated view that included positive feelings (Delaney, Jackson, & Mohr-Schroeder, 2017). For example, many students cited their participation in the informal learning experience as influential for piquing their interest in STEM careers (Denson et al., 2015; Kitchen et al., 2018; Maiorca et al., 2020; Vela et al., 2020). The increased interest in STEM careers is one indicator of students developing a stronger STEM identity. The application of disciplinary ideas was critical in students' shift in their views about STEM (Denson et al., 2015; Maiorca et al., 2020; Roberts et al., 2018). Many students experienced positive shifts in their views of mathematics due to learning experiences that connected mathematical ideas to real-world contexts, especially robotics (Roberts et al., 2019). Not only did students begin to understand applications of the content, they also began to see the utility of STEM. Many students noted how their experiences in the informal STEM learning experience reinforced the importance of the individual STEM subjects in school (Denson et al., 2015; Roberts et al., 2018). Further evaluation of the See Blue See STEM model showed students carried this view with them in the formal learning environment as participation in the informal STEM learning experience led to statistically significant differences in 6th and 7th grade state test scores between students who participated in the informal learning experience and non-participants (Kentucky Center for Statistics, 2019). Students who participated in the See Blue See STEM model also achieved higher overall ACT mathematics scores than non-participants (Kentucky Center for Statistics, 2019). These measures not only show the impact of the model on students' academic performance, but also have implications for students' STEM identities and dispositions as performance often contributes to students' identity development (Berry III, 2008).

Students also recognized their experiences in this informal STEM learning experience are unique because without the informal STEM learning experience, most students do not have access to STEM experts, authentic STEM workspaces, and to high-quality STEM learning experiences (Roberts et al., 2018). Students cited lack of resources, such as technology, in their schools. They also noted STEM was not always a part of their curriculum but was offered only as electives or after-school programs. These models, often the product of systems of privilege and oppression, limited their ability to participate in high-quality STEM learning experiences. Through the informal STEM learning experience, students had opportunities to explore STEM content through hands-on inquiries in robotics and STEM activities such as DNA extraction and dissecting pigs. These high-quality learning experiences made the learning come to life (Roberts et al., 2018) and helped students connect STEM knowledge to their lives (Maiorca et al., 2020). Oftentimes, students were motivated by empathy when they discussed the utility and applicability of STEM (Maiorca et al., 2020; Roberts et al., 2018). The desire to help people or animals, save lives, and improve the world through engineering were consistently cited as reasons students wanted to pursue STEM careers (Maiorca et al., 2020).

This growing body of research demonstrates the positive impact on students' STEM literacy by participating in the See Blue See STEM model. The model seeks to disrupt systems of privilege and oppression by providing opportunity and access for minoritized students in STEM to participate in high-quality STEM learning experiences in a community of practice consisting of students and STEM experts exploring STEM topics in authentic STEM settings. Students who participate in the See Blue See STEM model become empowered to explore STEM content because they make connections about how disciplinary knowledge is applied in the real world. This often leads students to see the utility of STEM and to express interest in pursuing a STEM career. Students often cite empathetic reasons for wanting to pursue a STEM career. Moreover, students' more positive dispositions toward STEM and STEM subjects, increased interest in STEM careers, and increased likelihood to perform better on state assessments are all indicators that they are building more positive STEM identities. These varied components reinforce one another to increase students' STEM literacy.

Implications and applications of framework in research and practice

We envision this conceptual framework to be used in a variety of ways. First, the Equity-Oriented STEM Literacy conceptual framework should be used as a guide for programs, schools, and other opportunities to develop rich, integrated STEM learning experiences for each and every student (see Fig. 2). When developing a STEM experience, whether within a formal or informal learning environment, the program must ensure that each of the components of the framework are attended to in the planning and execution of the STEM experience in order to continue to disrupt the systems of oppression and privilege. Leaving out one component of the framework risks further disadvantaging minoritized student populations.

Second, the equity-oriented framework should be used as a conceptual framework for studying STEM literacy in empirical research studies. This framework, rooted in

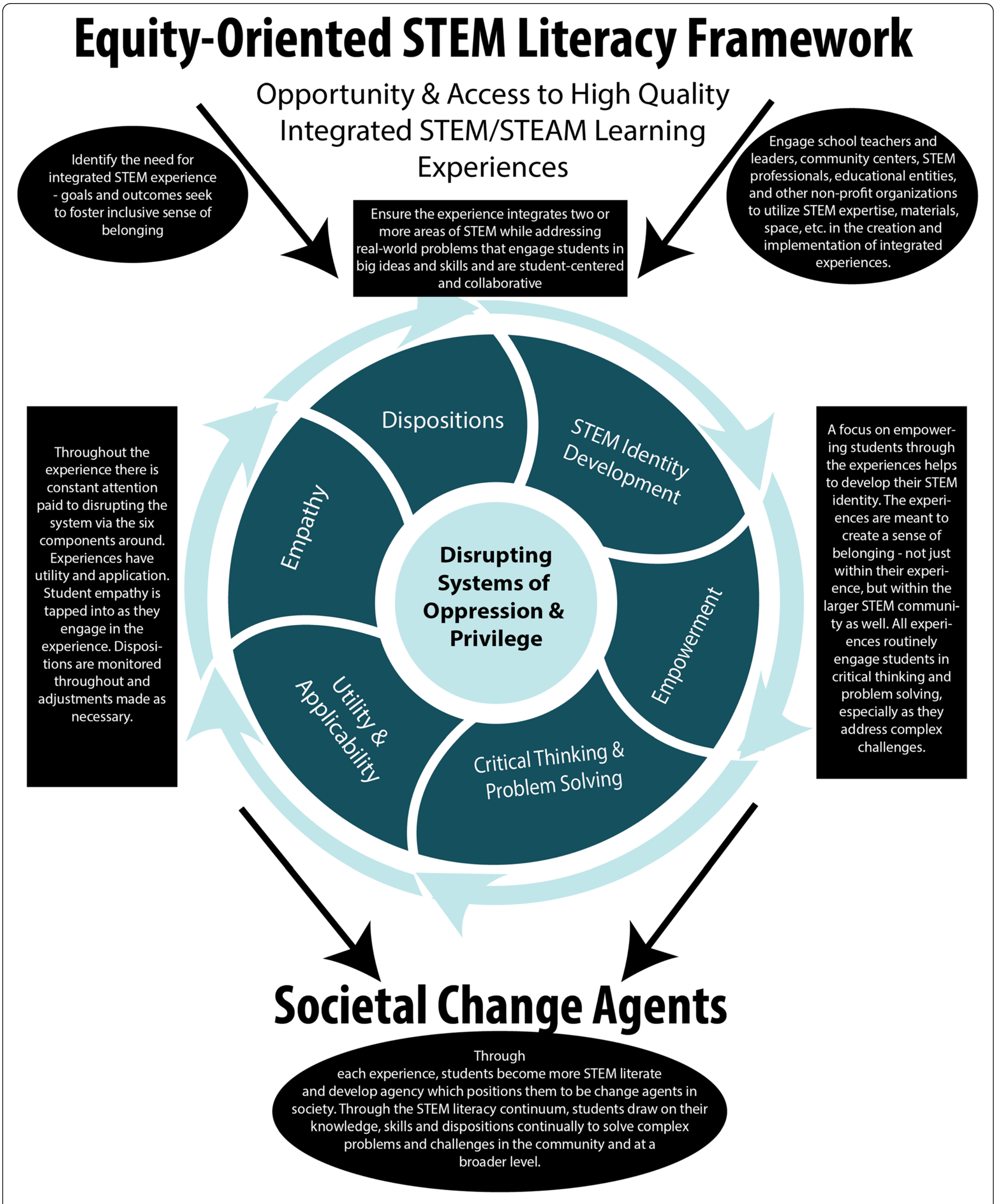

Fig. 2 Implementation of the Equity-Oriented STEM Literacy Framework

our own empirical work and other research-based contributions, should be used in future studies regarding STEM literacy as a conceptual foundation to the study and as a lens for analyzing and interpreting the data resulting from the study. Using this framework in future studies will help to ensure that equity does not remain a by-product or add-on of the study, but rather as an integral component. Finally, the Equity-Oriented STEM Literacy conceptual Framework should be used as an example for future developments of frameworks. As mentioned previously, our systematic review and our own prior empirical work found that current frameworks do not intentionally integrate equity as a core element within the framework. When we do not position equity as a non-negotiable foundation, we continue to perpetuate the systems of oppression and privilege, which further disadvantages minoritized populations. While this is often not the intent of prior frameworks or empirical studies, it is imperative that as we move forward as a field of STEM education, equity remains at the core of everything we do.

Conclusion

The purpose of this paper was to describe the engagement in a multi-phased, multi-year process to develop a research-based framework for K-12 STEM literacy that posited equity as its central core. There has been much momentum around research in STEM literacy over the past 5 years and this framework sought to bring the results and implications of the prior work into a usable framework that continues to put the focus on opportunity and access for each and every student, especially our minoritized students. Future research should empirically explore applications of this framework for both research and practitioner audiences in a variety of integrated STEM/STEAM learning settings. The importance of creating opportunity and access to students cannot be overstated as STEM continues to infiltrate society and impact our everyday lives. We must disrupt the systems of oppression and privilege that restrain minoritized groups from having access and opportunity to engage in high-quality STEM learning experiences in order to develop and strengthen student's STEM literacy.

Abbreviations

AAAS: American Association for the Advancement of Science; NRC: National Research Council; NGSS: Next Generation Science Standards; NCTM: National Council of Teachers of Mathematics; NCSM: National Council of Supervisors of Mathematics; CCSSM: Common Core State Standards for Mathematics; STEM: Science, Technology, Engineering, and Mathematics

Authors' contributions

CJ conceptualized the Equity-Oriented STEM Literacy Framework. All authors participated in reviewing literature, writing, revising, and approving the final manuscript.

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Availability of data and materials

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Declarations

Competing interests

The authors declare that they have no competing interests.

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