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Review Article

# Role of pedagogical approaches in fostering innovation among K-12 students in STEM education

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ABSTRACT

The intricate challenges of the modern world demand students to be equipped with advanced skills and knowledge to thrive in an increasingly competitive global landscape. Science, technology, engineering, and mathematics (STEM) practices can help develop these capabilities in students from an early age. However, as technology continues to advance rapidly, STEM education has experienced a rapid transformation with seamless integration of various technologies. Students in the K-12 education is required to keep up with the growing innovation and to bridge this gap, pedagogical approaches play a crucial role. Therefore, this review presents the current landscape, developmental trends, and future directions of the various pedagogical practices used to integrate innovation in K-12 STEM. The characteristics and environmental perceptions that influence the development of innovation in students using such approaches are examined. Results from 42 systematically shortlisted studies indicate positive correlations of personalized pedagogical approaches in promoting innovation in students, thereby increasing STEM literacy in K-12 education. However, limitations that remain with teacher competencies and school facilities to cope with various pedagogical approaches are also discussed. Finally, we conclude with our recommendations on effective and efficient approaches that can be implemented in K-12 STEM education to develop the skills and mindset in students necessary to become innovative thinkers and prepare them for a technology-driven society.

## 1. Introduction

### 1.1. Importance of K-12 STEM education

In our fast-evolving society, the demand for knowledge and skills in science, technology, engineering, and mathematics (STEM) is continuously growing (Freeman et al., 2019; Thiry et al., 2019). Having a solid foundation in STEM principles has become crucial in the job market, not only for STEM-specific fields but across various career sectors (Tanenbaum, 2016; Zilberman & Ice, 2021). Unfortunately, inequalities persist in access, participation, and success in STEM subjects, influenced by cultural, social, economic, gender, and geographical factors. These gaps in STEM education pose a threat to addressing literacy and poverty disparities, meeting the demands of a technology-driven market, ensuring national security, and maintaining leadership in scientific research and development. Therefore, effective STEM education is required to nurture essential skills and mindsets in students from early school years, also being culturally inclusive, and employing problem-solving and inquiry-based approaches. However, despite the known importance of STEM education, current strategies and practices are not widespread. Many educational systems still employ traditional learning approaches that struggle to effectively engage students. A notable example is the conventional approach to teaching STEM in K-12 schools, which often prioritizes theory over practical application and hands-on learning (Forum, 2017; Nadelson & Seifert, 2017). This pressing needs to captivate students in STEM fields, becomes even more crucial with the current technological advancements of the modern world. The appropriate integration of technology in STEM education, if harnessed, has the potential to enhance student engagement in STEM learning and improve the quality of STEM education.

### 1.2. Evolution of STEM education with technology

Constant calls for modes of instruction to integrate STEM courses into the K-12 curricula emphasize the obligation to further improve learners' intricate technical competencies through innovation, which is

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essential to partake in a knowledge-based economy (Holmlund et al., 2018; Li et al., 2019). As defined by (Sannino & Nocon, 2008), innovation in the present context is educational innovation which is "desirable and doable changes in school teaching and learning that mediate individual, collective and organizational development, whether triggered by new pedagogical ideas, new technologies, or new collaborative relations between the school and the world outside." The appeals to enhance innovation in K-12 students often arise from organizations and policy makers worried about the deficiency of workplace-competent experts to satisfy existing and emergent vacancies, especially in technology-based firms. They regard education to be responsible, asserting that 'the scarcity of employability is ascribed to the old-fashioned curriculums and scarcity of innovation at the K-12 level (Garry et al., 2020; Newhouse, 2017). Therefore, imminent economic and sustainable growth and social advancement depends on innovation. Besides the technical know-what and know-how, the fundamental capabilities for innovation are critical thought, originality, metacognitive, global collaboration, and communication (Kärkkäinen & Vincent-Lancrin, 2013). This necessitates innovation in K-12 STEM education with enhanced scholastic technologies, pedagogical approaches, core curriculums, evaluation methodologies or practices for educators to work together.

The students in the current technologically reformed world are "ultra-communicators" with access to state-of-the-art technologies to collaborate and learn beyond the classrooms. Learning in the K-12 STEM education platform has been more reformed than ever, with new possibilities for imparting knowledge to students most effectively and efficiently. This drastic change in the last decade has rapidly evolved since 2019 due to the occurrence of the unprecedented novel COVID-19 (Delen & Yüksel, 2023). The pandemic brought about positive changes by introducing new ideas and technologies that are expected to last beyond its impact (Lempinen, 2020). It highlighted the effectiveness of technology in delivering engaging content for both students and educators, ultimately elevating the role of teachers to co-creators of knowledge, coaches, mentors, and evaluators (Allen, 2020; Janssen, 2020). Importantly, the pandemic reinforced the value of STEM education, showcasing how students could apply their skills to mitigate the effects of the crisis.

Therefore, the changing demands of 21st century society and the students nurturing in it create a fundamental challenge to our contemporary assumption about what education should look like. Educationists have started to adopt new online/blended learning methods as their primary method of teaching students. Moreover, this pedagogy has become normalized for the general masses, making it more comfortable and adaptable. The goal of next-generation learning is to supply students with more personalized and student-centric learning experiences and build environments that provide dramatic changes in student outcomes. This personalization leads to learning experiences that are student-owned and student-perceived, meeting the various learning needs of each student daily and empowering them with the latest skills, information, and tools that are required to manage their learning. Most importantly, next-generation learning aims to optimize the combination of teacher and technology-facilitated learning in a group as well as individual work. This form of revolutionized learning has great potential to loosen the resource constraints of conventional methods in terms of time, space, and human capital. Moreover, the flexibility offered by such technology-integrated education allows differentiated approaches to the challenges of content, assessment, pacing, and learning methodologies.

Technological integration in school can be primarily grouped into three categories; technology used as a direct learning tool, instructional delivery, and instructional preparation (Inan et al., 2010). Professional use of technology by instructors includes preparation of classroom material, communication between parents, students, and peers, and creating learning plans. When instructional delivery is aided by technology, both the students and teachers use it. For instance, the teacher can use a smartboard and projectors to present instruction. Students can also utilize computer-aided functions like tutorials, homework, and modeling. When technology is employed as a means for direct knowledge, students can derive their abilities to solve problems and collaborate their perspectives using software-aided technological applications.

### 1.3. *Challenges in integration of technology*

The challenge in general today is to provide a deep sense of understanding and personalized experience to K-12 STEM students so that they can achieve a greater level of core standards and dispositions to match society's needs. These required attributes in students are a declaration of learning experiences students require for building a successful career. But learning for the generations is challenging to incorporate. Societal and technological constraints limit the efficacy of reformed technology integrated education. This is because the growing accessibility of technologies at schools does not inevitably contribute to progress in classroom pedagogies (Lim & Chai, 2008). Also, this problem is exacerbated by students' low digital literacy and societal accessibility (Resta & Laferrière, 2015). Students who don't know how to use technology well or who live in remote places have difficulty getting a well-rounded STEM education. Their limited access to resources and technologies prevents them from engaging in STEM-related activities.

Moreover, there are not enough empirical results from studies indicating that access to technology directly increases student learning. A possibility of these outcomes can be associated with educationists and instructors lacking the vital technical knowledge to infuse classroom automation (Surahman & Wang, 2023). The integration process can also be a gradual and intricate method affected through numerous other indirect aspects such as the teacher's belief and attitude, school setting, demographics of characteristics of the instructors at school, access to resources and support provided by the school (Cuomo & Roffi, 2023; Inan et al., 2010).

Furthermore, while technology presents enormous promise to improve STEM education, the STEM community is still working to take full advantage of it (Chiu & Li, 2023). Even though it seems like teachers and kids are embracing technology more easily, there is a constant demand for more. Considering how quickly technologies are developing, research suggests that early K-12 educators encounter challenges when attempting to teach STEM to young children in a way that corresponds with their developmental stages (Pasnik & Hupert, 2016). These difficulties include mainly the lack of pedagogical approaches that support successful learning, along with a lack of basic STEM knowledge, restricted access to professional development opportunities centered around STEM, and insufficient availability of high-quality materials (Brenneman, 2010; Guerzon & Busbus, 2023). Given the dynamic changes in education, these circumstances emphasize the need of innovative teaching practices that can help overcome these disparities, thereby ensuring that K-12 students can achieve learning outcomes in line with the transforming technological world. It should be noted that the term "innovative practice/curriculum" is used in this review for pedagogical practices or curriculum designs that enculturate an innovation mindset in students.

### 1.4. *Research objectives and aims*

Therefore, as mentioned above, various factors are crucial for integrating innovation in K-12 STEM education. These different aspects constitute the whole learning process which can be varied using different pedagogical practices or approaches. In the long run, the practices used for transferring vital knowledge to students through innovative practices can create a superposition effect of efficient learning. Also, in the past few times, studies have signaled the worth of imparting STEM learning to students, termed as STEM literacy, and posed it as the required result from the STEM teaching and learning pedagogies (Garry et al., 2020). However, future research is required to broaden the scope to probe the relationship between pedagogical practices at schools and the enculturation of innovation among learners. Such findings may shed new light on exploiting new education technology to facilitate student achievement. Moreover, the growth of new learning practices in education opens the door for further opportunities in educational research. Pedagogical practices have been developed to conceptualize the integration of innovation in early STEM education. However, little research has been done to synthesize these approaches the current landscape, developmental trends, and future directions of the various pedagogical practices used to foster innovation in K-12 STEM. Therefore, to achieve this, the present study aims to answer the following research question:

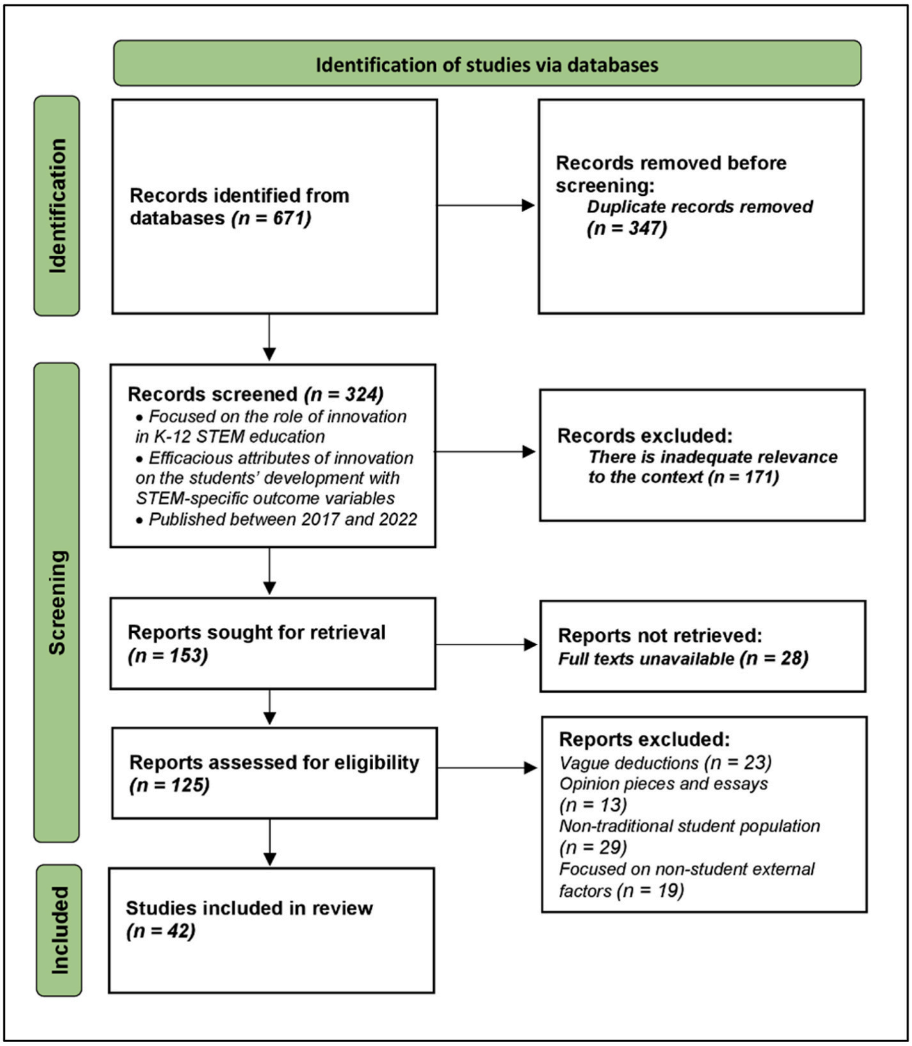
- ➢ What are the different pedagogical approaches used to effectively foster innovation in K-12 STEM education?

## 2. Method

### 2.1. Search process

To clearly and methodically investigate published studies reporting the pedagogical approaches that foster innovation in K-12 STEM education, a systematic review was performed. A systematic review is an evident and reproducible approach to the literature review that resolves research questions established on responsible procedures with specific conditions that include or exclude present research papers. Information is obtained through accounts of peer-reviewed papers, methodically synthesizing available information on a distinct subject matter (Harden & Gough, 2012; Møller & Myles, 2016). To confirm the reliability, uniformity, and precision, this systematic review was organized in correspondence with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Page et al., 2021). In specific, PRISMA guidelines list out a comprehensive checklist adopting key portions of a systematic study, presenting an evidence-based standard ensuring clarity in detecting, choosing, assessing, and producing the findings being assessed (Moher et al., 2009).

To detect bibliographical records propositioning the role of pedagogical approaches in fostering innovation among K-12 students in STEM education, we conducted web searches from the following online databases: Scopus, ERIC (Education Resources Information Center), ProQuest, and Web of Science. These archives were selected based on their global perception, significant knowledge in the educational area, and specialized subject matter in educational research. In this regard, the databases satisfy the comprehensive coverage benchmark and demonstrate an ideal database combination. After operating trial runs, the closing search was executed in January 2023. Our search term was established as follows: ((“STEM education”) AND (“early” OR ″k-12″)



**Note.** Figure by authors.

**Fig. 1.** PRISMA flow chart of the inclusion and evaluation process of the research studies. **Note.** Figure by authors.

AND (“innovation” OR “novelty” OR “invention” OR “transformation” OR “modernization” OR “renovation” OR “restructure” OR “revolution” OR “integrated” OR “integration”) AND (“approach*” OR “practice*” OR “method*” OR “strateg*” OR “learning” OR “technique” OR “model” OR “design” OR “type” OR “framework”)). The results poised all findings if the search request was met in the articles’ title, abstract, or keywords. To restrict the results of our review with the latest findings, and in accordance with modern practices, we selected the search period of the last 6 years, i.e., between 2017 and 2022. The Scopus, ERIC, ProQuest, and Web of Science directories resulted in 178, 281, 112, and 100 hits, respectively. In total, 671 articles were obtained. We read titles and browsed abstracts to verify if the papers discovered in the search were concentrated on the role of pedagogical approaches in fostering innovation in K-12 STEM education.

### 2.2. *Inclusion and evaluation of studies*

Consequent filtering of studies was needed to incorporate only pertinent and concise accounts. Fig. 1 demonstrates the step-by-step sorting of the search process. The studies passing the examination policy were extracted from the data resources, and their abstracts and conclusion were meticulously investigated. To conform with our inclusion criteria, articles had to satisfy the following: (a) be focused on the role of pedagogical approaches in fostering innovation in STEM education; (b) imply the efficacious attributes of innovation on the students’ development; (c) consist of STEM-specific outcome variables (e.g., achievement, interest, integration); (d) must be performed at the k-12 level of education and not undergraduate, vocational, or graduate education; and (e) be published between 2017 and 2022 in a peer-reviewed journal in the English language. The decision to include studies from the last five years aims to capture the latest trends in STEM education, aligning with the rapid evolution of technology and pedagogical practices. This timeframe ensures a focus on contemporary insights, reflecting the dynamic nature of the field and meeting scholarly expectations for relevance and applicability in the review. The above-stated stipulations were observed for the preliminary assessment of the articles. All the authors worked collaboratively to make all inclusion determinations. After removing duplicates, a temporary nomination of 153 publications was acquired based on the inclusion conditions. Regarding the exclusion criteria, we inspected for the following: (a) opinion pieces and essays, even if they were peer-reviewed; (b) articles addressing the non-K-12 education levels (e.g., undergraduate, post-graduate, etc.); (c) findings on non-traditional and underrepresented student groups; (d) studies aimed at other variables like educator’s experience, student incapacities, non-relevant environmental, and other social or cultural factors. Such articles were rejected.

We initially assessed the titles and abstracts of the studies matching these inclusion/exclusion criteria. However, given the limited knowledge offered in abstracts and titles, studies were dismissed at this stage only when the presented evidence was enough to deduce that a criterion was not met (e.g., the study did not involve a STEM discipline). This procedure narrowed down the candidature of prospective studies to 125 records. Ultimately, the authors conducted a concluding selection through careful consideration, confirming 42 studies for this study—these chosen bibliographies fulfilled all inclusion and exclusion criteria (see Fig. 1). Table 1 presents the features of the qualified articles centered on seven distinguished features: (a) author(s), (b) proposed pedagogical approach, (c) specific field of innovation, (d) type of study, (e) outcomes of the study, and (f) country of publication. These studies were evaluated based on the excellence of their discoveries and effectiveness by emphasizing the thematic traits like the specialty of their approach and its associating effects on student development (see supplementary data). However, like any other study, recognizing the potential for bias is crucial in ensuring the trustworthiness and generalizability of this systematic review. This was addressed by using a transparent selection criteria with predefined inclusion and exclusion criteria to ensure objectivity and reduce the risk of subjective selection based on personal preferences or preconceived notions. Also, thematic analysis of the included studies facilitated the identification of recurring patterns and trends across different methodologies and contexts. This helped to triangulate findings and reduce the impact of potential bias within individual studies. Overall, the PRISMA methodology provides a transparent and reproducible account of the search, selection, and data extraction process, contributing to a more robust and reliable review process.

## 3. Results

Unlike conventional learning experiences in which students concentrate on specific subject areas, STEM education stresses combining several subject fields in a manner that integrates them, connecting various disciplines and correlating them practically and coherently. Much importance of such practices is being imparted through various pedagogies in K-12 STEM learning, which eradicates the conventional difficulties between subjects, and as an alternative, aims at practices of contextual problem-solving utilizing current tools and technologies. The following section offers a comprehensive review of such studies and discusses the diverse pedagogies deployed to spark innovative characteristics in early students, along with their correlational consequences on student learning.

### 3.1. *Integrated STEM learning to solve real-world problems*

The need to integrate STEM learning arises due to the certainty that the STEM disciplines contribute to several commonalities that can collaboratively enrich student abilities (Bicer et al., 2017). Also, since STEM disciplines are synergistic hotbeds for modern inventions and breakthroughs, low attention to these fields poses threats to the economic stability and innovative status of developed nations (Council, 2011). The integration of STEM disciplines is also because of grounds apart from global interests. Several scientific disciplines demand competence in math to comprehend theories and procedures, whereas math, bereft of scientific perspective, can be regarded as a field worthy of learning just for its own sake. Nevertheless, this is due to the interconnection of such fundamental fields that scientific and engineering inventions frequently occur. So, though the description “STEM” might have been derived owing to global interests, merging such disciplines was more genuine than merely assigning necessity for advancement. Therefore, the goal of STEM integration is to assist students in comprehending and acknowledging the different aspects of subject contents taught by various curricula together form our world. Studies employ this strategy to ignite the innovation instincts in students by offering them real-world challenges, therefore building application-based solid knowledge and skills. Conforming this, (Wong & Huen, 2017) illustrated the implementation of integrated STEM-related activities laced with scientific inquiry and innovation into the existing K-12 curricula. Their strategy presents to enhance the connection between theoretical knowledge learned at school and real-life applications experienced by students through the integration of scientific inquiry and engineering design. Moreover, scientific inquiry is an outstanding context for engrossing students in perceiving the world around them and nurturing an inquisitive intellect. This incites increased attention and incentive among the learners to grasp concepts and learn. Another critical attribute embedded in scientific inquiry, essential in K-12 STEM education, is the progress of information and skills; the ability to systematically resolve problems by logical reasoning and problem-solving using advanced thought processes like deductive reasoning. Sometimes, these methodologies are not compatible with integrated STEM education approaches. For this, (Crotty et al., 2017; Shahali et al., 2016) assessed the need to examine various approaches in K-12 classrooms to clarify how STEM education (particularly engineering) is being integrated. Their findings imply that the positioning of engineering within STEM

**Table 1**

Studies outlined in the literature between 2017 and 2022 reporting the role of pedagogical approaches in fostering innovation in K-12 STEM education.

| Authors | Pedagogical Approach | Specific Field of Innovation | Type of Study | Outcomes | Country |
|---|---|---|---|---|---|
| 1. (Weng et al., 2022) | Problem-based learning | STEM | Qualitative | Development of students' creativity and entrepreneurship skills | China |
| 2. (Ortiz-Revilla et al., 2021) | Integrated STEM | STEM | Theoretical Framework | Enhance the evolution of student abilities from a humanistic view. | Spain |
| 3. (Hadani et al., 2021) | Playful Learning Landscapes | STEM | Theoretical Framework | Increased understanding of mathematical concepts. | USA |
| 4. (Garner et al., 2021) | STEM-based invention education program | STEM | Pre- and post-assessments | Students' self-perceptions congruent with their inventive mindset, and development of identity exploration. | USA |
| 5. (Holmes et al., 2021) | Localized STEM Pedagogy | STEM | Review Analysis | Enhanced interests in STEM learning, affirmative STEM career aspirations, and the evolution of transferable competencies. | Australia |
| 6. (Kartini et al., 2021) | Project-Based Learning | Seismology | Pre- and post-assessments | Increased content knowledge and problem-solving abilities. | Indonesia |
| 7. (Gould et al., 2021) | Integrated STEM | Robotics | Theoretical Framework | Development of early skills in science, literacy, and numeracy. | USA |
| 8. (Cabello et al., 2021) | STEAM Approach | STEAM | Survey | Scientific enculturation, enthusiasm, and positive engagement in students. | Chile |
| 9. (Megri & Hamoush, 2020) | Consortium management based on active learning | Advanced Manufacturing, 3D Printing | Mixed-method study | Improved student performance to match cutting-edge technology and encouragement to pursue higher studies. | USA |
| 10. (Yu & Jen, 2020) | Integrated STEM | Nanotechnology | Pre- and post-assessments | Enhanced and positive learning of advanced concepts of STEM curriculum. | Taiwan |
| 11. (Reynante et al., 2020) | Integrated STEM (iSTEM) | STEM | Thematic Analysis | Aiding students to understand the epistemologies of a field and helping students confront the very nature of these disciplines. | USA |
| 12. (Kewalramani et al., 2020) | Design Based Research | Robotics, Electronics | Pre- and post-assessments | Fostered cognitive development, metacognitive and social knowledge construction, along with enhanced collaboration. | Australia |
| 13. (Ryu et al., 2020) | Drone Workshop | Aerospace | Survey | Improved preparedness for college and careers in STEM fields. | USA |
| 14. (Parker et al., 2020) | Integrated STEM | STEM | Survey | Awareness of engineering among students, student knowledge about engineering was informational rather than aspirational. | USA |
| 15. (Hatfield et al., 2020) | Drone Camp | Aerospace | Survey Report | Significant interest in its educational programs. | USA |
| 16. (Garry et al., 2020) | STEM Literacy | STEM | Review Analysis | Locating STEM curriculum in authentic contexts with a focus on knowledge, engagement, endeavor, and awareness. | Australia |
| 17. (Çetin & Demircan, 2020) | Integrated STEM | Robotics | Review Analysis | Efficient educational means to precisely involve children with engineering and technology, integrated into wider curricula. | Turkey |
| 18. (Wan et al., 2020) | Web-based learning environment | Artificial Intelligence and Machine Learning | Questionnaire | Positive change in learning ML concepts, methods, and sensemaking of patterns with evidence-based scientific discovery | USA |
| 19. (Tezza et al., 2020) | 5-Session Intensive Course | Aerospace | Survey | Enhanced interests and motivation to further pursue STEM education | USA |
| 20. (Long et al., 2020) | Kolb's experiential learning theory | STEM | Questionnaire | Effective cultivation of knowledge construction, inherent enthusiasm and enjoyment of learners, and improved curiosity in STEM fields. | Vietnam |
| 21. (AlAydaroos, 2019) | Integrated applied interdisciplinary STEM | Aerospace | Report | Exposure to real-life experiences, projects, and activities. | UAE |
| 22. (Ching et al., 2019) | Project-based Integrated STEM | Robotics | Pre- and post-assessments | Reinforced STEM content understanding and connection, commitment, and dedication, and improved teamwork skills. | USA |
| 23. (Wright et al., 2019) | 5E Instructional Model | STEM | Report | Development of science inquiry skills and effective communication of new skills through storytelling. | Australia |
| 24. (Stein & Lédeczi, 2019) | Integrated STEM | Robotics | Theoretical Framework | Low barrier access for students with differing coding skills to cooperate with the programming field. | USA |
| 25. (Jiang et al., 2019) | Interdisciplinary STEM learning | STEM | Survey | Developed management skills and collaborative studying abilities in interdisciplinary groups with discipline-specific role-taking. | USA |
| 26. (Mustaffa et al., 2018) | Problem-based Learning | Mathematics | Assessments and Survey | Improvement in the algebraic thinking of the students. | Malaysia |
| 27. (Garner et al., 2018) | Curricula infused with arts and social-emotional learning content | STEM | Feedback | Holistic STEM-related curriculum, enriching students' interests in scientific applications. | USA |
| 28. (Cook & Bush, 2018) | Design Thinking | STEAM | Review Analysis | Encouragement and increased passion in students to solve problems. | USA |
| 29. (Tran, 2018) | Integrated STEM | Computer Science | Pre- and post-assessments | Enhanced enthusiasm in computer science lessons and motivation to pursue future careers. | USA |
| 30. (Alemdar et al., 2018) | Problem-Based Learning | Engineering | Assessment Tests, Survey, and Interview | Substantial gains on state-level consistent science and mathematics tests and intellectual and social engagement improvement. | USA |

(*continued on next page*)

**Table 1** (*continued*)

| Authors | Pedagogical Approach | Specific Field of Innovation | Type of Study | Outcomes | Country |
|---|---|---|---|---|---|
| 31. (Safiee et al., 2018) | Project-based Inquiry Learning | STEM | Questionnaire | Elevated attitudes, concept understanding, and a higher level of student engagement. | Malaysia |
| 32. (Ioannou et al., 2018) | Integrated STEM | Robotics | Questionnaire | An inventive and non-intrusive blend of educational robotics in the curriculum with increased question-solving and teamwork abilities simultaneously with field expertise. | Cyprus |
| 33. (Gupta et al., 2017) | Workshop | Chemistry | Pre- and post-assessments | Efficient scientific hands-on activities with improved involvement. | USA |
| 34. (Ismail et al., 2017) | Project-based Learning | Seismology | Pre- and post-assessments | Increased concept understanding, scientific thinking, and awareness of the importance of mastering STEM. | Malaysia |
| 35. (Crotty et al., 2017) | Integrated STEM | Engineering | Pre- and post-assessments | Stronger engineering understanding for students. | USA |
| 36. (Tippett & Milford, 2017) | Design-based Research | STEM | Questionnaire | Fostered student curiosity, enthusiasm, and appropriate understanding of concepts. | Canada |
| 37. (Jahan et al., 2017) | Curriculum-based research outreach program | Algal Technology | Theoretical Framework | Development of a curriculum that has a multitude of topics but a unity in content. | USA |
| 38. (Henderson et al., 2017) | Curriculum-based scaffolded program | STEM | Theoretical Framework | Enhanced creativity, fortitude, and ability in students to solve real-world problems. | USA |
| 39. (Padmanabhan et al., 2017) | Integrated STEM | STEM | Pre- and post-assessments | Awareness of using STEM-based solutions, unique perspective of students on solving real-world problems | USA |
| 40. (Shahali et al., 2016) | Non-formal integrated STEM | Engineering | Pre- and post-assessments | Increased students' interest level towards STEM subjects and careers. | Malaysia |
| 41. (Dickerson, 2017) | Hands-on activity workshop | Internet of Things | Survey | Increased interest in IoT and motivation to pursue electrical and computer engineering careers. | USA |
| 42. (Wong & Huen, 2017) | Integrated STEM | Knowledge from various curricula | Theoretical Framework | Enhanced connections between conceptual and real-life problems. | China |

Note. Table by authors.

components was associated with various student learning gains. Moreover, the study acknowledged that students need to participate in meaningful and innovative engineering design courses in their STEM encounters. Thus, just adding an engineering design project to an existing scientific unit cannot guarantee students with prospects to exercise and study science in reliable and authentic ways. Therefore, while integrated STEM plans persist in enhancing STEM learning, the now overloaded syllabus frequently gives not enough space for authentic integration of subject matters.

One such hot topic in integrated STEM education within K-12 curriculums provoking the role of innovation is the use of educational robotics. This innovation-laced field is deemed to be a progressive and adaptable didactic tool for training and educating students of all age groups. Moreover, within a constructivist essence, the utilization of instructive technology seeks to aid learners to participate in analytical, communal, and creative learning. Educational robotics is regarded as one such expertise that imparts precise knowledge in a field such as engineering and is intended to succeed as a coding means to encourage rational and computational reasoning. One study by (Ioannou et al., 2018) examined educational robotics incorporated into school subjects in an innovative and non-intrusive way, thereby developing the syllabus and allowing learners to develop skills such as rational thinking and collaboration while studying the school curriculum. The method was found to be positively suitable and helpful for students, showcasing their enhanced learning processes. Another study by (Çetin & Demircan, 2020) showed that computer programming through educational robotics could be a capable application for integrating engineering technology in K-12 STEM education. Also, programmable toys and robotics construction kits are an embraceable proposition for enculturing innovation during the early childhood setting. Such innovative measures can impart a jump-start for children with programming concepts and induce their creative thinking mindset, helping them to discover and understand interdisciplinary knowledge. Further, (Stein & Lédeczi, 2019) proposed a framework to enhance the process by delivering motion tracking and mixed reality integration of robots applicable to K-12 STEM education. Similarly, (Tran, 2018) studies elementary-aged students' experiences of STEM, career decisions, and impacts from pre-to post-test intercession of computer science lessons during a three-month interval. Their findings reported positive and meaningful changes concerning student responses and accounted for enhanced enjoyment of programming lessons, exposure, and prospects for a future career. Moreover, a typical misconception that such innovative STEM practices are only suitable for mature students or are merely essential for students who do exceptionally well does not hold in such innovative-integrated STEM frameworks. A study by (Gould et al., 2021) proved this by engaging young students in robotics-based activities to explore, discover, and create using STEM concepts, developing enhanced confidence, curiosity, and imagination. Using a similar integrated STEM approach, (Padmanabhan et al., 2017) incorporated design thinking and computational modeling to solve a real-world problem concerning illegal poaching. This aided in developing a unique perspective in students with innovation as a means to solve global challenges. In addition, their study pointed out that in conjunction with intellectual, scientific, and technical advances, it is highly vital to continuously foster the much-needed consciousness of public awareness of STEM and its underlying foundation.

Many concerns about disparities in STEM engagement and success have been aimed primarily at the interest and ambitions of students in learning science and engineering. Interest and aspirations are important prerequisites for engagement in science and engineering (Renninger & Hidi, 2011). However, interest, defined as the student's dedicated awareness or engagement with the environment, is acknowledged as the key driver in learning integrated STEM education. When students reveal their curiosity about a topic, they exhibit better endurance and a more optimistic involvement. Studying this, (Parker et al., 2020) studied the implementation of an integrated STEM driven by awareness of innovation in the science and engineering fields. Their strategy proved to inspire learners with early engrossment and cognizance of the technical and scientific aspects of engineering. A similar idea was applied by (Yu & Jen, 2020) to integrate the development of nanotechnology instruction through evidence-based experiences. Their study helped to augment school students' interests and perception of scientific fundamentals to generate technological innovations. This emphasizes forming STEM courses that foster creative teaching interfaces assisted with hands-on learning activities. Moreover, integrating these disciplines into student communities holds the capacity to grow anticipation and curiosity in science and engineering, especially for those who are traditionally put at risk. Therefore, integrated and innovative STEM provides a probable and distinctive pedagogical methodology in contrast to traditional instructions (Reynante et al., 2020). It grants K-12 students the capability to discover the application-based relevance of a discipline and helps to aid students in confronting the essential nature of such disciplines. Also, the students' content knowledge of disciplines can be further enhanced by facilitating interdisciplinary learning. This was demonstrated by (Jiang et al., 2019) through an integrated after-school STEM program where young learners were appointed discipline-specific functions (author, researcher, artist, and engineer). Results yielded positive consequences of discipline-specific tasks on participants' interdisciplinary and collaborative learning activities. In such a way, science and literacy were integrated, providing students with a deep learning atmosphere where they are exposed to different identities helping them to comprehend essential disciplinary knowledge besides participating in expert practices. A similar idea was demonstrated by (Wright et al., 2019) using a multidisciplinary method to engage primary school children in an innovative research project through active training of their scientific inquiry competencies and efficacious communication of concepts through storytelling. Their strategy implemented the '5E Instructional Model' comprising the Engagement, Exploration, Explanation, Elaboration, and Evaluation elements. This tactic was successful in fostering young students' zeal for data-based scientific inquiry and advocating future generations of scientists. Therefore, the studies using the integrated STEM approach to provoke innovation in K-12 STEM education signify a broad consensus on the essence to promote scientific innovation and literacy. Although this attitude is pertinently in the evolving stage, the constant investigation of conventional STEM learning pedagogies, owing to their inadequacy, prompts the way for the emergence of learning methods that integrate the instruction of various scientific fields through added contextualized, comprehensible, and extensive manner (Ortiz-Revilla et al., 2021).

Despite the promises of integrated STEM learning, some limitations and potential drawbacks do remain. One major concern is overburdened curricula, where squeezing multiple disciplines into one program might lead to shallow understanding and hinder authentic integration (Council, 2014). Additionally, not all teachers possess the necessary expertise across STEM fields, requiring extensive professional development and support (Havice et al., 2018). Furthermore, ensuring equitable access to resources like robotics technology and maintaining inclusivity for diverse learners within these innovative approaches remain vital challenges (Aikenhead, 2006). Continued research and refinement are crucial to mitigate these limitations and unlock the full potential of integrated STEM for fostering scientific literacy and innovation in all students.

### 3.2. *Formal learning practices to reform STEM*

When students partake in projects to conduct investigations and involve in innovations to answer their individual doubts, their rational abilities are most likely prompted and developed (Barron et al., 1998; Bell, 2010; Kokotsaki et al., 2016). Likewise, participation in projects employs students in responsible and cooperative roles by which they take initiative in the inquiry process through queries, data collection and analysis, investigation process, and reports. This eventually gives an improved school engagement and accomplishment in the long run. Moreover, by inducing innovation into STEM learning pedagogies, children learn to nurture ideas, recognize advanced concepts, fostering their critical thinking abilities. Affirming this, (Ching et al., 2019) analyzed the implications of project-based learning (PBL) for elementary students by incorporating robotics into the curricula. The study focused on developing specific traits of perceived learning comprising content understanding and context, participation and persistence, and academic progress and collaboration. Students demonstrated positive learning experiences in all the attributes, with more optimistic results in attitudes towards mathematics-perceived learning. Similarly, (Ismail et al., 2017) attempted to assess the motivation levels of students in a STEM module deploying PBL inspired to study the technical aspects of natural disasters, where students collaboratively designed a project to withstand earthquakes. This prompted the students to apply their scientific reasoning and deduce judgments about the subject matter. The study showed that provoking students to innovate buildings and structures that can resist earthquakes enhanced their understanding of the significance of mastering STEM fields. Moreover, learners' enthusiasm highlighted the potential of innovative STEM pedagogies and emphasized the implications of boosting such didactics infused with PBL strategies among early STEM education children. The positive rational and affective impacts of using PBL in the context of innovative STEM practices were also shown by (Safiee et al., 2018). Their module also enhanced students' attitudes in science fields, evident through teaching students the concept of magnets in a PBL environment. Therefore, such project-based curriculum-infused didactics reveal the successful engagement of students in learning STEM concepts, leveraging the role of innovation in K-12 STEM education. Also, the PBL strategy efficiently increases students' low-performance rates in STEM subjects and significantly increases the achievement gap of students who face difficulty grasping STEM concepts through conventional methods (Han et al., 2015).

STEM learning objectives try to communicate the rationale behind specialized skills in science, technology, engineering, and mathematics. PBL addresses this strategy of STEM education through hands-on activity, enabling students to nurture their conceptual understanding in solving real-life problems. (Kartini et al., 2021) revealed similar outcomes through the implementation of a STEM PBL, with substantial improvements in the problem-solving abilities of participants. Thus, students learned to define problem statements, inspect the solutions through content knowledge and fully understand the conceptual theory of the application. Supplementing the aims of PBL (Cook & Bush, 2018) proposed a Design Thinking (DT) approach that can help learners tackle problems that involve an innovative redefinition and reanalyzing of explanations. Like other student-centered inquiry-based methods, this pedagogy provides students with a distinct pathway to refine their creative mindset, paving the way for innovation. Moreover, this framework offered an opportunity to expand the teaching scope to a greater extent than the fixed zones of STEM, delivering a genuine transdisciplinary experience for young learners to keenly invest in resolving real-world issues. Further, another study by (Alemdar et al., 2018) used an analogous Problem-Based Strategy (PBS) in the Engineering discipline, adopting a cognitive-apprenticeship approach to invoke the essence of engineering innovation in students. This led to collaborative work among students, promoting active learning and flexible thinking, with a statistically significant rise in their analytical and social engagement in STEM learning. Also, (Weng et al., 2022) used problem-based learning using the 5E learning cycle with real-world problems to foster students' creativity and entrepreneurship in a wide variety of paths throughout the learning cycle. Similarly, (Çetin & Demircan, 2020) proposed an online-friendly PBL approach to overcome the traditional approach of teaching mathematics through writing and solving equations. This integrated the students' mathematical reasoning through the handling of equations, procedures, and relationships, utilizing algebra as a means to enhance the student's intellectual thinking. Therefore, with pioneered use of STEM learning, students' interest in STEM subjects can be augmented by redefining how creativity, learning, and innovation are managed in the curriculum. The aim of the curriculum should be to confirm the maximum quality of STEM learning to enhance understanding and conception of STEM concepts. Furthermore, such curriculums should provide a multidisciplinary proposition to STEM learning and should illustrate the connection between various disciplines by integrating critical thinking abilities in students to orient them towards solving global challenges. For instance, a study by (Jahan et al., 2017) devised a curriculum for local K-12 students that concentrated on the application of algae-based technology to foster a generation of engineers who are more informed on resolving global humanitarian concerns. Similarly, (Henderson et al., 2017) employed innovative practices in STEAM (Science, Technology, Engineering, Arts, and Mathematics) through PBL to enhance the school culture and curriculum. Their goal for such curriculum-based learning was to demonstrate to the school children to be independent and invoke their critical problem-solving skills. Moreover, this approach to a scaffolded curriculum showed positive implications with increased creativity, fortitude and learning abilities in students. Also, (Cabello et al., 2021) implemented a pilot program on STEAM learning integrated with arts to enrich early students' interests, commitment, and inspiration for education in an integrated sense, transcending beyond various disciplines peculiarities. Such learning aims incite application-based challenges and expose learners to recognize risks and move forward beyond preconceived constraints and aspirations. Therefore, students who realize barriers and tasks, vigorously look forward to innovative and pioneering solutions, creating impactful differences in the world.

However, the challenges that remain with these learning practices intending to reform STEM is the increased complexity of managing project-based curricula, potentially demanding significant resources and teacher expertise (Boss & Krauss, 2022). Additionally, ensuring equitable access to technology and project materials can exacerbate existing educational disparities (Aikenhead, 2006). Furthermore, effectively assessing student learning within open-ended projects requires specialized evaluation methods beyond traditional tests, demanding further professional development for educators. Addressing these limitations through robust planning, resource allocation, and assessment strategies is crucial to maximize the success of innovative STEM pedagogies and ensure all students benefit from their potential.

### 3.3. *Informal hands-on activities for practical STEM knowledge*

Creating resolutions for society's complicated challenges entails the evolution of diversified STEM talent dedicated to technical and societal innovation (Couch et al., 2020). This necessity requires STEM objectives that encourage implementing innovative mentality in K-12 programs through awareness and out-of-school activities fostering creative thinking, problem-solving, teamwork, and perseverance in students. Moreover, such students naturally are inclined toward science activities arising from their perception of inquisitiveness and capability to discover answers founded on innovation and inventiveness (Dejarnette, 2018; McClure, 2017). Hence, they are prone to engaging in scientific procedures like conducting analyses, reflecting upon various aspects of the environment and understanding designs and symmetries, or describing the roots of natural events (Legare & Gelman, 2014). Hands-on application-based programs and workshops offer these advantages and combine STEM education with activity-based learning (Naizer, 2014). Further, personalized efforts to stimulate STEM curiosity strongly concentrate on workshops and informal camps to nurture activity-based learning for young students (Pecen & Nayir, 2010; Schmidt et al., 2012). Recognizing this (Gupta et al., 2017) implemented and assessed the formulation of a chemistry-based workshop comprising lectures, hands-on activities, and laboratory safety protocols enclosed within pre-and post-surveys. Students depicted great enthusiasm in grasping new concepts and showed enhanced learning abilities. Similarly, (Megri & Hamoush, 2020) led a summer workshop for secondary students exposing them to 3D printers and advanced manufacturing technologies. Their outcomes illustrated improved student achievements along with aspirations to pursue higher studies. Also, (Ryu et al., 2020) conducted an informal STEM activity using drones to motivate and associate school students in STEM research and education. The practical drone workshops were integrated with computer science exposing students to constructing, programming, and flying drones. The participants were also subjected to interaction with drone professionals and were familiarized in a wide array of drone research applications. Their assessment results implied an enhanced level of preparedness to pursue future studies and careers in STEM fields. Similarly, (Hatfield et al., 2020) engaged pre-college students in their academic development by organizing a drone camp to improve learning prospects for students, encouraging them to consider futures in STEM-related disciplines. Another report by (Tezza et al., 2020) supports using drones as an innovative teaching method that can help generate early interest in education, creating an easier pathway for students' engagement in classrooms. Moreover, (Dickerson, 2017) incorporated a similar strategy through hands-on to initiate high schoolers in learning the fundamentals of the Internet-of-Things (IoT). This built enthusiasm in students to learn the technical aspects of IoT and fostered their interests to pursue careers in electrical and computer engineering. Further, (Wan et al., 2020) developed an experiential and participatory learning module to aid students into entry-level Machine Learning (ML) technology. This led to constructive transformation in high school students' knowledge of ML theories, procedures, and observations. Outcomes of their analysis clearly demonstrated the role of innovative practices such as ML to be a data-enabled attempt encouraging meaningful scientific inquiry in K-12 STEM education. Therefore, various research and assessment studies depict positive impacts of innovation orientated informal STEM workshops and programs, as constructive outreach activities that promote innovation and STEM interests for future studies and careers of K-12 students.

Another effective strategy incorporating informal learning elements in K-12 STEM education is playful learning, emphasizing structured learning activities focused on a learning objective (Zosh et al., 2018). Such learning-oriented play allows students to discover fundamental skills like mathematics, literacy, and logic while advocating innovation, problem-solving, and teamwork (Weisberg et al., 2016). (Hadani et al., 2021) demonstrated this tactic as a promising way to integrate innovation into young children's lives. Moreover, their study pointed out that such informal learning enhances understanding of mathematical concepts, increases science learning, promotes a healthy and constructive instructor-child relationship, and enriches the instructor's attitudes towards the play-learning relationship. Therefore, through the integration of informal learning and playful learning, young children may learn in an energetic, significant, collaborative, and engaging context. This is supported by (AlAydaroos, 2019), who reported the positive implications of an innovative mock summit at a primary school, exposing students to research from a young age. This informal experience enabled students to investigate their interests, envision ideas, and invent solutions for the real world, cultivating a culture of discovery, innovation, and scientific literacy in early STEM. A suitable playful STEM learning is one that inspires and provokes students to grasp fundamental practical abilities as they pursue academic endeavors in a playful manner. Rather than providing schooling through a ritualized practice of knowledge to be memorized, adequate student support is vital in their education by delivering prospects that aid students' hands-on caliber in the real world (Katz, 2010). Daily practical life is abundant in science experiences; however, such encounters effectively promote STEM understanding when adults systematize the setting for science discovery, concentrate on students' thought processes, and offer mentoring and constructive interactions (Children, 2013). Therefore, it is crucial for adults to assist children's playful learning activities, guide their experiences, and control the complications of information provided to them. Also, parents and instructors need to orient the students in this informal learning experience accordingly to maintain their inquisitiveness, content learning, and perception of STEM subject matters. A relevant study by (Tippett & Milford, 2017) supported this with their systematic analysis, which compiled data from several participants to elucidate STEM playful learning as a helpful tactic to nurture innovative thinking and curiosity in pre-kindergarten students about the surrounding environment. Further, (Kewalramani et al., 2020) studied young students' use of the Internet of Toys to develop their rational thinking, innovation, analytical, and critical thinking capabilities. Findings proved that incorporating playful STEM informal experiences aided kids' logical, inquiry, design thinking, and innovation abilities. Also, (Long et al., 2020) showed a conception of innovation in early STEM education through an informal learning experience using the Kolb's model of experiential learning to build micro-activities in each activity of an engineering design process. These sequences of experimental activities in the engineering design experience were found to be immensely efficient for participating students to foster their skill-building, subject interests, and satisfaction in STEM learning.

Nevertheless, while informal hands-on STEM pedagogies hold immense potential for fostering innovation, challenges remain. One concern is the limited reach of these initiatives, disproportionately benefiting majorly students who have access to resources and supportive families (Valla & Williams, 2012). Additionally, ensuring quality control and consistent learning outcomes within varied informal settings can be difficult (Council, 2014). Furthermore, integrating informal learning effectively with formal curricula requires careful planning and coordination to prevent fragmentation and ensure learning objectives are met. Addressing these limitations through targeted outreach, robust evaluation frameworks, and seamless curriculum integration is crucial to maximize the benefits of informal STEM practices and ensure equitable access to their potential for all students.

## 4. Discussion

Developing young problem-solvers to meet the demands of the world's complex challenges necessitates the evolution of a diversified and innovative workforce. This necessity can be tackled by implementing an innovative mentality in K-12 STEM education through formal, informal, and other collaborative measures that advocate persistent creativity, ideation, critical thinking, logical reasoning, and teamwork. Nonetheless, the purpose to generate a skilled community that deliberately pursues innovation in their career and individual life entails a carefully inclusive attitude (Garry et al., 2020). To develop and nurture the young population attracted towards innovation, early STEM education needs to confront the challenges of promoting innovation skills and discovery-inclined mindsets of observing the environment in learners. For this, educationists propose customary practices consisting of integrated STEM pedagogies, curriculum-reformed approaches, and informal workshops and camps. These didactics frequently emphasize inquiry-based project or problem-based learning methods, design-based thinking, and hands-on practical experiences in real-world situations. Though, in all such methodologies, students are inspired to discover and create solutions to significant problems, as compared to authentic STEM education, research on innovative STEM education still lags in its early stages. Therefore, this study tries to compile positive innovation practices in K-12 STEM education initiatives that demonstrate effective strategies to nurture and stimulate young students to transform into pioneers and innovators.

Implanting innovation at the K-12 school level provides access to a large audience and supports early exposure to learners, thus paving the way for sustainable and economical educational development (Council, 2015). Even more, this is as per conclusions that support students' early exposure to innovative practices, deeming it critical for their scientific literacy and academic development (Bell et al., 2019). Moreover, innovative STEM experiences present suitable perspectives for young learners not just to gain practical knowledge about inventing, using devices, and acquiring abilities but also provide the opportunity for students to visualize themselves as future doctors, engineers, scientists, etc. (Garner et al., 2021). This can be leveraged as a vital idea from which innovative experiences can be modulated in such a way that students are exposed to discover their opinions about innovation in the context of their personal and career resolutions and aims. Such integration of identity-focused paradigms in early STEM-oriented programs allows students to discover their roles' importance and potential in the economic world. However, to implement such innovative character successfully in students, their self-perceptions and self-definitions about innovation need to be consistent with what invention or innovation is. Yet, this is not an easy task. Studies employing PBL approaches in curriculums point out complexities faced in the teaching-learning process, which includes deploying constructivist tactics to adept student-focused pedagogies, formulation of assessments for PBL practices, student supervision problems, and inadequate support system for integrating collaboration amongst students (Mitchell et al., 2009; Zhang et al., 2019). Each of these signifiers depicts a gap in the well-known contextual elements of learning settings that present the concept of identity exploration. Hence, through innovative STEM education may provide a framework for identity exploration, learning pedagogies deployed in such modules must reflect this needs to be incorporated into the learning environment as it may not necessarily happen naturally during the design activities.

Educationally, innovative STEM practices are advocated as a method of tackling declining STEM participation by emphasizing the integration of disciplinary information to resolve challenges in natural and real-world settings. When implemented with innovative practices, such integrated STEM practices lay the grounds for improving essential student talents and capabilities, effective on both academic and career levels. These involve creativity, inventive mindset, content knowledge, scientific literacy and enculturation, cognitive and metacognitive developments, awareness about STEM, collaboration, teamwork, and communication. Further, the formal learning pedagogies using problem and project-based frameworks try to mirror and replicate the practices commonly employed at the industrial and commercial levels. Informal learning practices shed light on the significance of hands-on experiments, play, and students' practicalities, especially during their early years of STEM learning. K-12 STEM encounters must be practical, enabling learners to experiment with their creativity and discover concepts in profound circumstances; such encounters are associated with future educational and societal success in students' careers (Tippett & Milford, 2017). In all these approaches, the developmental focus relied on increasing STEM literacy, thus positioning the core of K-12 STEM education towards curriculum reformation and academic achievement. Although variations exist in the alignment of field expertise, many of the studies stress on curriculum reforms contended for the need to deploy multi-disciplinary approaches and emplacement of STEM curricula in contexts aimed at resolving challenges, prospects, and opportunities. Also, aspects of design thinking, consisting of scientific study, problem identification, and proposition highlighted notably in studies, correlate with multi-disciplinary integration beyond the STEM curricula. This exemplifies that transformation headed for interdisciplinary K-12 STEM learning can be feasibly incorporated into current learning pedagogies, and this holds high potential to give considerable advantages in developing a holistic STEM literacy. Overall, much of the general agreement subsisted on the attraction towards student-centered innovation strategies that prove to be highly consistent in conjunction with STEM proficiencies and prospects. Further, there is a mutual perception in most of the findings that instructors and mentors play a central role in K-12 STEM education in implementing innovative practices and creating the essential learning atmosphere for developing STEM capacities. Therefore, considerable attention must be paid to developing teaching pedagogies to successfully implement innovation-motivated STEM learning. One way for this approach can be to incorporate mentor training workshops and programs for instructors and teachers to curate their teaching skills and orient their pedagogies to support innovative practices at school. Further, public-private collaboration in STEM education is vital for innovation and sustainability. Leveraging the strengths of both sectors – private innovation and public accessibility will create a dynamic ecosystem (National Academies of Sciences & Medicine, 2016). These partnerships have the potential to adapt curricula, address challenges, and prepare K-12 students for a tech-driven future. The result can be a thriving environment that equips students to meet future demands efficiently. Also, facilitating professional development and research and development (R&D) events for teachers at campuses and industrial sites can be of immense advantage. By engaging in application-based R&D practices, teachers can develop strategies to reform their tutoring procedures and integrate innovative experiences into students' STEM learning. This can help restructure an innovative environment to inspire students into exploration, inquiry, and discovery practices as part of their STEM education.

While the studies covered in this review report the role of innovation in K-12 STEM education, all of the studies share a common goal of significantly impacting the STEM literacy of students. Additionally, it is observed that the approach to implementing the role of innovation is apparent in all major types of STEM pedagogies (integrated STEM, project-based, problem-based, design thinking, etc. Therefore, the role of innovation is an integral part of STEM literacy and can be positively correlated with the increase in STEM literacy. Consequently, this brings attention towards conceptualizing a framework that lays out practical guidance about core components of early STEM learning, directing their collaborative goal to attain STEM literacy. (Garry et al., 2020) report such a framework to draw links relating to the pivotal elements in K-12 STEM education to optimize the effective development and execution of STEM pedagogy for K-12 students. This proposed structure, in Fig. 2, acknowledges the general purpose of STEM literacy, recognizing distinct entry points, subject understanding inclinations, and instructional methods that can foster consideration of various methodologies, policies, and functions for a literate K-12 STEM population. The notion of the framework is related to the four crucial fundamentals to achieve STEM literacy - knowledge, engagement, endeavor, and awareness. These describe the characteristics of learners along with their capabilities, personalities, subject understanding, and talent that need to be considered for STEM literacy. This is signified in the core of the figure, also implying their centrality in the learning process (the double-sided arrows represent their bi-directional interaction). The STEM disciplines around the core correspond to different possible entry points signaling the potential that any STEM field can act as a gateway to STEM education. However, even though the entry might be through a single gateway, the experience is multidisciplinary with other STEM subjects playing a role to some extent. This is represented by double-sided arrows spanning the bars, symbolizing the integration of disciplines. Realistically, this unfolds prospects for educationists and policymakers to devise discipline-oriented programs, deploying the potential of other STEM subjects to integrate discipline expertise. Further, the top part of the structure recognizes the scope of settings or initiation ideas for STEM learning in terms of wants, opportunities, needs, or problems as promoters for stimulating the various work processes like communications, engaging stakeholders, knowledge transfers, and exchange, networking, collaboration and several 'combinations' of STEM-field knowledge. The lighter grey arrow signifies their weaker association with a single-discipline orientation. The inner ring of work processes is engaged by the inward-pointing arrows, which represent issues, needs, opportunities, and wants as project motivators or contexts. The bottom section of the framework features curriculum, instruction, and learning environment traits related to various discipline preferences. Here, the instructional tactics can differ, corresponding to the type of STEM learning, project-focused or subject-focused. However, the pedagogy of both alignments will most probably demand distinct instructional strategies, learning practices, and mentor responsibilities. The design thinking method's two-fold role (dual sided arrows) is demonstrated due to its central links with both the discipline and interdisciplinary

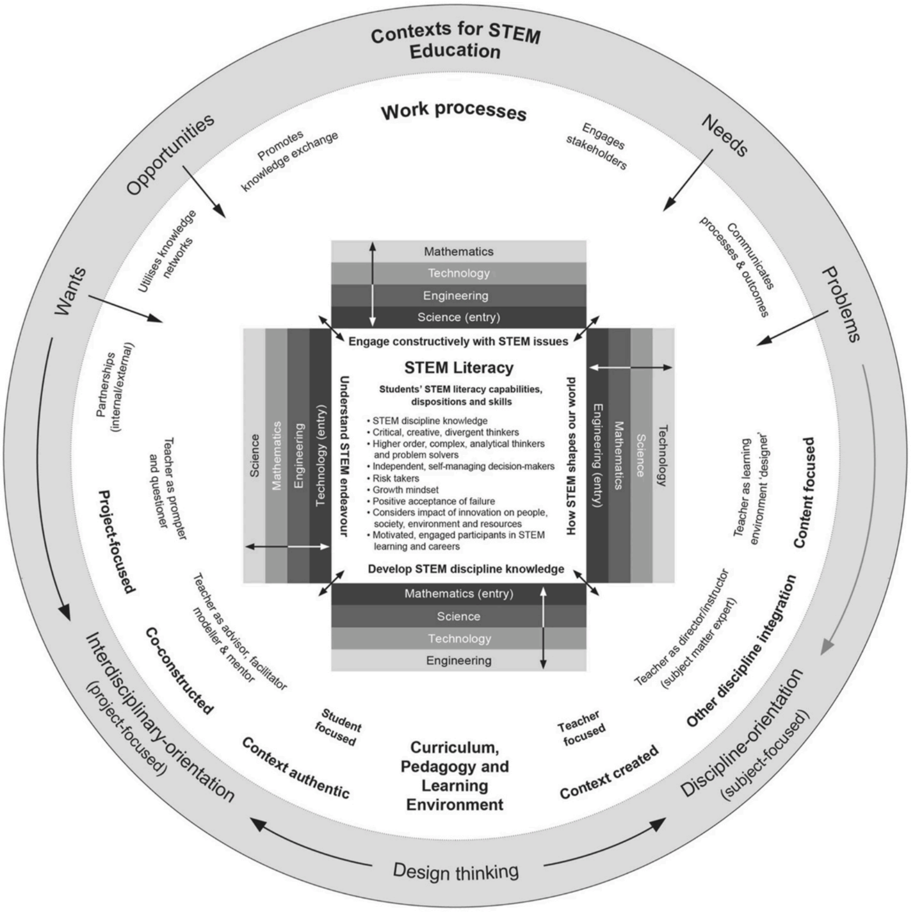


**Fig. 2.** Proposed framework for developing STEM Literacy and enhancing the role of innovation in K-12 STEM education. Reproduced with permission from Garry et al. (2020). Copyright Springer, 2020.

orientations. Therefore, the framework in Fig. 2 provides a solid context to understand the pivotal roles required for initiating effective STEM literate pedagogies and reforming the existing STEM practices to command better authenticity and significance. Moreover, it supports the outcome to enhance the role of innovation through STEM literacy, advocating the basis on which recognized pedagogical methods and systems can be based.

However, concerns and limitations remain, which must be addressed to amplify the gains from the STEM pedagogies discussed in this study. These factors involve a dearth of global standardized core curricula and education practices. Also, the innovative education approaches reported in this study are still developing and cannot be claimed to be entirely free from conventional disciplinary limits. “Cookbook” measures (where students are given detailed, step-by-step directions for carrying out experiments) and procedures like textbook culture, are, however, widespread across various schools (Oliveira & Bonito, 2023). Employing such strategies entails learners simply executing prescribed procedures from the teacher without much contemplation or intent (Anderson, 2013). For instance, it is mentioned by Fraser et al. (2012) that there is a scarcity of opportunities for students in US schools to utilize higher-level cognitive skills or discuss substantive scientific knowledge in investigations. Tasks often adhering to a cookbook approach lead to prioritizing the development of lower-level skills. Therefore, teachers need much-focused attention to develop their expertise and help them associate the subject matter with innovative and inquiry-driven perspectives to enhance the student learning processes. Also, a lack of community involvement provides operational constraints in STEM programs for implementing innovative practices. This poses a challenge for policymakers and community members to allocate strategies for embedded innovative STEM learning within the confines of the STEM program that can help cultivate collaborative arrangements to assist instructors in engaging with out-of-school practices.

Therefore, to address the challenges identified in implementing innovative pedagogical approaches in K-12 STEM education, proactive measures are essential for both educators and policymakers. Establishing targeted professional development programs for teachers can empower them with the necessary skills to seamlessly integrate innovative and inquiry-driven perspectives into their classrooms. These programs should focus on pedagogical strategies that foster creativity, critical thinking, and problem-solving skills, aligning with the demands of a technology-driven society. Additionally, overcoming resource constraints necessitates collaborative efforts between educational institutions and local communities. Policymakers can facilitate partnerships with industries and organizations to provide schools with the essential instruments and equipment required for hands-on, practical STEM experiences. Moreover, fostering a culture of community involvement and support will not only enhance the implementation of innovative STEM practices but also contribute to cultivating collaborative arrangements to assist instructors in engaging with out-of-school practices. By strategically addressing these aspects, educators can navigate the challenges associated with innovation in STEM education, ensuring a dynamic and effective learning environment for K-12 students.

Furthermore, this review holds profound implications for educational stakeholders. Policymakers can draw on the positive correlations identified between innovative, technology-driven pedagogies and enhanced STEM literacy to inform policy decisions, paving the way for STEM practices that aligned with the demands of a technology-driven society. Educators, through this review, can gain valuable direction for instructional practices, emphasizing the effectiveness of practical learning strategies and the imperative for well-trained instructors. Furthermore, the findings inspire a call for further research, particularly in developing effective teacher training programs and overcoming challenges associated with integrating technology into K-12 STEM education. The emphasis on collaboration across institutions highlights the importance of creating networks for knowledge exchange, while the recommendation for continuous evaluation underscores the need for adaptive curricula and accessible resources. In this way, the implications of this review extend beyond its pages, offering a practical dimension to shape policies, guide instructional practices, and inspire ongoing research in the dynamic landscape of K-12 STEM education.

## 5. Concluding remarks

In conclusion, fostering a culture of innovation across schools is paramount for advancing STEM education and preparing students for a technology-driven future. All students, beginning at an early age, need entry to innovative opportunities that will aid them in obtaining the abilities necessary to prosper in higher studies, workplace, and life. Studies show that hands-on pedagogical strategies are the most effective way to establish a strong integration of innovation in the STEM curriculum from the first day of elementary school through senior year. Students who perform inquiry from a young age are better equipped to identify and explore their interests, create, and build solutions to real-world issues, and become self-sufficient and confident in their problem-solving abilities. Along with their implementation, these strategies should undergo regular assessment in both formal curriculum and informal STEM programs using specific assessment tools or frameworks, such as rubrics evaluating project outcomes, standardized tests measuring STEM literacy, and surveys gauging student engagement. This will provide educators with valuable insights into program success providing room for continuous improvement. Furthermore, public-private collaboration between schools and institutions through joint workshops can effectively enhance the culture of innovation. Shared resources, such as cutting-edge technological tools and materials, can alleviate resource constraints and provide a more equitable learning experience. Additionally, establishing exchange programs where educators move between institutions can facilitate the cross-pollination of innovative teaching methods. The benefits of such collaborations are multifaceted, with learners experiencing enhanced engagement, exposure to diverse perspectives, and the development of critical innovation skills. Simultaneously, educators gain opportunities for professional growth, increased efficacy in implementing innovative practices, and a supportive network to navigate challenges. Moreover, the learning in K-12 STEM that is built on innovation must be well-organized. During the creation process and before the information is presented to students, instructors must be trained to convey and describe the content to students. For this, mentor training workshops and programs need to be implemented for instructors and teachers to align their teaching skills and pedagogies with technology integrated STEM education. Along with this, it is also important to make sure that school facilities are equipped with the essential instruments and equipment to aid the technology integration. Therefore, the journey towards a culture of innovation in STEM education requires collective commitment and sustained effort. Achieving the pragmatic roadmap presented in this review has the potential to empower K-12 students to become visionary leaders who contribute to a more innovative and inclusive society.

## Author note

We have no conflict of interest to disclose.

## Unlisted references

Nadelson & Seifert, 2017; Li et al., 2019; Møller & Myles, 2016; Ortiz-Revilla et al., 2021; Children, 2013; Springer, 2020.

## CRediT authorship contribution statement

**Mohammad Ammar:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Noora J. Al-Thani:** Visualization, Supervision, Resources, Project administration,

Conceptualization. **Zubair Ahmad:** Writing – review & editing, Visualization, Validation, Project administration, Conceptualization.

## Declaration of competing interest

The authors declare no conflict of interest.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ssaho.2024.100839.

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