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Harnessing pedagogical innovation and educational technology to revolutionize STEM beyond the classroom: Future directions

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ABSTRACT

The rapid advancements in pedagogical innovation and educational technology have opened new avenues for transforming Science, Technology, Engineering, and Mathematics (STEM) education beyond traditional formal learning settings. This paper delves into emerging learning models and investigates the potential of integrating technology to revolutionize STEM education by fostering the skill sets necessary for the future. Specifically, this paper examines key pedagogical approaches, blended learning and inquiry-based learning, that can be effectively combined with educational technologies to bridge learning across diverse contexts, extending beyond the confines of the classroom. By highlighting educational technologies, this paper aims to advocate for the utilization of learning tools to create immersive and interactive learning experiences. It is argued that by designing these learning experiences, the gap could be bridged between abstract concepts taught within the classroom and the real-world challenges encountered beyond its boundaries.

Key words: STEM education, informal learning, inquiry-based learning, blended learning, educational application

INTRODUCTION

It has not been more crucial than now to consider the evolving landscape of the current and future of Science, Technology, Engineering, and Mathematics (STEM) education, which has great potential to equip students with the necessary skills to tackle complex future problems. The promises of STEM education lie in its applied and interdisciplinary nature, connecting scientific theories and technology to drive societal progress. Not only does this promote problem-solving skills, critical thinking, and other 21st-century skills, but also instils in students a sense of ethics and responsibility to better their environments and address global challenges. As an important driver for the current and future economy, STEM education is a priority—not only for educators but for governments, parents, and stakeholders in the industry. Therefore, there is a necessity to bridge formal learning contexts and informal learning environments to fulfill the transformative power of STEM.

One significant challenge faced by traditional formal STEM education is that it primarily emphasizes formal instruction within classroom settings. Formal learning often occurs in a systematic manner, guided by predefined goals, but with limited relevance to students' prior knowledge and experiences outside the classroom.[1] Given the evolving landscape of education and the changing demands of learning, traditional learning designs are facing criticism from scholars for their inability to meet the needs of the 21st century.[2,3] For instance, Gilbert argues that formal curricula may restrict teaching strategies, impeding the elaboration and utilization of captivating scientific illustrations.[4]

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Moreover, Isman highlights the lack of technology integration in instructional activities, which is crucial for enhancing students' conceptual understanding.[5] Other scholars recognize that while formal learning contexts facilitate knowledge acquisition, they may not be the most effective pedagogical approach for fostering identity and motivation, both of which are essential for lifelong learning.[6] In essence, there are disparities between the learning designs of traditional STEM education and the evolving landscape of future learning.

There are emerging needs to redefine STEM education such that real-world problems and 21st-century skills are emphasized in order to address the future of STEM education.[7] This entails prioritizing complex, cross-disciplinary problems that have relevance across classroom and real-life contexts.[8] To establish stronger connections between learning and real-world problems, various emerging pedagogies and technologies can be effectively utilized, allowing students to investigate natural phenomena inside and outside of the classroom.[9] This may expand the current scope of STEM education. This integration aims to blend knowledge, understanding, and skills across contexts to adequately equip students to meet future demands.[10] By doing so, learning may surpass the confines of formal classroom settings, reaching into everyday informal learning environments.

THE NECESSITY TO BRIDGE FORMAL AND INFORMAL STEM EDUCATION

Informal STEM learning experiences can help address the limitations of formal learning contexts by fostering students' interest, knowledge, and inquiry of STEM.[11,12] Studies have suggested that students who struggle in formal STEM learning contexts tend to have increased interest and motivation in STEM when learning experiences are more engaging and interactive.[13,14] Compared to formal learning, informal STEM learning contexts allow educators to design immersive learning experiences using real-world problems and challenges that students are connected to and are also relevant for 21st-century skills. Such connection can enhance conceptual understanding in STEM.[15] For example, out-of-school STEM summer camps and courses (*i.e.*, science centers, museums, and out-of-school laboratories) not only increase students' STEM understanding but also interest and inquiry in STEM.[12,16]

Despite the call to extend learning beyond the traditional classroom setting, effective implementation remains ambiguous.[17] This raises important questions regarding the pedagogical approaches and technologies that can create learning experiences to bridge formal and informal learning. To address this, the current article explores emerging learning models of inquiry-based learning and blended learning to propose how educational technologies may be integrated into these models to enhance STEM learning across diverse learning contexts.

INQUIRY-BASED LEARNING: BRIDGING FORMAL AND INFORMAL LEARNING

Inquiry-based learning, grounded in John Dewey's philosophy that learning starts with students' curiosity, is not a new idea. Nonetheless, it probes reflections regarding how we may reimagine STEM learning outside of formal classroom learning. At the core of inquiry-based learning are skills such as questioning, critical thinking, and problem-solving, which are highly valued in the 21st century. Unlike instructional-based learning models, inquiry-based learning places a stronger emphasis on encompassing the affective, cognitive, and psychomotor dimensions of learning. This enables students to engage in scientific reasoning and develop a more comprehensive understanding of the nature of science.[18] As inquiry involves exploring the natural and material world, inquiry-based STEM learning is closely connected to student's everyday environments, such as home, playground, and in nature. For instance, the conceptual understanding of the relationship between hypotheses and evidence can be grasped through everyday observations, questions, and participation during play and other activities. Through this process, knowledge can be reflected upon and co-constructed by the students themselves.

There is extensive evidence supporting inquiry-based learning in STEM albeit various types of inquiry-based learning can evoke different outcomes. By and large, research has suggested that inquiry-based learning enhances interest and persistence in STEM for young children.[19–21] Cognitively and academically, students in inquiry-based science classrooms also demonstrated superior scientific reasoning skills and scientific process skills and attitudes compared to non-inquiry science classrooms.[17,22] The evidence on inquiry-based learning demonstrates benefits to students' affective, cognitive, and academic outcomes in STEM. A meta-analysis conducted by Lazonder and Harmsen suggests that guided inquiry learning, which involves teachers providing scaffolding, demonstrated superior results in mathematics and science education.[23] Similarly, Kang and Keinonen highlight that guided inquiry significantly contributed to students' science motivation and achievement, whereas student-directed open inquiry had a negative impact.[24] Supporting this notion, Kirschner *et al.* argue that increased guidance and scaffolding, such as utilizing worked examples or process worksheets, can enhance learning outcomes.[25]

As the future of STEM education envisioned in this article is beyond the classroom setting and may extend to different natural and cultural settings, guided inquiry can also be facilitated by various individuals such as parents. For example, researchers are starting to investigate STEM learning at home and have found that parents can support the inquiry process and guidance through various activities, such as picture books, games, cooking, and nature activities.[26–28] Results highlight parental guidance on STEM inquiry is associated with enhanced conceptual understanding of mathematics and scientific concepts as well as reasoning skills.[27] This inquiry process, including comparing, predicting, evaluating, and concluding, can be as simple as using *Wh* -questions (*i.e.*, what, when, where, why, how) such as "what do you notice?".[29] These findings turn to the potential of connecting formal and informal STEM learning with parental guidance on inquiry-based activities within student's everyday home environments.

BLENDED LEARNING: AN EMERGING MODE OF LEARNING IN STEM

Blended learning, an emerging educational model, integrates elements of face-to-face instruction with virtual experiences, such as labs, simulations, tutorials, and assessments.[30] Rooted in constructivism, blended learning combines traditional and technology-mediated learning, surpassing the effectiveness of solely face-to-face or fully online modes of instruction.[31] Consequently, it serves as an effective pedagogical approach for bridging formal and informal STEM learning.[32] Huang *et al.* outline three key characteristics of blended learning that contribute to learning effectiveness.[33] First, it enhances flexibility by providing diverse learning materials and resources. Second, it promotes self-regulation by accommodating learning diversity. Third, virtual learning environments improve existing teaching practices. These characteristics hold significant value in STEM education, especially when combined with effective educational technologies to enhance personalization in learning.

Blended learning may alleviate several learning issues faced by students under the traditional learning approach, such as the pace of learning, engagement, and motivation in STEM education. For instance, delivering conceptual and theoretical content in a gamified manner through multimedia resources like educational videos can cater learning to diverse learning needs or preferences.[34] By engaging students through auditory, visual, emotional, and aesthetic modes, blended learning may support multisensory and personalized learning, thereby fostering motivation and engagement.[35] Furthermore, technology integration enables the inclusion of real-time quizzes or interactive tasks that offer immediate feedback and support self-directed learning.[36] Departing from traditional instruction-based pedagogy, blended learning facilitates the integration of real-world problems into classroom instruction, allowing students to synthesize and apply knowledge in real-time.[37]

Blended learning can be a catalyst approach to promoting 21st-century skills in the future of STEM education. Many of what we consider as 21st-century skills are essentially higher-order thinking skills. Blended learning has been shown to enhance skills such as problem-solving, communication, reasoning, and computational thinking, which are not typically addressed within traditional STEM curricula.[38,39] For instance, in a controlled experimental study conducted by Hasanah and Malik, it was observed that students' critical thinking and communication abilities exhibited improvement as a result of engaging in blended learning, which was not observed within the control group.[40] Similarly, Tsai *et al.* reveal that the utilization of blended learning within the context of online externally facilitated regulated learning for computational thinking led to students demonstrating superior computing skills compared to alternative forms of facilitation.[41]

FUTURE DIRECTIONS: INTEGRATING EDUCATIONAL TECHNOLOGIES WITH INNOVATIVE PEDAGOGIES

Inquiry-based learning and blended learning, in conjunction with educational technologies such as educational application (APPs), virtual labs, and generative artificial intelligence (GenAI), may offer the potential to facilitate ubiquitous learning that seamlessly integrates formal and informal STEM education. These technologies provide interactive, multisensory, personalized, and real-world relevant learning experiences, promoting effective STEM learning across diverse contexts.

Educational APPs have emerged as a novel medium for STEM education, enabling students to engage in educational activities anywhere and anytime outside the traditional classroom setting.[42,43] Cherner and Fegely elucidate that educational APPs can be utilized in various ways to enhance learning outcomes.[44] Firstly, "skill-based" APPs can deliver and test conceptual knowledge such as multiple-choice questions in video games. The games can be based on real-world scenarios that students are familiar with and interested in. Secondly, "content-based" APPs provide students with flexible access to knowledge, such as viewing educational videos on platforms like YouTube. Thirdly, "creationbased" APPs afford students the opportunity to generate artifacts that demonstrate their knowledge, such as developing a multimedia video to showcase their work. All these approaches can be implemented outside of the classroom to support blended learning and inquiry-based learning in STEM.[44] However, cautions should be applied due to the diversity and flexibility of educational APPs, which could introduce complexities within a blended learning environment.[44] To mitigate potential challenges, it is advisable for educators and parents to incorporate inquiry-based guidance and scaffolding when utilizing educational APPs for STEM learning.

Hands-on laboratory activities are traditionally organized in the classroom, but the metaverse has created new multisensory ways to support blending learning and inquiry-based STEM activities. In formal learning contexts, STEM education often necessitates construction tools, electronic materials, among other costly resources.[45] The metaverse, a digital space that integrates the real world and the virtual world, may address problems in traditional laboratory-based activities through blended learning. This is especially the case with the increasing utilization of augmented reality (AR) and virtual reality (VR), which give rise to virtual learning experiences that transcend the limitations of time and space, immersing students in virtual environments that were once inaccessible. For example, virtual laboratories enable students to visualize complex physical structures, observe microscopic organisms, and ask questions about the inner workings of machines through interactive simulations.[46] On the other hand, virtual field trips can provide guided exploration for students to discover remote or otherwise inaccessible locations. Through immersive learning experiences, students can visit historical sites, delve into the depths of the ocean, or even venture into outer spaces.[47] Virtual learning environments offer several advantages, including accessibility, low cost, immediate feedback, and the ability to repeat experiments.[48] Such experiential learning not only aids in visualizing abstract concepts, but also enhances discussion of inquiry in inquiry-based learning while introducing students to real-world problems.[49] The multisensory approach of the metaverse is especially useful to bridge formal and informal learning, which could greatly enhance students' engagement, interest, and confidence in these subjects.[50]

GenAI can enhance blended- and inquiry-based learning by empowering personalized learning, which targets each student's strengths, needs and interests to offer flexibility and support better learning outcomes.[51] For example, to create individual learning materials, provide customized feedback, design simulated environments for immersive learning experiences, and develop interactive educational content.[52,53] Such tailored educational support may enhance learning effectiveness and efficiency. Indeed, one of the greatest potentials of GenAI in STEM education is creating personalized, adaptive assessments according to the students' learning progress, adjusting difficulty based on performance, and giving real-time individualized feedback. Engaging students in authentic learning opportunities that are personalized may help students engage deeper and develop essential skills.[54] For example, Bitzenbauer demonstrates promises in using GenAI such as Chat Generative Pre-trained Transformer (ChatGPT) in physics education to foster critical thinking skills.[55]

CONCLUSION

The landscape of STEM education is undergoing a transformative shift to prepare students for future challenges. By leveraging innovative pedagogical approaches and embracing the potential of educational technologies, STEM education can be revolutionized, offering dynamic and engaging learning journeys that equip students with future-ready 21st-century skills. This paper has explored the integration of educational APPs, the metaverse, and GenAI in inquiry-based learning and blended learning, respectively enhancing learning engagement, a multisensory approach to learning, and personalization in STEM education—essential elements for the future of learning. Looking ahead, the future direction of STEM education lies in further exploration and implementation of innovative pedagogical approaches and educational technologies that support learning across diverse contexts. Continued research and development in this field are necessary to refine existing tools and methods and create new ones that bridge formal and informal learning. Moreover, fostering partnerships among educational institutions, technology developers, and industry professionals will be instrumental in shaping the future of STEM education. Such collaboration can facilitate the alignment of learning content with the evolving demands of the real world, enabling students to acquire the relevant skills and knowledge outside of the classroom.

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Author contributions

Lai RP: Conceptualization, Investigation, Resources, Writing—Original draft, Writing—Review and Editing.

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