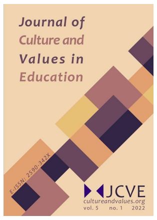

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STEM Education Practical Work in Remote Classrooms: Prospects and Future Directions in the Post-Pandemic Era

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ABSTRACT

Practical work is pivotal for the development of important skills inherent to science, technology, engineering, and mathematics (STEM) education. Through practical work, learners engage in skills that include critical thinking, problem-solving, and inquiry-based learning, which are important outcomes of STEM education. Given the rise in significance of remote learning as reinforced by the COVID-19 pandemic, there is a need to reimagine the facilitation of practical work for learners. This paper uses the preferred reporting items for systematic reviews and meta-analyses (PRISMA) qualitative research design, an interpretive paradigm, and a mix of connectivism and community of inquiry (CoI) frameworks to explore the facilitation of STEM education practical work in remote classrooms. A systematic meta-analysis of purposively selected papers using the preferred items, techniques of identification, screening, eligibility, and inclusion, and published between 2017 and 2021, was conducted. The following key words were used to conduct a search using Google Scholar: STEM practical work + STEM education in remote classrooms + Practical work in remote classrooms + STEM education in online classrooms + STEM education in virtual classrooms + Virtual practical work + Teaching STEM and COVID-19 + Practical work and COVID-19. Fifty papers were identified, of which fifteen were included in the study. Thematic content analysis techniques were used to analyze the papers. Five strategies to facilitate STEM practical work in remote classrooms were identified and the findings point to the prospects and future directions of practices in facilitating practical work for learners remotely.

KEYWORDS

COVID-19, practical work, remote classrooms, STEM education; online education.

INTRODUCTION

At face value, science, technology, engineering, and mathematics (STEM) education may be seen as a way of grouping similar disciplines together. However, the STEM movement and the resulting curriculum innovations are driven by complex aspirations, such as the one to develop innovative talent in citizens to meet the needs related to economic development and environmental and social wellbeing of the 21st century (Wang et al., 2018). At the core of STEM education is the development of important skills for the 21st century environments, which include problem-solving, creativity, critical thinking, teamwork and collaboration, responsible leadership, and digital literacies (Hadinugrahaningsiha et al., 2017). These skills, aimed at improving life in the 21st century, seek curriculum practices that enable learners to apply what they learn in real-life situations. For that reason, Ejiwale (2013) explained that STEM should be taught as a meta-discipline created by the integration of science, technology, engineering, and mathematics with the aim to develop specific skills that support the 21st century economies and environments.

As the use of transdisciplinary knowledge increases coupled with transforming societal needs, a synthesis age has been created in which new professions are forming as driven by the Fourth Industrial Revolution (4IR), and STEM education is viewed as one of the ways to prepare citizens for the evolving professions (Nadelson & Seifert, 2017). In light of the evolving professions, Du Plessis (2018) asserted that 75% of the fastest growing occupations require STEM skills. Based on the perceived usefulness and application of STEM education to people's lives, curriculum developers have shown that teaching and learning should be conducted in authentic and real-life situations (Bybee, 2013; Nadelson & Seifert, 2017; Srikoom et al., 2018).

One of the STEM teaching and learning strategies lauded for providing authentic environments in which learners engage in hands-on and minds-on activities that have application to real-life situations is practical work. Practical work encompasses a wide range of activities in which learners are actively involved and engaged. School STEM practical activities may include field trips, experiments, investigations, internet searches, laboratory work, building of models, drawing, simulations, and work-integrated learning, among other activities. Many conventional school STEM practical work activities are conducted in authentic prepared environments such as classrooms, laboratories, and workshops. Learners can also conduct practical work activities in natural and prepared environments outside the classroom. The practical work teaching and learning strategy in STEM education can also be very expensive because of the need to replace some of the perishable materials and broken equipment that are prescribed in curriculum policies. In the face of the impeding challenges, teachers are expected to improvise when the prescribed materials and equipment are not available by using locally available materials and substances, re-designing experimental procedures, and finding alternatives to hands-on activities (Tsakeni, 2020).

The advent of the COVID-19 pandemic, which caused the emergency transition to remote teaching and learning with very minimal preparation (Cutri et al., 2020), brought an element of uncertainty to the use of practical work strategies. Some teachers were unsure of how to teach using practical work strategies in remote classrooms and in some cases, these were abandoned (Makamure & Tsakeni, 2020). Practical work is one of the readily used strategies and vehicles for the facilitation of important STEM education skills such as inquiry, problem-solving, creativity, innovation, and critical thinking, among other skills. With practical work being central to STEM education and the sudden move to remote teaching and learning in 2020 due to the COVID-19 pandemic, teachers needed to find new ways to facilitate practical work. Teachers are not new to improvisation when resources to facilitate practical work are scarce. However, before the pandemic, most teachers were not familiar with teaching STEM education in virtual learning environments and remote classrooms. It has been acknowledged that COVID-19 hampered practical work and, in some cases, instructors improvised by using emergency teaching strategies such as do-it-yourself (DIY) open technologies, mobile learning and simulations, household reagents to conduct DIY experiments, and online multimedia (Abriata, 2021). Teachers had to decide between using synchronous and asynchronous online teaching (Tsakeni, 2021), resulting in the divide between the virtual learning elite and others who had limited access to 4IR technologies (Hove & Dube, 2021). It is against this backdrop that this study sought to synthesize from literature some of the strategies that teachers can use to facilitate practical work in STEM classrooms remotely.

The practice of STEM education practical work in remote classrooms through virtual learning environment tools and educational technologies was already a feasible idea before the emergency move to remote learning due to the advent of the COVID-19 pandemic. However, in some cases, the experimental component of some of the STEM subjects was suspended at the start of the pandemic (Cottle, 2021). Akuma and Callaghan (2019) explained that practical work is when learners engage in hands-on and/or computer-based activities. The sudden rise to prominence of remote teaching opened up opportunities for innovative ways of conducting STEM practical work. However, the practice of remote STEM practical work in schools was still undervalued and less implemented than other forms of practical work implemented in physical classrooms, laboratories, workshops, and natural environments. Lal et al. (2018) confirmed that practical work activities facilitated face to face in physical environments are still a preferred choice to distance education options. Bozkurt and Sharma (2020) observed that the education systems in most countries were poorly prepared for the emergency remote teaching caused by the COVID-19 pandemic. Consequently, inspired by the events of the emergency remote learning experienced globally from 2020, this paper explores how STEM practical work can be used as an instructional strategy in remote classrooms. Following a literature review research design, this study contributes by synthesizing the perspectives on possible strategies to conduct remote STEM practical work in the post-pandemic era.

Research Questions

The main research question of this study is: How can STEM practical work be taught in remote classrooms?

The main research question has been broken down into the following two sub-questions:

- What are the methods used by teachers to teach STEM practical work in remote classrooms?
- What are the prospects and future directions in teaching STEM practical work in remote classrooms?

REVIEW OF THEORIES

STEM Practical Work in Remote Classrooms

It is important to provide an operational definition of remote classrooms in the backdrop of discourses that use similar terms differently. To start with, the term emergency remote teaching gained traction to describe the modes of teaching enacted in response to the threat of COVID-19. Hodges et al. (2020) referred to emergency remote teaching as the alternative modes of instructional delivery put in place when the usual practices are discontinued due to an emergency. The term remote teaching puts emphasis on spatial distance whereby teachers and learners are not co-located (Bozkurt & Sharma, 2020). An example of remote teaching in STEM education is the use of remote laboratories in which learners are not physically co-located with the equipment (Lindsay & Wankat, 2012). The learners perform experiments with real and physical equipment, because the control of the equipment is made possible by the use of technology and the internet. In this study, it is considered that the facilitation of practical work in remote classrooms happens when the learner is not co-located with the teacher and other learners. In addition, the learner may or may not be co-located with some of the learning materials. Questions have been asked on whether remote practical work can replace face-to-face facilitation (Lindsay & Wankat, 2012), and, if so, with what and with whom do learners interact during remote practical work and what learning outcomes result from those interactions (Treagust et al., 2016). In a study by Benitti and Spolaôr (2017), learners designed 3D objects that they fabricated remotely in a distant laboratory, showing that learners can conduct practical work remotely. Other studies have explored how to promote learner collaboration when conducting practical work in remote classrooms and one of the ways proposed was the groupwork strategy. Mujkanovic et al. (2012) used multiple linear regression to systematically form groups in remotely accessible laboratories based on optimal collective characteristics in order to address specific learning outcomes.

Practical work has many benefits in the STEM classrooms and teachers can use this strategy to provide experiential learning for learners aimed at developing various skills. The skills include some that are inherent to STEM education, such as critical thinking, problem-solving, creativity, and handling and manipulation of equipment. STEM education enables learning in authentic environments, such as real-life experiences or simulations of real-life experiences (Bybee, 2013). Similarly, practical work brings abstract STEM concepts to life by providing the needed concrete contexts that learners can relate to. Semali (2020) confirmed that practical work bridges the gap between what is learnt in STEM classrooms and real life. For example, Muhardias et al. (2020) explored how STEM practical work can improve learner creativity using an activity to manufacture liquid sugar from cassava. One of the overarching aims of education is to prepare learners for life and the world of work. The broader objectives of STEM education as envisioned by politicians and governments similarly seek to achieve this. STEM education is driven by the belief that its implementation will result in the development of the much-needed workforce with the requisite skills to develop national economies (Bybee, 2013). STEM education allows for the use of interdisciplinary approaches. Semali (2020) asserted that combining innovation, STEM disciplines, practical work, application, conceptualization, and entrepreneurship enables learners to study and produce products and solutions for everyday-life use. The developing of economies is supported by the advanced and ubiquitous technologies powered by the 4IR, resulting in new professions that need a specialized workforce (Nadelson & Seifert, 2017).

As discussed in the preceding section, practical work provides authentic environments for learning. These authentic environments can be hands-on and computer-based activities that are either teacher- or learner-centered. Akuma and Callaghan (2019) explained that both teacher- and learner-centered approaches to practical work can be used in the classroom based on the planned curriculum outcomes. However, learner-centered approaches, such as inquiry-based practical work, are more beneficial, because they help learners to develop more complex skills and learners exercise more autonomy in problem-solving, critical thinking, and creativity. Conventionally, the authentic environments for STEM practical work can be classrooms, laboratories, and outside of the classrooms, but advances in technologies have enhanced ways of facilitating STEM practical work for learners to include virtual environments. Lal et al. (2018) pointed out that practical work and, in this case, laboratory work can be conducted in both physical and virtual environments. For example, there is an increased use of virtual learning environments for learners to conduct practical work. Virtual reality (VR) tools include simulators, virtual laboratories, demonstrations, and virtual field trips, among other tools, all of which can be used in STEM education (Truchly et al., 2018). In virtual laboratories, learners can conduct experiments in which they can manipulate variables, record measurements, analyze data, and draw conclusions. In their study, Ghergulescu et al. (2018) found that learners who conducted practical work in virtual laboratories improved in mental traits such as creative thinking, fluidity, originality, and flexibility. The finding affirms that practical work in virtual environments also helps in achieving important learning outcomes in STEM education. Internet connectivity has enabled the use of web-based and online virtual laboratories, opening up opportunities for sharing content and collaboration (Kefalis & Drigas, 2019). The downside to the use virtual learning environments is that some teachers are not familiar with these tools (Bada & Jita, 2021).

Theories for Online Learning

The ubiquity of the new technologies and the growth of technology-assisted learning necessitated the reimagining of how learning happens in these new environments. The increased use of the internet and Web 2.0 tools such as social media, online office, and conferencing tools enables the connection of more people and sharing of diverse views (Goldie, 2016). The use of these technologies supports the alternative learning environments, such as e-learning and online learning, and in addition enhances distance education practices. The increased use of educational technologies creates a gap in the use of long-existing theories to understand the resultant e-learning. Siemens (2004) argued that the theories of behaviorism, cognitivism, and constructivism could not fully explain technology-aided learning and from there the theory of connectivism was propounded. One of the weaknesses of the theories of behaviorism, cognitivism, and constructivism in explaining e-learning, as argued by Siemens (2004), is the notion that learning principally happens in the human mind. Through the theory of connectivism, Siemens (2004) opined that non-human appliances have the capability to learn and acquire knowledge. Connectivism also explains the learning that happens in learning communities formed by individuals and devices connected to each other by means of technologies. One of the technologies that enables people and things to form learning communities is the IoT (internet of things). IoT is described as the network of digital devices embedded with internet, thereby enabling communication among people and things (Mukhopadhyay & Suryadevara, 2014). Connectivism, however, is criticized for being a “new theory” yet having its tenets in existing theories, with the claim that non-human appliances can learn remaining contentious (Goldie, 2016).

Another widely used theory in studies that seek to understand online learning is the community of inquiry (CoI) framework by Garrison et al. (2000). CoI consists of three components which are types of presence in online classrooms. These are teaching presence (how the online instruction is designed to support cognitive presence and social presence), cognitive presence (how learners make meaning in online classrooms), and social presence (the sense that individuals have of being in a social setting or part of a group). The three types of presence are used by researchers as a framework to study how online learning is experienced. Nagel and Kotzé (2010) found in their study that the three components of CoI can be measured and are correlated to the quality of teaching and success rates especially in big classes. The teaching presence in particular is believed to have greater influence on how the other two types of presence (cognitive and social) are experienced. Instructors can develop an effective teaching presence by giving prompt feedback. Through this, learners feel valued and supported, causing them to be receptive to instruction (Cox et al., 2015). The teaching, cognitive, and social presence can be designed by instructors in ways that build effective and productive discussions in online classrooms (DeNoyelles et al., 2014). Immediate feedback, audio-recorded feedback, peer mentoring, and discussion forums were found to enhance the teaching, cognitive, and social presence in asynchronous online classrooms (DeNoyelles et al., 2014).

Despite the usefulness of CoI to understand the experiences of learners in online classrooms, there is evidence that the framework may not be sufficient by itself. Anderson (2011) considered CoI to be one of the components in an e-learning environment. Figure 1 shows a model of e-learning by Anderson (2011) that puts emphasis on the interactions among the different participants and components that make learning possible in online classrooms. The interactions are among learners (collaboration), learners and teachers (CoI), and teachers and content (teachers developing learning activities). Interactions are also among learners and content (learning independently/learning presence), content and content (programmed and automated interaction between information sources), and teachers and their community of practice/stakeholders. At the core of the model of e-learning by Anderson (2011) are the learners, the teacher, and the content.

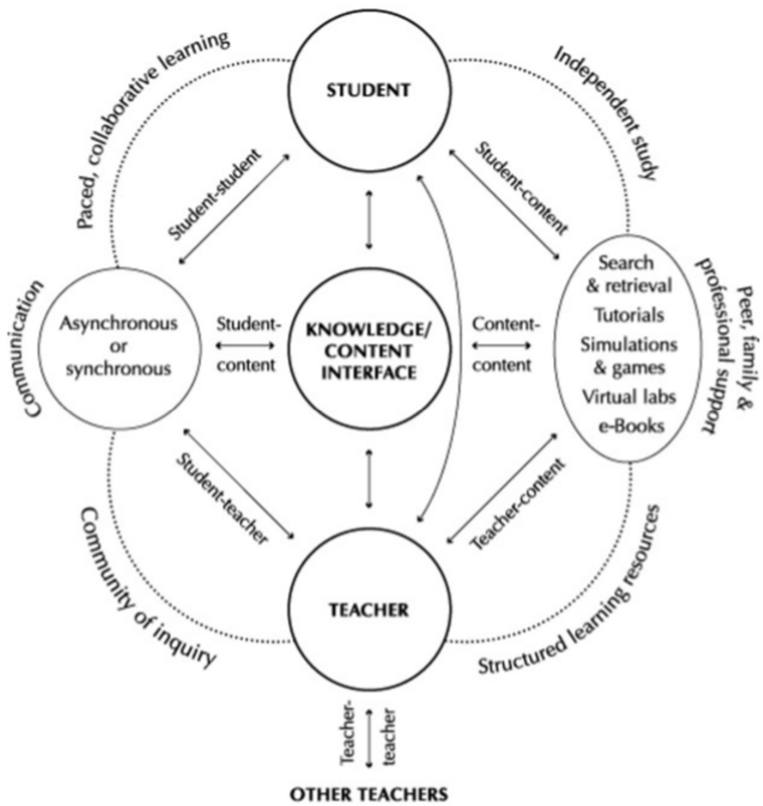

Figure 1. A model of e-learning (adapted from Anderson, 2011, p. 49)

Although the CoI framework continues to be used to explain important factors that influence online learning, what is apparent is that there are other variables that need to be taken into account in addition to the teaching, cognitive, and social presence (Kaul et al., 2018). For example, Shea et al. (2012) described another form of presence that explains how learners can learn through discovery and independent work. They called it the learning presence, and Anderson (2011) showed that it results from the interaction between students and content, as seen in Figure 1. Significant work seeks to build on the CoI framework in order to understand other variables that are present in online classrooms. Learner satisfaction with the e-learning experiences is one of the factors that can be measured and has to be taken into account in virtual learning environments (Liman Kaban, 2021). In support, Lee et al. (2021) asserted that learning satisfaction is achieved by balancing the three types of presence in online classrooms and two more factors, which are the perceived ease of use of online tools and content quality. Figure 2 shows how the establishment of effective teaching, cognitive, and social presence with sufficient content quality and the perceived ease of use of the online tools can result in learner satisfaction with e-learning experiences.

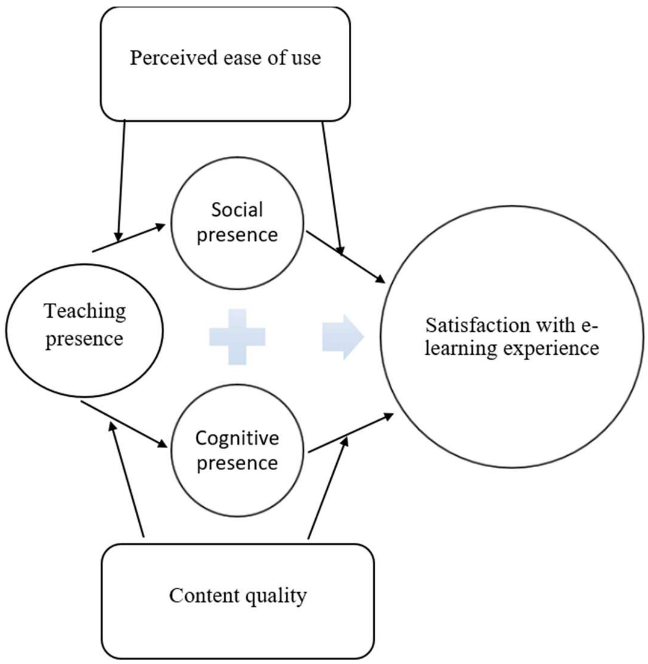

Figure 2. An extended community of inquiry model (adapted from Lee et al., 2021, p. 3)

The realization that the CoI framework may not sufficiently explain all the factors that are at play in online classrooms has resulted in other researchers combining it with other theoretical frameworks. For example, Radovan and Kristl (2017) combined CoI with the unified theory of acceptance and use of technology (UTAUT) and confirmed that more factors need to be considered when using learning management systems (LMSs) such as Blackboard and Moodley. These factors include the perceived ease of use of the tools, instructor acceptance of the LMS, and the characteristics of the tools in the LMS. For this study, it is acknowledged that the frameworks discussed above are useful in understanding the complexity of e-learning. They can be used to understand how STEM practical work can be facilitated for learners in remote classrooms and can provide a framework for the prospects and future directions for STEM practical work in remote classrooms.

METHODOLOGY

Research Design

In this study, an interpretive paradigm and a qualitative meta-analysis design were used to explore how STEM practical work can be taught in remote classrooms. Literature reviews are one of the research methods used when studying technologies used to facilitate practical work in STEM classrooms. Similar studies have reviewed this. Sırakaya and Alsancak Sırakaya (2020) reviewed the use of augmented reality (AR) in STEM education. In addition, Kefalis and Drigas (2019) reviewed literature to determine the latest trends in web-based and online STEM education. For this study, the qualitative meta-analysis was guided by the steps of the preferred reporting items for systematic reviews and meta-analyses (PRISMA) by Tawfik et al. (2019). PRISMA is mostly applied in medical research (Tawfik et al., 2019) and the method enhances the transparency, validity, and reliability aspects of literature review studies by making them systematic (Liberati et al., 2009).

Data Sources

In determining the preferred items for reporting, a pre-search of items on the topic was conducted in order to select the database to be used in the search. The Google Scholar search engine was preferred because it was easily accessible to the researcher. In addition, the publication dates for the search were purposively determined to be between 2017 and 2021 (5 years), presenting a glimpse of STEM practical work practices immediately before and during the first two years of the COVID-19 pandemic. This decision was made with the aim of gaining insights on the implementation of STEM education practical work just before and during the pandemic.

Data Collection

In preparation for data collection based on the document analysis technique, a synthesis question was formulated as: How can STEM practical work be taught in remote classrooms? The following search terms were used: *STEM practical work + STEM education in remote classrooms + Practical work in remote classrooms + STEM education in online classrooms + STEM education in virtual classrooms + Virtual practical work + Teaching STEM and COVID-19 + Practical work and COVID-19*. While the search terms encompassed the inclusion criteria of the searched items, publications which were not between 2017 and 2021 were excluded. In addition, publications that focused on one discipline (e.g. science) with no reference to STEM education were excluded. Publications that focused on STEM education in virtual learning environments without reference to practical work were also excluded. Figure 3 shows how a total of 50 articles were screened and selected, as guided by Tawfik et al. (2019). A total of 15 articles were obtained and analyzed through thematic content analysis techniques.

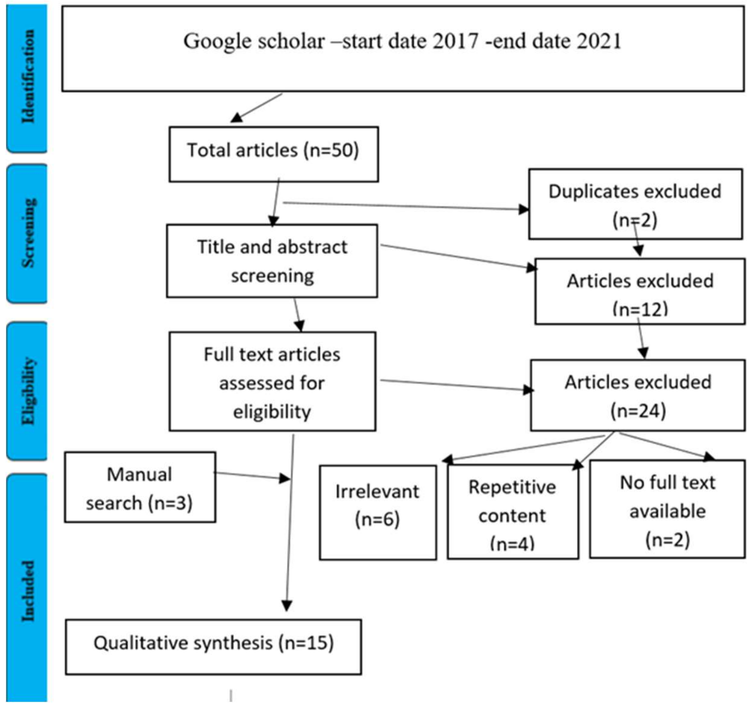

Figure 3. Flow diagram of article selection and screening

Data Analysis

Thematic analysis was used to analyze the content of the selected publications. Nowell et al. (2017) applauded thematic analysis for being flexible, because it aligns with multiple paradigms in qualitative research. The articles selected were divided into two categories, those published before and during the COVID-19 pandemic, respectively, as shown in Tables 1 and 2.

The pre-COVID-19 publications consisted of one journal article, five conference proceedings, and two book chapters. In these publications, practical work in remote classrooms was enabled by the use of VR, remote laboratories, e-learning technologies, and educational robotics.

The mid-COVID-19 publications consisted of six journal articles and one conference proceeding. In these studies, practical work in remote classrooms was enabled by the use of VR, remote laboratories, AR, and take-home DIY experiments.

Table 1. List of publications conducted before the COVID-19 pandemic

Literature reviewed	**Journal/ conference/ book chapter**	**Technology / approach to enable remote learning**	**Tools to enable practical work**	**Content**
Degboe et al. (2018)	*International Conference on e-Infrastructure and e-Services for Developing Countries*	VR	Combined the web of things (WoT) with web-based application	Developed a web-based application that allowed learners experiential learning through virtual field trips and to engage in collaborative practical work.
Scanlon et al. (2019)	Educational visions: Lessons from 40 years of innovation (book chapter)	VR e-learning TV broadcasts Residential schools	Take-home DIY experiments, VR simulations and modelling, TV-broadcasted demonstrations, and physical environments complementing virtual presentations	Showed ways in which an open university facilitated practical work activities for its STEM students. The methods include the use of virtual laboratories contained in take-home DIY kits.
Wei et al. (2019)	*Disciplinary and Interdisciplinary Science Education Research*	Remote laboratories	Computers and worksheets	Compared interactions in face-to-face physical laboratories and remote laboratories and found interactions to be limited in the latter.
Lal et al. (2018)	*ASEE Annual Conference and Exposition, Conference Proceedings*	Remote laboratories	Computers and worksheets	Observed that if the laboratory work focuses purely on technical aspects, learners may find it difficult to develop other social skills such as

				collaboration and teamwork.
Togou et al. (2018)	*International Conference on Education and New Learning Technologies (EduLearn)*	Remote laboratory	Digital fabrication	Through digital fabrication, learners designed objects that they sent remotely for fabrication.
Plaza et al. (2017)	*2017 IEEE Global Engineering Education Conference (EDUCON)*	Educational robotics	Take-home DIY robots	Proposed the use of educational robotics at home in addition to their use in remote laboratories and STEM classrooms. Claimed the use of robotics provides an easy alternative to teach STEM and it turns the learning of boring concepts into exciting experiences.
Lynch and Ghergulescu (2017)	*2017 IEEE Global Engineering Education Conference (EDUCON)*	VR	Virtual laboratories	Found that the use of virtual laboratories cuts on teachers' preparation time and provides immediate feedback to learners, thereby keeping learners motivated.
Benitti and Spolaôr (2017)	Robotics in STEM education	Remote laboratories	Digital fabrication	Learners designed 3D objects that they digitally fabricated in remote laboratories.

Table 2. List of publications conducted during the COVID-19 pandemic

Literature reviewed	**Journal/ conference/ book chapter**	**Technology/ approach to enable remote learning**	**Tools to enable practical work**	**Content**
Gya and Bjune (2020)	*Ecology and evolution*	Take-home DIY experiments	Experiment kits	The DIY experiments increased learner autonomy in processes such as hypothesis formulation and design of the experiments to complement the theory learnt virtually.
Aji and Khan (2021)	*2021 ASEE Virtual Annual Conference Content Access*	VR	3D visualizations	3D VR technologies were used to teach the introductory math, biology, physics, aerospace engineering, and electrical engineering courses during the COVID-19 pandemic.
Abouhashem et al. (2021)	*Sustainability*	VR Synchronous and asynchronous PowerPoint presentations	Videos, interactive quizzes, innovative games, and online simulations	Developed a VR STEM course based on games, simulations, and hands-on activities for middle school learners taught during the vacation during the COVID-19 pandemic.
Mystakidis et al. (2021)	*Education and Information Technologies*	AR	3D visualization mobile tools with a camera superimposed on	Conducted a meta-analysis of studies conducted on the use of AR in STEM education of studies from 2010–2020. The studies outlined a taxonomy of

			components and landmarks in the real world	instructional strategies used to apply AR in STEM education.
Chu et al. (2021)	*Research in Science & Technological Education*	VR	Mobile learning	Implemented an innovative use of smartphones as an experimental tool that replaced conventional laboratory work and a way of overcoming distance learning during the pandemic.
Lal et al. (2020)	*European Journal of Engineering Education*	Remote laboratories	Computers and worksheets	Compared students' perceptions of worksheets in face-to-face (before the pandemic) and remote laboratories (during the pandemic).
West et al. (2021)	*Educational Technology Research and Development*	VR	Web-based and online laboratories	Explored how the five inquiry phases for online laboratories, namely orientation, conceptualization, investigation, conclusion, and discussion, can be implemented in VR-inquiry activities.

FINDINGS AND DISCUSSION

The findings of the study are discussed under two themes. These are: (i) methods used by teachers to teach STEM practical work in remote classrooms and (ii) prospects and future directions for STEM practical work in remote classrooms.

Methods Used by Teachers to Teach STEM Practical Work in Remote Classrooms

The methods used by teachers are discussed under five categories. These are: (i) STEM practical work in VR environments, (ii) STEM practical work in remote laboratories, (iii) STEM practical work in AR environments, (iv) use of take-home DIY STEM practical work kits, and (v) use of educational robotics to teach STEM practical work.

STEM practical work in virtual reality environments

VR STEM practical work environments can be computer-based applications or web-based and online applications. Degboe et al. (2018) set up a remote practical work platform for STEM using WoT and the WebRTC Kurento multimedia server. The platform enabled the teacher and learners to go on virtual trips to conduct practical work. This VR platform was useful because learners had not been able to conduct a real-world trip as part of a biodiversity course due to some inhibiting factors. Therefore, the VR trips were an effective alternative way of conducting the requisite field trips. In this case, the VR technology served as a solution to challenges experienced by teachers and learners in STEM practical work. Similarly, Lynch and Ghergulescu (2017) lauded the use of virtual laboratories because they free up time for teachers. They reduce the time needed to prepare and there is no need to clean up at the end of each practical work session. Dogboe et al. (2018) noted that the use of WoT technologies enables connection among the learning community members of the VR-enabled practical work activities, thereby improving opportunities of learner-learner and learner-teacher interactions. The authors suggested the use of virtual field trips and the sharing of resources on a collaborative platform enabled by the WoT technologies. One of the observed advantages of VR-enabled STEM practical work is that they provide immediate feedback to learners, thereby keeping learners motivated (Lynch & Ghergulescu, 2017).

The COVID-19 pandemic brought another dimension to the challenges experienced in STEM practical work. Remote learning was put in place as a measure to counter the emergency. In order to ensure the experiential learning afforded by practical work, Aji and Khan (2021) used 3D VR technologies to teach introductory math, biology, physics, aerospace engineering, and electrical engineering courses. The 3D visualizations helped the students in conceptual understanding. Students were engaged through the learner-content interactions. Similarly, in response to COVID-19, Abouhashem et al. (2021) developed a VR STEM course based on games, simulations, and hands-on activities for middle school learners taught during school vacations remotely. In developing the materials, the teachers found the process to be engaging and challenging. Chu et al. (2021) used mobile learning as an alternative to physical classroom STEM practical work instruction that was not possible during the COVID-19 pandemic. Smartphones were used innovatively to engage learners in practical work by means of STEM practical work VR kits which the learners used to conduct experiments on the topic of sound.

STEM practical work in remote laboratories

While exploring the idea of facilitating practical work in laboratories that are remotely controlled by the learners, Lal et al. (2018) observed in their study that if the laboratory work focused purely on technical aspects, learners may find it difficult to develop social skills such as collaboration and teamwork. In a follow-up study inspired by the COVID-19 pandemic, Lal et al. (2020) compared students’ perceptions of worksheets in face-to-face physical laboratory work and remote laboratories. In both environments, students valued the laboratory instruction sheet because it gave them a sense of the student-equipment interaction. However, Lal et al. (2020) recommended that the instruction sheet should be adapted accordingly to each laboratory environment. Wei et al. (2021) conducted a similar study in which they compared the interactions observed in physical laboratory work environments (before the pandemic) and those experienced in remote laboratories (during the pandemic), and noticed that interactions in the latter were limited. The finding on limited interactions by Wei et al. (2021) aligns with the observation made by Lal et al. (2018) that students may struggle to develop social skills in remote laboratories.

STEM practical work in augmented reality environments

A rise has been observed in the use of AR in schools. This observation was made by Mystakidis et al. (2021) after conducting a meta-analysis of studies (2010–2020) focusing on the use of AR in STEM education. Based on the meta-analysis, Mystakidis et al. (2021) outlined a taxonomy of instructional strategies used to apply AR in STEM education. AR allows learners to have a 3D visualization of STEM phenomena. It also brings to life objects that are invisible, abstract, and complex through the use of vision technologies such as mobile devices superimposed on real-world features and landmarks. If used in remote laboratories, this technology may enhance the learners' experiences. After arguing that not all in-person laboratory activities can be replicated in online laboratories, West et al. (2021) recommended that the online laboratories should be designed to be more authentic by, for example, combining the VR and AR technologies.

Use of take-home DIY STEM practical work kits

One of the strategies that can be used to facilitate STEM practical work is the use of take-home DIY experiments. The materials are prepared as kits given to learners and used together with worksheets and other virtual interactions. In this case, the learners have physical materials that they use to conduct experiments and write reports. One distance education university used this approach as one of the ways to make sure students conducted STEM practical work activities (Scanlon et al., 2019). The university used this approach together with other strategies, which were TV broadcasts, VR simulations, modelling, and residential periods in which students did in-person laboratory work. During the COVID-19 pandemic, Gya and Bjune (2020) and Mystakidis et al. (2021) explored the use of take-home DIY practical work kits. These kits can be computer-based or other physical hands-on activity materials and equipment. The DIY practical work increased learner autonomy in processes such as hypothesis formulation and experiment design, and complemented the theory learnt virtually (Gya & Bjune, 2020).

Use of educational robotics to teach STEM practical work

Robotics is one area where all the STEM disciplines can easily be incorporated, supports problem-solving and teamwork, and can be used in extra-curricular activities (Plaza et al., 2017). In a study by Benitti and Spolaôr (2017), robotics was used by teachers to integrate technology and engineering as a way of applying science and mathematics to real-life problem-solving. Robotics can also be prepared as take-home kits. Plaza et al. (2017) proposed the use of educational robotics at home in addition to their use in remote laboratories and STEM classrooms. In their study, Plaza et al. (2017) claimed that the use of robotics provides an easy alternative to teach STEM and that it turns the learning of boring concepts into exciting experiences.

Prospects and Future Directions of STEM Practical Work in Remote Classrooms

The five instructional strategies discussed above can be used by teachers to facilitate STEM practical work in remote classrooms. The review of the purposively selected literature showed that remote practical work facilitation strategies in STEM classrooms were in existence before the inception of the emergency remote learning caused by the COVID-19 pandemic. The possibilities for practicing STEM practical work are closely related to the digital technologies characterizing 4IR environments. Goldie (2016) asserted that as the digital technologies are fast emerging, so are new ways of communication. Through the theory of connectivism, Siemens and Conole (2011) affirmed that the new ways of communication influence the teaching and learning processes. Notably, the Web 2.0 tools and the connectivity enabled by IoT and its WoT branch enable easier communication among humans and things. Anderson (2011) (see Figure 1) showed that technology-enabled learning results from different types of interactions, which include teacher-learner, learner-learner, learner-content, teacher-content, and content-content interactions.

While remote learning was considered a component of distance education environments (e.g., Anderson [2011] opined that online learning is a form of distance learning), and undervalued and underutilized in schools, the COVID-19 pandemic showed that this instructional mode has value and can be used. A distinctive tenet of the emergency remote learning during the COVID-19 pandemic is that the teachers and leaners were not co-located and the learners were learning from home instead of the prepared environments, such as classrooms, laboratories, and workshops. After years of practice, it would be expected that the prepared learning environments and instructional strategies used by teachers conformed to the prescriptions of the STEM curricula in terms of the materials and equipment needed to conduct practical work activities. Therefore, in some cases, the sudden unavailability of the prepared environments for STEM practical work resulted in the abandonment of this instructional strategy (Cottle, 2021; Makamure & Tsakeni, 2020). However, there is evidence that ways to implement STEM practical work were explored through improvisation, use of technologies, and change of teaching strategies (Abriata, 2021).

Digital technologies have played an important role in the implementation of STEM practical work in remote classrooms. Notably, the use of remote laboratories aligns with the tenets of the theory of connectivism (Goldie, 2016; Siemens, 2004; Siemens & Conole, 2011) in that they are based on the notions that knowledge and learning do not reside in humans only, but that machines can also learn and construct knowledge. Consequently, digital tools such as AR, VR, WoT; web-based applications such as online laboratories and simulations, interactive quizzes, innovative games, videos; and many similar tools provide alternative STEM practical work environments (Abouhashem et al., 2021). However, as Treagust et al. (2016) explained, it is important to understand with what and whom the learners interact, how they interact, and for what purpose. The model of e-learning in Figure 1 seems useful when teachers are planning for the types of interactions to enable STEM practical work in remote classrooms. From the findings of this study, independent learning through learner-content interactions (Anderson, 2011) was one of the strategies found useful in remote classrooms. Learners can interact with practical work kits and resources such as materials and equipment, robotics kits, VR and AR kits, WoT tools, online laboratories, computers, and worksheets. These interactions complement other virtual interactions between the teacher and the learners and among learners. Social interactions need to be ensured since they enable collaboration and teamwork and increase social presence (Mujkanovic et al., 2012).

Both the theory of connectivism (Siemens, 2004) and the model of e-learning by Anderson (2011) underscore the importance of interactions, communications, collaborations, knowledge sharing, and knowledge co-construction during remote learning. These communication processes for remote learning occur in a CoI. Teachers have a further task to ensure a CoI by designing and implementing the teaching, cognitive, and social presence commensurate to effective learning (Anderson, 2011; Garrison et al., 2000; Lee et al., 2021). In addition, the fostering of a learning presence is also important (Shea et al., 2012) because it enables independent learning through learner-content interactions (Anderson, 2011). As learners conduct STEM practical work in remote classrooms, independent learning enables them to interact with the learning materials. However, Lee et al. (2021) added that an effective CoI needs to enable quality content and ensure that the tools used are perceived as easy to use by learners and teachers. Consequently, this study recommends that more studies need to be conducted on what constitutes quality content in remote STEM practical work and on how to develop tools that are perceived as easy to use in the remote classroom CoI. In addition, more tools that respond to STEM curriculum needs at different school levels need to be developed.

CONCLUSION

This study explored how STEM practical work can be taught in remote classrooms. From the literature reviewed, five strategies were extracted. These are: STEM practical work in remote laboratories, STEM practical work in VR environments, STEM practical work in AR environments, use of take-home DIY STEM practical work kits, and use of educational robotics to teach STEM practical work. These strategies help in developing STEM skills such as digital literacies envisioned for citizens to possessA in the 21st century environments through STEM education. These strategies can be used in combination and as tools for other strategies. For example, the take-home DIY practical work kits can contain educational robotics, VR and AR tools, equipment, materials, and chemicals. These strategies are enabled by the ability to connect things and people through digital technologies prevalent in 4IR environments. Although in remote learning, teachers and learners are not co-located, the social interactions and human-things interactions (teacher-learner, learner-learner, and learner-practical work materials) are made possible by connectivity technologies.

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