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Leveraging Simulators and Virtual Labs for Stem Education: A Digital Approach to Science and Health Education

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Abstract

In this digital era of constantly evolving education, STEM education has been transformed by integrating digital tools like Virtual Labs and Simulators, particularly in the field of Health and Science. These tools, which are AI-enhanced, provide a practical experience for students, increasing student involvement, promoting a deeper understanding of complex concepts using a digital approach in a safe, cost-effective, and controlled environment. The Practical and Critical skills of students can be improved when they use Simulators and Virtual Labs to carry out experiments without the requirement for physical equipment or space, to understand and explore the phenomenon behind it. In the case of Science and Health education, the use of digital tools is beneficial where real-time experimentation is inaccessible, costly, and hazardous. Students get an opportunity to get hands-on experience using simulators that can replicate intricate and complex processes like Biological medical procedures, Chemical reactions, and Real-time phenomena in Physics. These AI-empowered tools can give real-time, immediate feedback and personalized learning experiences as per each student's needs. Leveraging STEM education by integrating these modern technologies into the curricula for a more advanced, engaging, and active learning for students, making complex topics easily understandable and interesting, is the need of the hour. With the escalation of digital learning, Simulators and Virtual Labs tend to meet the demands, making learning exciting by enhancing the students' learning outcomes in Science and Health education.

Keywords: Simulators, Virtual Labs, STEM Education, Digital Learning, Science Education, Health Education, AI in Education, Interactive Learning, Personalized Learning.

Introduction

In STEM education, where the concepts are very complex, unlike in the olden days, in these present days of technology boom, topics are taught using simulators and virtual labs to enhance understanding and learning. Demonstrations can be done using smart technology to make concepts feel lighter, and students can have a real-time learning experience. AI-powered tools aid in giving a practical experience to the students in the field of Science and Medicine, where experiential learning is very crucial, as they will have to practically implement the knowledge gained when they begin their professional career. Educational institutions must integrate these advanced digital learning tools into the curriculum to give students a digital learning experience. By amalgamating simulators and virtual labs in the teaching process, educators can create an atmosphere that makes learning fun and interesting, enhancing the learning process. STEM education promotes an interdisciplinary approach to teaching where all concepts related to Science, Technology, Engineering, and Medicine are combined to enhance understanding and critical thinking skills. Students get a hands-on experiential learning experience by using these digital tools, which will foster their analytical thinking skills. STEM education learning strengthens the cognitive skills in students, boosting their problem-solving capacity, thus improving creativity in them. The exploration abilities in trainees will be enhanced when they are exposed to the simulated digital tools, which generate an interactive version of a context they are learning about, for better understanding. Students who are training in the field of health and medicine will find it very helpful, as these AI tools will help them to have a practical approach to physically performing the process in an environment that replicates a real-time scenario.

Evolution of Stem Education

STEM Education, which includes the subjects of Science, Technology, Engineering, and Mathematics, is considered the core subject of education. It has now branched out and integrated fields like Social Science, Environmental Science, and Computer Science into the mainstream. In higher education, STEM has enhanced different skills in students related to the nature of the subject, like Science and Technology strengthened the practical aspects in education through demonstrations and lab activities. Students' analytical

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thinking and problem-solving skills are enriched by Engineering. In STEM education, Mathematics focuses on the logical reasoning skill development in individuals. Computer Science that has been integrated into STEM education aids students in sharpening their computer-based computational skills, Environmental Sciences provides students with the required knowledge about the environment around them and stimulates sustainable practices for a greener planet, whereas Social Science raises awareness of the society and its issues (Zhan & Niu, 2023) [34]. STEAM refers to the integration of the Arts and Humanities into STEM education, which enables students' artistic ability and creativity to be inculcated in their engineering and science practices.

Integrating EdTech in Science and Health Learning

Integrating modern education technology into the classroom environment by utilizing interesting and engaging methods like Virtual labs and Simulators is referred to as EdTech. The amalgamation of EdTech in education upskills students' tech-savviness, equipping them to meet the growing professional demands for a technologically enhanced world. In today's scenario inclusion of digital tools in science learning has become mandatory to make learning experiences interesting and captivating for students. These digital tools have also simplified complex concepts, making them easy to understand, thus enhancing students' learning outcomes. (Ishman *et al*., 2007). Digital tools used in the field of Medicine and Health Sciences have incorporated practical and hands-on learning into the educational process, enabling students to be exposed to a learning environment that allows trial-and-error learning. Students can learn in a safe environment through problem-solving methods, boosting their confidence when it comes to real-life experiences (Alrashed *et al*., 2024) [3].

Virtual Labs and Simulators – An Overview

Virtual Labs: Utilizing Digital Space to Recreate Experiments

Virtual Labs mimic the real-time laboratories, making learning easily accessible and engaging. V-Labs are widely used nowadays, which inculcate e-learning techniques in the field of Science, Medicine, and Health Sciences without human-to-human interaction. Complex processes and experiments can be carried out in a digital risk-free environment without the danger of handling harmful chemicals, reducing the chances of hazardous disasters (Essam & Essam, 2024) [8]. In the case of distance learning, where the students cannot access real-time laboratories or physical resources, virtual labs aid in learning at their own pace and convenience. Scientific concepts can be learned by conducting virtual experiments, imaging, and visualizing microscopic visuals, and conducting virtual complex medical procedures to enhance learning. In STEM education, Virtual learning plays an important role by taking the learning experience to the next level when students can access complex concepts through a virtual environment using virtual apparatus and instruments, which then assists them to perform well in a real-time scenario on their professional front (Virtual Laboratories in STEM Higher Education: A Scoping Review | Nordic Journal of Systematic Reviews in Education, n.d.-a). Virtual labs help in personalized learning, which meets the needs of the learning ability of every individual. Virtual labs save the time that is used in the setup of the apparatus and the clean-up after the process is complete. Gathering data, analyzing the data, and interpreting the data is also possible with tools integrated in Virtual labs. Using virtual labs also aids in giving immediate feedback to the students regarding the process they are carrying out, enhancing their learning abilities and individual experiences. In medicine, Virtual Labs help students carry out dissection on virtual samples, aiding in a practical learning experience of human and animal anatomy.

Simulators Explained: Interactive and Immersive Learning Tools

Simulators are used to create a realistic experience of a real-life scenario in a digital environment. Scientific contexts and concepts that are difficult to perform in real-life scenarios, like chemical reactions dealing with harsh chemicals, observing climate change effects, etc, can be carried out by the use of Simulators. Scientific skills like problem-solving, data collection, and analysis can also be taught. Various illustrations in the form of videos, animations, and games etc, can be used in simulators for a better demonstration of concepts, making learning interesting and engaging (Simulations to teach complex scientific concepts online?, 2023). Complex concepts can be visualized and made accessible by allowing learners to interact, making learning engaging and motivating to learn at their own pace, meeting the need for personalized learning. The process of learning is made fun by integrating gamified elements like setting goals, easy-to-difficult levels, with a reward for each level that is cleared. Immediate feedback given helps the learned to reflect on their learning outcomes and rectify them for a better understanding of the concept. The use of simulators encourages students to use prior knowledge to learn new and different scenarios. Quizzes, Instructional material, Videos, etc, can be incorporated in simulators. In simulators, students are allowed to analyze, manipulate, and draw their conclusions about a context they are dealing with. Simulators are also designed to suit the requirements of students of various age groups.

V-Labs and Simulators enhance students' skills and knowledge, and make education and learning more interactive and productive.

Applications of V-Labs and Simulators in the Field of Science

Biological Simulations and Virtual Dissections

Biological dissections that are done in the traditional setup require students to physically cut up organisms, like human parts and animals, to learn about the concept being taught. Virtual dissections make use of digital tools and virtual organisms to carry out the dissection process (IXRLabs, n.d.), which makes it easy to learn about the physiology and internal structures by carrying out the dissection multiple times without needing a new sample every time. This can save the need for having many human or animal samples, which are difficult to arrange. Students can carry out the process many times till they have clarity about the concept. Examples – PraxiLabs is a virtual lab to learn science concepts (Essam & Essam, 2025) [9], LabXchange is also a virtual lab simulation to understand various biological concepts, etc (LabXchange, n.d.). LabSims (Lab Simulation Software - Virtual Lab Solutions - LearnSCI, n.d.)

Chemistry Cloud Labs

These Chemistry cloud labs mainly aid in conducting experiments practically from anywhere, from a remote location, by getting access to science apparatus and instruments. Experiments are done by issuing commands over

the internet, which are then run in a highly sophisticated central facility. The individual has full control over every single step of the experiment conducted, from which chemical to use to how much chemical to add for the reactions, processing the data, interpreting, and analyzing the results. Cloud Labs use robots to conduct experiments, which helps in reducing human error and saving time for the user. They increase efficiency in the process and also scale up flexibility. Cloud Labs are cost-effective as they reduce the cost of conducting experiments using traditional setup equipment. These labs are accessible to a wide range of students and researchers who find it difficult to access the Lab areas. Quantum chemical simulations are used to make experiments carried out more effective and accurate. Users can process large amounts of data and explore complex chemical experiments. A large number of chemicals can be screened quickly and accurately. Hands-on experiments can be carried out in a safe, controlled, and confined environment, paving the way to innovation and fast processes. Example – Emerald Cloud Lab (Emerald Cloud Lab: Remote Controlled Life Sciences lab, n.d.).

Physics Experimentation - A Simulation-based Approach

Simulations are an approach in which Physical concepts, phenomena, and real-time experiences can be carried out using computer-designed physics experiments. The use of simulators makes content accessible for students in remote places. Simulators are designed such that they can be used to carry out virtual experiments remotely in a controlled environment without any physical space constraints. They bring down the cost of conducting complex experiments using sophisticated apparatus physically, thus saving time too. Simulators provide access to conditions during the experiment, like temperature and pressure, without the danger of hazards. They allow better visualization of complex processes (Google Search, n.d.), leading to a better understanding of concepts. Simulators can give insights into experimental mechanisms, hypothesis testing, and analysis of an experimental design. Some experiments that Simulators are used to visualize are particle collision, chemical reactions, interaction between molecules and atoms, transfer of heat, and flow of fluid etc. Thus, the use of simulators makes learning easy and accessible, concepts are simplified due to the visual representations, which makes concepts understandable. When students use simulators, they can repeat the experiments several times without the apparatus getting heated up. As these tools can be accessed by students at any time, they can learn at their own pace and convenience. Example – PhET (Physics Education Technology) – Simulators for students to carry out Physics experiments using simulators which integrate graphics, click and drag options, manipulate controls, etc (PHET Interactive Simulations, n.d.).

Application of V-Labs and Simulators in the Field of Health and Medical Education

Simulated Scenarios - Training of Healthcare Professionals: There has been an advancement in the field of Healthcare and Medicine by integrating the use of simulators in STEM education in this technological era. Future healthcare practitioners and professionals who are in the learning process can use simulators to learn and refine their skills. Individuals can practice their medical skills on simulators without any patient being harmed during the learning process. Technical and non-technical skills like CPR, first aid, incubating infants, operating biomedical instruments, etc, can be learned first on simulators, which leads to perfection. Training facilities provided using simulators can give rise to an interdisciplinary approach to education where students are trained by experts from many disciplines working as a team. Medical complexities and situations in real-life scenarios (Elendu *et al*., 2024) [6] can be taught to medical students using these tools, which in turn enhances their confidence and readiness to deal with these situations. Use of simulators during the training process improves the overall patient care outcomes when students begin to practice as interns, decreasing the chances of errors. Students under training can be updated with the latest technologies by using simulators, which can aid them in learning the latest complex, sophisticated medical processes with ease and convenience, helping them to perfect them as they can repeat the process multiple times to become experts. This exposure that the healthcare trainees get to the virtual world, which exposes them to realistic experiences, enables them to become professionals and assists them in making decisions depending on the scenario of the case. Examples - Laerdal's SimMan 3G PLUS simulator – This simulator is used to train students in various medical procedures like BP checking, IV administering, tube intubation, monitor breathing function, trauma, CPR, etc (Laerdal Medical, n.d.). METIman (CAE Healthcare) to train students with defibrillation, cardioversion, and pacing (WHAT IS METIman (CAE Healthcare) - *Google Search*, n.d.). CAE Healthcare's iStan is a wireless simulator that replicates the physiology of a human and is used in training students in the field of nursing and emergency first aid medicine training, like CPR, trauma, asynchronous Mechanical ventilation, cardiac training, etc (CAE iStan, 28223).

Physiology Labs and Virtual Anatomy

Students training in the medical field get a hands-on exposure in the field of Virtual Anatomy and Physiology Labs, with the integration of AI tools like simulators. These simulations can replace expensive equipment, which would otherwise be very expensive to train the students. Virtual anatomy can be practiced by students repeatedly to get perfect at the procedure without the need for a fresh sample every time, thus saving the cost for the institution. Several scientific methods like graphical representations, formulas, chemical reactions, dissections, etc, can be carried out easily using simulators. Pre-lab training using simulators can be considered in microbiological lab activities to enhance the preparedness and understanding of the concepts for students (Science Interactive, 2023). To bring about perfection in students, experiments can be run and re-run several times in a virtual mode. Critical analysis skills of students escalate as they learn to integrate real-life scenarios with course content and objectives. Examples – Labster – used to teach science in higher education (Labster | Virtual Labs for Universities and High Schools, n.d.) making learning engaging, interactive, and accessible (Google Search, n.d.-c). The Anatomage Table helps students to learn about the human anatomy, permitting them to conduct virtual dissection. It consists of a huge touchscreen interactive display that gives a digital visualization of a 3D life-size cadaver of a real human (Anatomage, 2025) [4]. Learners can manipulate and dissect anatomical body structures, explore human anatomy, and gain a real-life experience (Ahmed, 2023) [2].

Surgical Simulators and Diagnostic Purposes

Medical college students and surgeons under training are

given training using simulators for their respective training procedures, avoiding the use of cadavers or animals. This training aids in enhancing the eye-hand coordination (Wikipedia contributors, 2023) and the ability of students to work with 3D images using a 2D screen to monitor and guide them before conducting the procedure on live human patients. These simulators constantly give feedback to the students regarding the procedure, thus helping them to improve and aiding perfection in the procedure. Students can manipulate the procedure based on the feedback provided by the simulators. Simulators play a vital role in training surgeons in laparoscopic surgery procedures, as these operations are conducted by making a small incision instead of a big cut on the body, and simulators make it possible to get a 3D graphical image of the internal organ on the screen to train the surgeon to perform the procedure. There are many modules of laparoscopic simulators that train individuals in various procedures like basic level skills, General surgery, Suturing techniques, Bariatric surgery, Colorectal surgery, Gynaecology surgery, thus aiding in experiential learning (Agha & Fowler, 2015) [1]. Examples - Lap Mentor by Simbionix (3D Systems) – used to train surgeons in laparoscopy operations (Medical, n.d.). 3D Organon educational ultrasound simulator aids in training learners in ultrasound techniques, including scanning techniques, visual settings, etc. It does not need a mannequin, and a VR controller acts as an ultrasound probe (Medis Media, 2025). The da Vinci Surgical Simulator enables students and surgeons to learn and practice surgical procedures with precise details (Intuitive Surgical, n.d.). VR Simbionix (by 3D Systems) are simulators used to train individuals on procedures like GI endoscopy, bronchoscopy, etc (More Than Simulators, 2024). NOELLE (Gaumard) and Lucina (CAE Healthcare) simulators assist in coaching students on how to conduct obstetric procedures, routine normal childbirth, and caesarean deliveries (Nasco Healthcare, n.d.). EyeSi (VRmagic) simulator helps students to learn how to conduct Ophthalmic surgeries like vitreoretinal procedures and cataract operations (Eyesi Surgical, n.d.). The URO Mentor simulator, developed by Simbionix, is a simulator that teaches learners endourological techniques like ureteroscopy and cystoscopy. It enables students to manipulate and learn procedures like TURP (transurethral resection of the prostate), manipulating a kidney stone, stricture treatment, etc. These tools provide students with feedback as they practice to improve their learning skills. The simulator provides an endoscopic view (camera-equipped tube to visualize the inside of the body and fluoroscopic views (uses X-rays to create an image) during procedures (New TURP Modules for URO Mentor Simulator - Surgical Science, 2024). The training provided using these tools also improves the diagnostic reasoning ability of learners as they practice the procedures, receiving real-time feedback, which helps them to make corrections to enhance their learning outcomes.

Learning Outcomes and Pedagogical Benefits

The use of Virtual Labs and Simulators in STEM education has many benefits when it comes to learning outcomes in students, and also improves pedagogical practices, as mentioned below.

Enhancing Motivation and Engagement: The use of Virtual Labs and Simulators in the field of STEM education keeps the students motivated, enhancing their learning outcomes and understanding of concepts and procedures. The Hands-on practical exposure keeps the students engaged and improves their expertise in the procedure, aiding them to repeat the process multiple times, as VR and Simulators do not deal with live apparatus and specimens.

Interactive and Diverse Learning Styles Supported: The diverse learning needs of learners in STEM education are supported by Virtual Labs and Simulators, as they are accessible to students at their convenience to learn at their own pace. Leaners who are finding a specific procedure tough can repeat it several times to gain experience with it. The visuals provided by these procedures enable learners to get a better understanding of the topic and content. The interactive hands-on practice assists in the retention of concepts, which supports the needs of learners of diverse learning styles, bringing in inclusivity in learning styles as compared to traditional methods (Vijayatheepan & Rajaratnam, 2023) [30].

Adaptive Learning and Real-time Feedback: The personalized feedback that is provided by Virtual Labs and Simulators aids learners in improving and rectifying their mistakes. These tools, based on the performance of every individual, adjust the complexity level of the task to be carried out. Knowledge gained and grasping of concepts are improved as activities can be conducted in a controlled and safe environment, thus providing real-time feedback pertaining to every learner's needs.

Advantages of Digital Simulations in Stem Education

Cost-effectiveness, Scalable, and Safe Learning: Virtual Labs and Simulators do not use apparatus or live specimens for student learning, thus eliminating the need to arrange a new specimen each time a student repeats the procedure for practice, which reduces costs during the training period. A flexible learning space can support learners in conducting experiments and procedures safely and in a controlled environment, without using real chemicals that could be dangerous or fragile apparatus.

Retention and Conceptual Understanding Enhanced: Virtual Labs uses techniques in which learners can manipulate apparatus and substances several times at their convenience. Simulators produce visuals that help in making the topic being learnt interesting and engaging. Hence, by these features of Virtual Labs and Simulators, the conceptual understanding of a topic is enhanced, and this aids in the retention of the concepts for a longer period by the students.

Promoting Real Like Experimentation without Restrictions: Both Simulators and Virtual Labs give an interactive, real-time experience to the learners while working on simulated procedures or experiments, without any time constraints. The activities can be conducted numerous times by the students till they master the topic in a safe, conducive, and controlled environment (D. Lee, 2025b) [22]. This promotes a real-like experimentation experience without restrictions, which escalates the learning outcomes in individuals.

Limitations and Challenges

Though Virtual Labs and Simulators are being introduced and used in STEM education in many institutions today, they have their challenges and limitations when used. The lack of direct physical contact and interaction with the apparatus and substances can create limitations in practical skill development and a deeper understanding of concepts. The students may not be exposed to the complexities and real-world variables of the on-the-ground challenges when working with these platforms (Kashaka & Nyiramukama, 2024). Teachers must also be adequately trained to teach the

students how to use these platforms. Tactile and olfactory experiences like the sense of touch, smell, experience rise in pressure, temperature, etc, may be missed out by students. If the simulated experiences are too different from real-life situations, students may find it difficult to inculcate them when they work on real apparatus and specimens. The Virtual Labs and Simulators should be designed to mirror real-time experiments and procedures so students can conduct better critical analysis of the concepts. Thus, authorities must make sure that Virtual Labs and simulators are integrated and aligned into the curriculum of STEM education to give students practice before they work in a real-time environment. Virtual Labs and Simulators must only be used to supplement and not to replace real-time hands-on experiences.

Conclusion

Utilization of Virtual Labs and Simulators in various fields in STEM education bridges the gap between traditional learning and digitalized learning. Care should be taken to ensure that policies for the usage of these apps are followed, and appropriate infrastructure for housing these devices should be allocated. In this era of technology boom, it is mandatory to integrate these systems into the mainstream of STEM education, keeping in mind to use them as a supplement to learning, and not replacing real-life hands-on practical exposure for students. Using Virtual labs and simulators exposes learners to an interactive learning experience, which assists them in mastering the subject and procedures they are learning. Hence, by using these platforms, educators and students can be empowered for a digital future to enhance the learning process, which will make them productive professionals of tomorrow.

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