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Artificial Intelligence–Enabled Virtual Laboratories in Pharmacy Education in Uganda: Students' Experiences, Perceptions, and Practical Competency Development

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Abstract

AI and digital learning technologies are revolutionizing health professions education by developing new ways to achieve hands-on skills. Laboratory training in the field of pharmacy education is still vital in developing technical skills, clinical reasoning, problem solving and professional confidence. In low and middle-income countries including Uganda, constraints like limited infrastructure, inadequate resources, rising enrolments and limited opportunities for repeated practice pose challenges to institutions. AI-powered virtual laboratories offer a promising alternative by using the interactive and learner-centered learning experiences to supplement traditional hands-on learning.

The qualitative narrative review focuses on the experiences and perceptions of students, and how the use of virtual laboratories with AI tools could help develop practical competency in Uganda's pharmacy students. Pharmacy and health professions education provides evidence of the potential for AI-assisted virtual learning to improve engagement, confidence, self-directed learning, and practical skills. But implementing this successfully needs proper digital infrastructure, preparedness of faculty, integration within curriculum and institutional support.

Keywords: Artificial intelligence, virtual laboratories, pharmacy education, digital learning; practical competencies; qualitative narrative review; Uganda

Introduction

Pharmacy education has now shifted from knowledge based education to competency based education (CBE) that focuses on the incorporation of scientific knowledge, technical skills, professional behaviors, communication, and clinical decision making skills. In the modern world, the knowledge and skills of a pharmacy graduate must include proficiency in pharmaceutical practice, laboratory skills, medication management, pharmaceutical care and problem solving using evidence. Competency-based approaches foster experiential and authentic learning activities that enable students to develop practice and demonstrate professional competencies prior to becoming healthcare providers (Frank *et al*., 2017; Englander *et al*., 2017; World Health Organization [WHO], 2022) [9,23, 7].

Practical laboratory training is an integral part of the Pharmacy curriculum as it builds up the technical skills of the students in pharmaceutical formulation, compounding, quality assurance and analysis as well as in the handling of medicines safely. Despite these efforts, there are still barriers in the training of pharmacy professionals, especially in low and middle-income countries (LMICs) with poorly equipped laboratory facilities, lack of training equipment, growing number of students in training, limited teaching staffs, and limited opportunities for repeated skills practice (World Health Organization, 2022; Barteit *et al*., 2020) [7, 1]. The challenges raised have prompted a greater interest in innovative approaches to learning that afford opportunities to expand access to practical learning.

Digital technologies have revolutionized health professions education and, with their rapid development, simulation-based learning, virtual learning environments, mobile technologies, and educational platforms with artificial intelligence (AI) are all increasingly used. These strategies offer flexibility, an interactive and learner-centered approach to learning and practice, feedback, reflection and competency development, and complement the traditional approaches that have been used in teaching (Gordon *et al*., 2020; Tudor Car *et al*., 2022; O'Connor *et al*., 2023) [20, 10, 32]. Artificial intelligence is the technology behind computer systems that can process information, identify patterns, make predictions, adjust to user actions and help in decision making. In the educational sector, AI can be used for intelligent tutoring systems, adaptive learning platforms, automated assessment, learning analytics, and personalized learning experiences (Chen *et al*., 2020; Kasneci *et al*., 2023) [27, 28].

AI Virtual Labs are a new innovation that combines AI, simulation, and digital environments to enhance hands-on learning. AI-based virtual labs can analyze student performance, give real-time feedback, and customize learning content and tasks, unlike traditional labs that offer pre-made simulations. The ability to repeat the procedures, correct the errors, gain confidence and become competent before entering actual laboratory or clinical setting (Radianti *et al*., 2020; Makransky & Petersen, 2021; Grassini, 2023) [33, 29, 19].

AI-powered virtual laboratories can overcome the drawbacks of real-world laboratory settings in pharmacy education, such as limited accessibility, self-directed learning, the need for fewer physical resources, and enhanced engagement, whilst providing students with greater access to laboratory experiences. Health professions education studies in recent years have found that virtual simulation and technology-enhanced learning has the potential to enhance learner confidence, knowledge application, clinical reasoning and skills competency when embedded within curricula to produce these outcomes (McGaghie *et al*., 2016; Barteit *et al*., 2020; Tudor Car *et al*., 2022) [30, 25, 1, 20]. In the field of Pharmacy education, virtual patient simulations and digital learning platforms have been found to be a way of improving clinical decision making, communication skills, and medication related problem solving skills among students (Beshir *et al*., 2023; Gaspar *et al*., 2024) [17, 15].

There is a high relevance of practical learning supported by AI in Uganda because the training and education of healthcare professionals in the medical sector, specifically in the field of pharmacy, is expanding. In Uganda, the relevance of practical learning supported by AI is especially notable given the increasing demand for healthcare professionals in the medical sector, particularly in the field of pharmacy. In spite of the expansion, institutions are still suffering from problems of laboratory capacity, enrolment, teacher availability, and the availability of modern education technologies. There are also opportunities to enhance practical training through the use of AI-powered virtual laboratories, but these need to be supported by sufficient infrastructure, cost, competence of faculty, curriculum integration, and being grounded in local contexts (Barteit *et al*., 2020; WHO, 2021; World Bank, 2023) [1].

In the successful implementation of education innovations supported by AI, student experiences and perceptions play a major role. The technology acceptance, usefulness, digital confidence, motivation, and engagement of emerging educational technologies influence the way learners engage with technology. Recent studies have highlighted that students are aware of the benefits of incorporating AI in their educational process, but they are still concerned about digital literacy, the reliability of information provided by AI tools, a lack of human interaction, and the dependency on technology (Kasneci *et al*., 2023; Sallam, 2023) [28, 16]. It is crucial, however, to understand the point of view of the learners in order to design effective, ethical and contextually appropriate approaches to education using AI.

The interest of the use of AI in education has grown significantly globally, but there is limited evidence on the use of AI-powered virtual laboratories in the education of Pharmacy in Uganda. Previous studies have mainly centered on digital health education, simulation-based learning, or the use of AI in health professions in general, but not on the hands-on learning experiences and competency-building of pharmacy students. Therefore, a qualitative narrative review can be beneficial to synthesize available literature, identify opportunities, practical challenges, and the strategies to incorporate AI-supported practical learning in pharmacy education in Uganda (Snyder, 2019) [21].

Rationale

Virtual Laboratories powered by Artificial Intelligence (AI) represent a promising strategy to enhance practical training and competency-based learning in the field of Pharmacy Education. With a greater focus on experiential learning in the Pharmacy curriculum, students need to practice procedures, cultivate clinical reasoning skills and build confidence before entering professional practice. Nevertheless, there are still several challenges that continue to plague the institutions of pharmacy in low- and middle-income countries such as Uganda, including the scarcity of infrastructure, equipment, repeated practice opportunities, and high enrolments (Barteit *et al*., 2020; World Health Organization [WHO], 2022) [1, 7].

The recent developments in AI, virtual simulations and digital learning enhance learner engagement, personalized feedback and competence building. However, there is scarce information regarding the feasibility and acceptability of virtual laboratories enabled by AI in Uganda's Pharmacy education, and their impact on teaching and learning. This is because comprehending students' experience and perceptions are vital to supporting the context-specific integration of AI into traditional approaches to laboratory training and competency development (Chen *et al*., 2020; Kasneci *et al*., 2023; Snyder, 2019) [28, 27, 21].

Methods and Materials

Study Design

A qualitative narrative literature review design was used for this study, which aimed to investigate the use of Artificial Intelligence (AI) in manufacturing virtual laboratories (VLs) in pharmacy education, focusing on students' practical competency building and experiences and perceptions. A narrative review approach was used to facilitate synthesizing and interpreting a wide variety of evidence types, such as qualitative studies, educational research, conceptual papers, and review articles, especially in the context of emerging research areas where evidence is a mix of different forms and specific to context (Snyder, 2019) [21]. This methodology allowed the key themes concerning the educational values, opportunities of implementation, and challenge of using AI-supported virtual laboratories in pharmacy education to be identified.

Extensive literature search was carried out to find articles related to the topics of artificial intelligence, virtual laboratory, simulation based education, digital learning, pharmacy education, and practical competency development. The relevant literature was retrieved from electronic databases such as PubMed/MEDLINE, Scopus, Web of Science, Google Scholar and Education Resources Information Center (ERIC) from January 2016 to December 2026. The time frame selected was considered appropriate to represent recent innovations in artificial intelligence, digital transformation, and technology-enhanced health professions education.

The search strategy was comprised of both controlled vocabulary and free-text keywords with the use of Boolean operators. The following terms were used in the search: "artificial intelligence," "AI-enabled learning," "virtual laboratory," "virtual simulation," "pharmacy education," "pharmacy students," "practical skills," "competency development," "digital learning," "simulation-based education," and "health professions education." For comprehensive coverage of existing evidence, additional relevant publications were found by screening the reference lists of selected articles.

Studies were included if they were published between 2016 and 2026; available in English; focused on health professions or pharmacy education on the topic of artificial intelligence, a virtual laboratory, simulation, or a related digital learning technology; explored students' experiences, perceptions, engagement, learning process or competency development; and offered insights relevant to practical skills training. Whereas studies were not included if they did not; consider applications of AI in the educational field, the technical development of AI systems without educational application, refer to virtual laboratory in non-health related field, were abstracts of conferences, or were not published in the relevant field of pharmaceutical sciences or practical skills education.

Literature Review

The roles of the pharmacists are evolving and getting more complex, the complexity in managing medicines is growing, and the requirements of qualified graduates with skills in technical, clinical, communication, and decision making skills have resulted in the shift of the model of pharmacy education from product-oriented to patient-centred and competency-based education (CBE). Modern pharmaceutical systems focus on the acquisition of pharmaceutical knowledge as well as on proven competency in professional practice (International Pharmaceutical Federation [FIP], 2020; World Health Organization [WHO], 2022) [7].

Student learning in CBE has now become a major strategy in Pharmacy Education and involves students applying their scientific knowledge, skills, professional attitudes and clinical judgement to produce an integrated learning framework. This has led to a call for changes in curriculum, more hands-on learning, and the shift to performance-based measures to measure readiness for practice (Englander *et al*., 2017; Frank *et al*., 2017) [23, 9].

Regardless of these, the practical skills for pharmaceutical formulation, compounding, quality assurance, medication safety and clinical decision making are still vital for gaining the competencies required. Laboratory practice, simulation and supervised placements allow for repeated practice, feedback, and reflection to build confidence and competence development by applying theory in practice (McGaghie *et al*., 2016; Cant & Cooper, 2017) [30, 25, 26].

Although skills training is essential in the education of a pharmacist, the organization of skills training in a pharmacy educational institution, especially those in LMICs, are marred by several problems such as limited laboratory facilities, lack of adequate equipment, rising number of students, scarcity of trained trainers and limited repetition of skills. Problems encountered by students may be a reflection of their lack of readiness for professional practice and also indicate the need for new teaching methods (Barteit *et al*., 2020; WHO, 2022) [1].

The use of simulation-based education has become a new form of educational approach to enhance practical skills development by allowing students to perform procedures, build up a clinical reasoning process and receive feedback, all without real patient contact. To date, simulation has quite significantly gained traction in the field of pharmacy education, with its use in medication counselling, patient assessment, communication and clinical decision-making (McGaghie *et al*., 2016; Cant & Cooper, 2017) [30, 25, 26].

Competency-based learning has also reshaped how competency is assessed, leading to the increased use of objective structured clinical examination (OSCE), workplace-based assessment and direct observation methods for evaluation of skills in real-world scenarios (Englander *et al*., 2017; FIP, 2020) [23, 9].

The expansion of the pharmacy education system in Uganda and other East African countries has been dependent on the demand for healthcare workers, where pharmacy schools are increasingly using competency-based curricula, skills laboratories and experiential learning techniques. But disparities in institutional capacity, insufficient resources and the lack of teachers persist and continue to impede effective implementation (WHO, 2022; Barteit *et al*., 2020) [1]. New technologies, such as AI-powered virtual labs and adaptive learning systems, offer possibilities of supporting hands-on education in a hands-on way by using feedback and self-directed learning. For successful integration, the necessary infrastructure, preparedness of the faculty, alignment of the curriculum, and adaptation in the context must be prepared (Chen *et al*., 2020; Radianti *et al*., 2020; Kasneci *et al*., 2023) [27, 33, 28].

Artificial intelligence (AI) has proven to be significant innovation in the field of health professions education, where it is used for personalized learning, intelligent tutoring, adaptive feedback, simulation and automated assessment. AI platforms can review learner performance, pinpoint learning gaps, and adapt learning experiences to meet the needs of each user for individualized competency development (Holmes *et al*., 2019; Chen *et al*., 2020; Kasneci *et al*., 2023) [27, 5, 28].

Virtual labs are emerging as virtual settings that provide learners with the opportunity to practise procedures explore concepts and acquire practical skills that are not possible in a traditional lab. The technology of VRs, immersive technology, and simulation platforms has evolved and made these environments more realistic and interactive, which has increased learner confidence, engagement, and knowledge application (Radianti *et al*., 2020; Makransky & Petersen, 2021) [33, 29].

By incorporating artificial intelligence into virtual labs, they can also simulate learning scenarios, provide individualized feedback, track student performance, and allow for multiple attempts, further enriching their educational value. Virtual labs powered by AI can be used in Pharmacy Education to enhance skills such as pharmaceutical calculations, formulation, quality control, medication safety, and clinical decision-making. There is evidence from Health Professions' education that simulation and digital learning methods can help boost confidence, practical performance and preparedness of learners when properly incorporated in curricula (McGaghie *et al*., 2016; Cant & Cooper, 2017; Tudor Car *et al*., 2022) [30, 25, 26, 20].

Digital learning technologies have emerged as a promising solution to the challenges COVID-19 brought, and have gained momentum as a result of the pandemic. In low resource areas, internet connectivity, digital infrastructure, technological competency, and institutional capacity were especially significant barriers to virtual learning (Gordon *et al*., 2020; Barteit *et al*., 2020) [10, 1].

AI-powered virtual labs offer opportunities to enhance hands-on learning in African settings where resource constraints, growing student numbers, and the lack of educators hinder hands-on learning experiences. But, to implement this successfully, technologies have to be affordable, infrastructures have to be adequate, faculty to be prepared, curriculum to have been aligned, and adaptation to local educational needs to be done (Barteit *et al*., 2020; WHO, 2021) [1].

While virtual laboratories with AI can present an opportunity, they should be used in conjunction with, and not in place of, physical laboratory practice and clinical experiences. Combined use of AI-assisted learning, simulation-based training, and hands-on training in combination with competency-based assessment could be most effective. The application of these in Ugandan pharmacy education, however, is still limited and it is important to understand students' experience and perceptions of their use and application in order to guide their sustainable use.

Students' Experiences and Perceptions of AI-Enabled Practical Learning

The role of students' experiences and perceptions in the context of the educational value and sustainability of virtual laboratories (VL) in university education that use artificial intelligence (AI) is crucial in understanding the role of the virtual laboratory. Virtual laboratory imparts educational value and sustainability through experiences and students' perceptions of artificial intelligence (AI) in virtual laboratory in pharmacy education.

While technological innovations offer other opportunities for the improvement of practical skills training, they are only effective if learners accept, engage, are confident and believe in their usefulness. Perceived usefulness, ease of use, social influence, and facilitating conditions are cited as the factors that influence students' willingness to adopt educational technologies by the Technology Acceptance Model (TAM) and the Unified Theory of Acceptance and Use of Technology (UTAUT) (Davis, 1989; Venkatesh *et al*., 2012) [3, 6, 14]. Thus, understanding learners' views is crucial for understanding the potential impact of AI-enhanced learning environments on competency building.

The current body of literature in health professions education confirms that, students have positive attitudes toward learning in a virtual environment or via technology. Students frequently state that they feel the digital simulations offer them safe environments to practice skills, make mistakes, get feedback, and practice procedures until they are confident. Virtual laboratories with AI can offer a more flexible access to the learning resources and enable students to practise their knowledge beyond the scope of a traditional laboratory. The attributes are considered conducive to self-directed learning and learner autonomy, an essential part of competency-based education (Cook *et al*., 2011; McGaghie *et al*., 2016) [2, 25, 30].

One of the key advantages of using AI-powered virtual laboratories is that it boosts students' confidence and readiness for lab work. Anxiety is a common occurrence among students in the Pharmacy program during new laboratory tasks and when having to transfer theory knowledge to actual clinical situations. This can be lessened in virtual environments where learners can interact with scenarios without the stress of a real-world situation. Students can acquire more self-efficacy and readiness for laboratory and clinical duties as a result of repetition and feedback (Bandura, 1997; Makransky & Petersen, 2021) [13, 29].

Additionally, AI-driven learning environments can enrich the learning experience for students by offering interactive and personalized learning experiences. Unlike basic methods of learning, where students would all be given the same learning opportunities, an AI system can tailor activities to each individual's performance and recognize and give feedback on areas of struggle. The personalized learning experiences can be tailored to address various learning requirements and enhance knowledge acquisition and skill building (Holmes *et al*., 2019; Chen *et al*., 2020) [5, 27].

However, concerns about AI reliability, accessibility, and relevance to professional practice could affect students' acceptance of these virtual labs. Learners in some situations may feel virtual experiences do not provide the same hands-on with equipment, materials and clinical environment as a physical laboratory experience. Practical competence is not just a matter of cognition; it must also involve psychomotor ability, professional judgment and adaptation to variability in the real world. As a result, the learning in AI virtual laboratories can be regarded as supplements to the learning in traditional laboratories (Cook *et al*., 2011; Radianti *et al*., 2020) [2, 33].

Institutions also play a role in shaping students' experiences, such as the availability of digital infrastructure, technical support, guidance from educators, and integrating technology into the curriculum. Lack of connectivity, device availability, digital literacy, and teacher training can have adverse effects on the use of AI tools to support learning. Technological innovation is especially relevant in low and middle-income contexts where it needs to be integrated with the educational context of the region. (Barteit *et al*., 2020; Gordon *et al*., 2020) [1, 10].

In Uganda, however, research on the experiences of the students of pharmacy specifically in relation to AI facilitated virtual laboratories is still limited. The use of technology in health education and simulation learning, however, provides some lessons that can help students to benefit from technology-enhanced training and learning approaches to provide more opportunities for students to practice the acquisition of competencies and support competency-based learning. It is crucial to understand students' perspectives to make sure that the integration of AI aligns with their learning needs and adds value to the education they receive in pharmacy.

Opportunities, Challenges, and Future Directions for AI Virtual Laboratories in Uganda

The introduction of virtual laboratories with AI capabilities in Pharmacy education programs in Uganda offers great potential for enhancing practical skills training. With the expansion of the programs and the rise in the number of students, the need for proper lab exposure and competencies are increasing all the more, putting pressure on the educational institutes. AI-powered virtual labs could offer a novel way to supplement current hands-on training opportunities by offering more opportunities for simulated learning experiences, repeated practice and reducing the reliance on limited physical resources (WHO, 2021; WHO, 2022).

A key opportunity is the possibility to enhance equity and access in the education of pharmacists. Virtual laboratories can provide students the opportunity to have access to practical learning materials outside of their regular lab schedule, so as to provide flexible and self-paced learning. This could be especially advantageous in situations where institutions are facing a lack of laboratory facilities, limited class space, and large classes. AI powered platforms can also help decrease the discrepancies in quality of practical training among institutions (Barteit *et al.*, 2020) [1] by offering standardized learning experiences.

AI virtual laboratories can also help enhance competency-based education by optimizing the assessment and feedback system. AI systems can track learner interactions, pinpoint areas for improvement, and give instant feedback to help learners continuously improve. The capacities are consistent with contemporary approaches to learning that focus on formative assessment, deliberate practice, and student progression towards evidence of learning (Frank *et al.*, 2010; Englander *et al.*, 2017) [4, 9].

The other opportunity is the possibility of incorporating AI virtual laboratories in blended learning models. AI technologies are meant to complement rather than replace hands-on lab training, and can be used to get students ready for lab sessions and to support revision, as well as to reinforce concepts after lab activities. This integrated model that integrates virtual simulation, laboratory practice, and clinical experiences may offer a more holistic approach to the development of the competencies of the pharmacy professional.

But some obstacles need to be overcome for the adoption of AI virtual laboratories in Uganda to become a reality. One of the major challenges is low technological capacity of institutions, poor Internet connectivity and availability of appropriate devices. Such challenges can limit access and be a barrier for equitable access to training, and can also result in inequities between well-resourced and under-resourced training institutions (Barteit *et al.*, 2020) [1].

Another key challenge is the sustainability of the finances. Creating, buying, operating and upgrading educational platforms that use artificial intelligence (AI) are costly endeavors. While costs of initial acquisition are important, institutions should also factor in the ongoing needs for educator training, software updates and maintenance, and technical support. AI programs could be confined to pilot projects if there are no sustainable funding sources, as they are unlikely to become a part of the educational curriculum.

The faculty's readiness is also very important to ensure successful implementation. Teachers need the right knowledge and skills for effective use of AI technologies in teaching, to guide digital learning, understand the meaning of the feedback and ensure that the use of AI fits in with the competencies curriculum. The use of technology in education does not guarantee the improvement of education if it is not pedagogically used by the educators (Holmes *et al.*, 2019) [5].

AI virtual labs in Uganda, then, need to be implemented using context-specific strategies that not only harness technology but also prioritize educational needs. Institutions should focus on investing in digital infrastructure, faculty development, incorporating digital content and research that assesses student experiences and learning outcomes. Local partnership between universities, regulatory agencies, technology developers and healthcare institutions can facilitate the creation of AI solutions that are relevant to the local context.

The perceptions, acceptance, competency outcomes, and experiences of Ugandan pharmacy students in using the virtual laboratory with AI would be interesting to explore further. Further research into the effectiveness of virtual lab experiences in improving performance in the practical laboratory and clinical setting in the future will also be significant. This will help to make informed decisions on the sustainable integration of AI in pharmacy education.

In conclusion, AI-driven virtual labs are an exciting development in the field of pharmacy education in Uganda that holds great promise for enhancing teaching and learning. But they will need to overcome technological, educational, financial and contextual hurdles, and make sure that AI is used as a tool to augment not supplant real-world hands-on learning.

Discussions

The Future of Health Professions Education Is Being Shaped by Ai And Digital Transformation

New evidence suggests that artificial intelligence (AI) is no longer limited to traditional digital learning platforms, but has evolved into adaptive, interactive and personalized learning systems. AI applications can enhance individualized study plans, automated feedback, learner analytics, and intelligent tutoring, which can revolutionize health professionals' learning experience.AI tools can facilitate personalized learning journeys, provide automated feedback, utilize learner analytics, and offer intelligent tutoring, thereby reshaping the way health professionals learn. Recent studies on the use of AI in health professions education show a move from a content-centred approach, which was previously common, to a learner-centred approach where AI tools are used for continuous assessment and personalized learning and improvement (Chen *et al.*, 2020; Chan & Zary, 2019; Kasneci *et al.*, 2023) [27, 8, 28].

The use of generative AI technologies, specifically large language models, have additionally broadened the opportunities for educational support through interaction-driven discussions that help students reach conclusions, clinical reasoning exercises, and virtual patient encounters. But recent research has pointed to the fact that despite the potential of AI, it should not supersede teachers, as issues with accuracy, bias, overreliance, and the ability of learners to develop their own professional judgment remain (Kasneci *et al*., 2023; Sallam, 2023) [28, 16].

Learning About the Basics of Virtual Simulation and Pharmacy Skills Development

There is growing evidence of the use of virtual patient simulations and computer-based simulation in Pharmacy education as shown in recent studies. The use of virtual simulation has been proven to enhance clinical reasoning, communication skills, confidence and involvement of students, especially in areas like medication counselling, patient evaluation and decision making. After a systematic review of virtual patient simulation in Pharmacy education, it was found that knowledge acquisition, higher order learning, counselling skills and the confidence of learners improved after exposure to the virtual simulation activities (Beshir *et al*., 2023) [17].

Likewise, there have been recent reviews of simulation approaches in pharmacy education, suggesting that simulation-based learning can give opportunities to students to practise professional tasks within a controlled environment prior to real-life experience with patients. These methods can be very useful when clinical exposure is limited or when there is a larger number of students than the numbers of training resources available (Gaspar *et al*., 2024) [18].

In Uganda, where the numbers of pharmacy programmes are growing, AI-powered virtual laboratories, therefore, could serve as yet another opportunity to provide more opportunities for hands-on experience while alleviating the strain on limited physical laboratory facilities.

Student Acceptance, Engagement, and Learning Experiences

A recent study underscores the critical role of students' perceptions of usefulness, availability, and relevance to professional work in successful adoption of AI. If students believe that AI-integrated learning technologies enhance their understanding, offer valuable feedback, and aid in competency development, they are more inclined to use them.

However, recent studies also show that students need sufficient digital skills and instruction in order to make the best use of AI. Several factors continue to be crucial in the context of health professions education, such as the concerns about AI-generated outputs being unreliable, the potential for it to diminish critical thinking skills and the overreliance on technology (Sallam, 2023) [16].

In the context of pharmacy education, there is emerging evidence that students are using AI tools to facilitate problem-solving, clinical reasoning, and learning activities, but a varied level of digital readiness and confidence exists. In recent years, research in the field of pharmacy education has focused on the need for responsible AI literacy for students and educators prior to widespread adoption.

AI Virtual Laboratories and Resource-Limited Settings

The literature of the last years highlights how AI and digital simulation could add value in low and middle-income countries (LMICs) where there is often a lack of laboratory, clinical placement opportunities and teachers in educational institutions. Even in the face of limited resources, digital platforms have the potential to enhance access to standardized learning experiences and to facilitate competency based education.

There are still a number of challenges for implementation, though. These include device limitation, financial restrictions, unreliable internet connectivity, financial risks, lack of technical support or lack of faculty preparedness. However, context-specific approaches must be implemented and adapted to the specific local conditions and educational needs of a country, such as Uganda, rather than simply applying models that have been developed in other countries with high-income economies (Barteit *et al*., 2020; WHO, 2021) [1].

The Future Directions of Ai-Enhanced Blended Pharmacy Education Will Be Set

Future of Pharmacy Education will probably be blended learning models including AI-based virtual laboratories, in-person laboratories, clinical rotations, and competency-based evaluations. New research indicates that AI-driven simulations can improve education flexibility and enrich learning experiences, but not be a replacement for real-world professional practice.

The recent developments of AI-driven virtual agents and simulation setups showcase the evolving capabilities of interactive clinical scenarios, communication training, and boosted confidence levels for learners. More studies are needed to understand the long-term impact on competency, professional practice and patient care (Wang *et al*., 2026) [31].

Future implementation efforts in Uganda should emphasize the creation of locally-appropriate solutions, the enhancement of educator skills, and the evidence gathered from experience with pharmacy students.

Conclusions

The potential of using virtual laboratories with AI to enhance competency-based pharmacy education and practical skills training in Uganda is immense. They can be used to facilitate repeated practice, to provide personalized feedback, to build confidence, and to facilitate students' self-directed learning, including in environments that do not have access to physical laboratory equipment. AI virtual laboratories should be used in tandem with, not instead of, classroom and lab practice and hands on experiences with teachers. This success will need investments in digital infrastructure, faculty capacity, and curriculum integration, as well as in making digital access equitable. There is a need for continued research to assess learners' experiences, competencies, and the effects of AI-enriched hands-on training in pharmacy training in Uganda.

In summary, the use of AI in the design of virtual labs is a valuable innovation that, when applied through context-sensitive, blended and learner-centered approaches, can help enhance the quality of Pharmacy education.

Recommendations

Curriculum Integration: Pharmacy training institutions must implement the use of virtual laboratories with AI capabilities, as an additional resource within the context of competency-based curricula, related to the learning outcomes of the profession.

Blended Learning Approaches: AI virtual laboratories should be integrated with physical laboratory sessions and simulation activities, clinical placements and workplace-based learning to ensure full practical competency development.

Digital infrastructure and access: Institutions should enhance the digital platforms, technical infrastructure, technical support, and Internet connectivity to ensure equitable access to learning with the assistance of AI.

Faculty Development: Train faculty in AI literacy and digital pedagogy, simulation facilitation, and technology-enhanced assessment for effective incorporation of AI tools.

Policy and Ethical Guidelines: Regulatory bodies and institutions should have policies and guidelines focusing on responsible use of AI, data protection, academic honesty and quality assurance in pharmacy education.

Context-Specific Research: There is a need for further studies on the experience, acceptance, learning outcomes and competency development of students using AI enabled virtual laboratories in Uganda.

Collaboration between Universities, policy makers, professional bodies and technology developers is required to locally adapt and sustain AI solutions to Uganda's educational context to ensure their affordability and sustainability.

Human Centred Education: Preserve educator mentorship, hands-on lab experience, clinical exposure, and professional judgment AI should augment.

Declaration

The authors declare no conflict of interest

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