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Can Virtual Microbiology Labs Achieve Comparable Outcomes to Traditional Hands-On Wetlabs in Pharmacy Education?

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Abstract

In pharmacy education, mastering clinical microbiology is essential for students. Traditionally, this is achieved through hands-on laboratory experiences, but alternative methods, such as simulation-based learning, are increasingly being explored. Previous studies have shown that simulations can enhance learning outcomes in healthcare education. The ongoing COVID-19 pandemic has underscored the value of technology in supporting educational goals. This study aims to evaluate and compare the effectiveness of a commercially available virtual microbiology simulation (VUMIE™) and a conventional wetlab in enhancing the knowledge, skills, and confidence of second-year pharmacy students in an integrated pharmacotherapeutics course. This research employed a randomized crossover design to compare the effectiveness of the VUMIE™ simulation versus a traditional wetlab intervention. Participants engaged in three sessions of 1–2 hours each for both interventions (totaling six sessions). Surveys were distributed at three key points: prior to any intervention (baseline), after the first intervention (VUMIE™ or wetlab), and at the final endpoint (following both interventions). Data were analyzed using SPSS Statistics 25 and Instat™ software. Initial survey response rates were around 50%, dropping to approximately 25% at the endpoint. Students who participated in the VUMIE™ simulation scored higher on post-intervention knowledge assessments (multiple-choice questions) compared to those in the wetlab group, with the highest scores appearing at the endpoint. Both interventions showed statistically significant improvements in knowledge, skills, and confidence when compared to baseline. Although VUMIE™ produced higher post-intervention scores across these areas, no significant statistical difference was found between the two approaches. Overall, the VUMIE™ simulation yielded comparable learning outcomes to the traditional wetlab. The study suggests that the VUMIE™ virtual simulation can achieve similar educational outcomes to the wetlab in terms of student knowledge, skills, and confidence. Additionally, the simulation method was more cost-effective, provided a safe and accessible learning environment, and offered the benefit of repeated practice, enhancing students' deliberate learning.

Keywords: Microbiology, Practice, Pharmacy, Education, Clinical, Simulation

Introduction

Pharmacy education requires the acquisition of specialized knowledge, skills, and competencies [1]. The integration of simulations and technology-enhanced learning is increasingly common in clinical programs, offering a way to reduce the financial burden of laboratory-based training, alleviate pressure on placement sites and facilities, and provide students with flexible, repeatable learning experiences to master key content, skills, and competencies [2, 3]. Developing clinical microbiology laboratory skills is considered a specialized area, not typically required in day-to-day pharmacy practice [4, 5]. However, pharmacy practice generally involves understanding the clinical aspects of microbiology, particularly in areas like antibiotic selection and usage, which graduates should be proficient in. While practical knowledge of microbiology is necessary for quality medication management, manual

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skills related to specialized fields such as microbiology may not be essential for pharmacists [6]. For foundational understanding, education in practical areas not usually part of typical pharmacy practice can be achieved through hands-on laboratory work or, alternatively, through digital simulation-based learning modalities. Furthermore, the ongoing COVID-19 pandemic has highlighted the necessity of replacing in-person learning with adaptable, online-based platforms, pushing educators to rely on virtual tools [7]. Due to the limited time to adapt, familiarity with available software tools has become crucial for effective online learning delivery [8, 9].

Although simulation training was previously seen as expensive, it has proven to be a versatile and sustainable educational method [10, 11]. The advantages of simulation-based education include cost savings on consumables and enhanced learning flexibility. Simulations help bridge the gap in clinical skill development, especially considering the difficulties in securing clinical placements due to large student populations and ethical or indemnity concerns, which arise when student actions might impact real patients [3, 12, 13]. Technology-enhanced learning also offers greater efficiency and more opportunities for thorough practice compared to the limited access students have to clinical settings, while also enabling flexible scheduling and repeated practice to ensure mastery of skills through deliberate practice [14, 15].

The feasibility and acceptability of virtual simulations in healthcare education is a topic of significant interest [16, 17]. Scholars have emphasized that when simulations are used as replacements for face-to-face learning, they must deliver similar learning outcomes to those provided by traditional methods [18, 19]. Recent research focuses primarily on addressing these concerns, as the academic community seeks to better understand the contexts in which simulation-based education is most effective, not just possible.

This study aimed to assess the impact of a commercially available virtual microbiology simulation (VUMIE™) compared to a traditional wetlab on students' knowledge, skills, and confidence in a second-year integrated therapeutics course for Bachelor of Pharmacy students. The learning activities focused on several key areas of clinical microbiology competence, such as Gram staining, the selection and use of media and biochemical tests, and susceptibility testing [20]. This research is particularly timely given the need for digital education platforms due to the COVID-19 pandemic.

Materials and Methods

From 2016 to 2019, the VUMIE™ platform was embedded in a second-year pharmacotherapeutics module of the Bachelor of Pharmacy programme. The results presented combine information across several annual student groups enrolled in this module. VUMIE™ is a dynamic, computer-based microbiology tool that recreates laboratory procedures in a highly realistic digital environment, featuring precise depictions of workspaces, instruments, and reagents. Approval for the study was provided by the institutional human research ethics committee (HREC 2016/231).

A randomised crossover trial was conducted to assess whether training through the virtual simulation (VUMIE™-based clinical microbiology practice) yields improvements in students' knowledge, skills, and confidence equivalent to those obtained from conventional hands-on wet laboratory sessions. Evaluation combined objective knowledge testing with self-assessment measures.

Each participant was provided with a personal software licence for VUMIE™, an online platform requiring a computer and internet access. Engagement in both types of practical activities was required as part of the curriculum, while survey participation remained voluntary. All students undertook three sessions per modality (virtual and wetlab), with individual sessions lasting between one and two hours. Wetlab sessions centred on microorganism identification tasks, encompassing Gram staining, inoculation and cultivation on media, and antimicrobial susceptibility testing to support therapeutic decisions in clinical vignettes. Corresponding VUMIE™ sessions replicated these tasks digitally in a computer-equipped classroom, ensuring content alignment. Because of the integrated nature of the topics, every session in both formats addressed the full range of required procedures.

Random allocation to initial groups was performed by an administrative staff member using student identification numbers. One group began with the standard wetlab component (three weekly sessions across three weeks), whereas the parallel group started with the virtual equivalent using VUMIE™ over the same timeframe. Subsequently, the groups switched modalities for another three-week period.

Students who provided consent were requested to fill out a pre-intervention baseline questionnaire, a mid-point questionnaire immediately after their first assigned modality (wetlab or VUMIE™), and a final questionnaire once both modalities were finished **(Figure 1).** All questionnaires were de-identified and linked via codes to maintain confidentiality. Responses from three participants were excluded because they could not complete the wetlab component and experienced only the virtual sessions.

The initial questionnaire gathered data on attitudes toward technology, demographic details (such as grade point average, gender, and any prior microbiology or laboratory exposure). Across all time points, participants used a 5-point Likert scale (ranging from 1 = strongly disagree to 5 = strongly agree) to rate their perceived competence in key clinical microbiology areas, including Gram staining, selection of growth media, biochemical assays, and susceptibility evaluation. Item phrasing remained consistent throughout to enable direct comparisons; illustrative statements were: "I have the appropriate knowledge to perform a Gram stain", "I have the appropriate skills to perform a Gram stain", and "I have the appropriate confidence to perform a Gram stain". Every questionnaire also featured the same set of four multiple-choice items targeting core course-related microbiology knowledge.

Questionnaire design was informed by revised Bloom's taxonomy and the Quality and Safety Education for Nurses (QSEN) competency framework, both of which have guided development of analogous instruments [20, 21]. Additional validation came from prior pilot testing in studies exploring technology-supported simulation within pharmacy training. Responses were captured using Jotform. Scale reliability was confirmed through Cronbach's alpha calculations in SPSS 25. The 16-item knowledge domain exhibited strong internal consistency (α = 0.971 baseline, 0.964 post-wetlab, 0.976 post-VUMIE™, 0.974 endpoint). The 12-item skills domain similarly showed robust reliability (α = 0.973 baseline, 0.943 post-wetlab, 0.972 post-VUMIE™, 0.966 endpoint). The 12-item confidence domain achieved high consistency (α = 0.983 baseline, 0.976 post-wetlab, 0.970 post-VUMIE™, 0.966 endpoint).

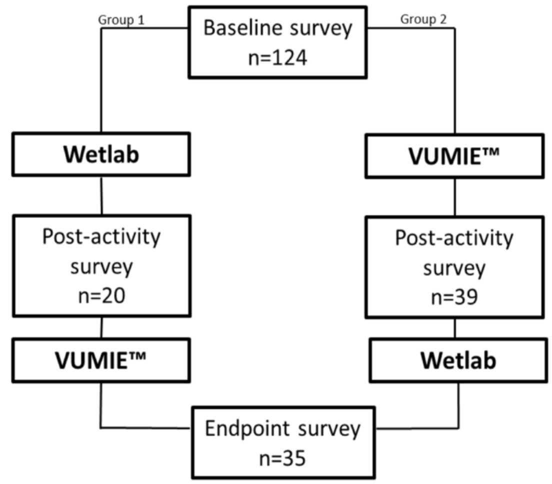

Figure 1. Flowchart of study process and survey administration.

A total of 124 students gave their consent for participation in the study, resulting in an 84% response rate. All students completed the baseline survey. After three weeks, 39 students responded to the post-VUMIE™ survey, while 20 students submitted the post-wetlab survey, with a 50% response rate. By the end of the six-week period, after both interventions had been completed, 35 students filled out the final survey. This provided the study with adequate power (80% power to detect a difference in means of 0.52 at a significance level of 0.05, two-tailed). Learning outcomes were analyzed using Instat™ software, while self-reported data was examined with SPSS Statistics 25. The reliability of survey items was assessed with Cronbach's alpha, and group comparisons were made using the Mann-Whitney test. The analysis compared baseline data with post-wetlab, post-VUMIE™, and final (endpoint) scores, as well as post-wetlab and post-VUMIE™ results.

Results and Discussion

The data compiled represents several cohorts from the course. Each cohort consisted of approximately 40 students, and multiple cohorts were included to ensure sufficient statistical power. The students who completed the surveys were, on average, younger than 25, mostly female, and had GPAs ranging between 4 and 6 (with 7 being the highest possible GPA, and anything below 4 considered a failing grade). These participants were representative of the broader population of students who took the course during the study period. Around 92% of the participants had completed a prior microbiology-related course as part of their university degree, with most having spent between 5 to 10 hours in laboratory settings **(Table 1).**

Table 1. Overview of participant demographics

Demographic Variable	Category	Percentage (%)	Number of Participants
Age	Under 25 years	83	103
	25 years or older	17	21
Gender	Male	33	41
	Female	67	83
Prior Experience in a Microbiology Course	Yes	92	114
	No	8	10
Total Hours Previously Spent in a Laboratory	Fewer than 5 hours	22	27
	5–10 hours	39	48
	11–20 hours	28	35
	More than 20 hours	11	14
Grade Point Average (GPA)	Below 4.0	6	8
	4.0–6.0	79	97
	Above 6.0	15	19

Self-Reported scores for knowledge, skills, and confidence

Tables 2, 3, and 4 below present the student survey response data collected at baseline, after the first assigned activity (either VUMIE™ or wetlab), and at the endpoint. Comparisons focused on the individual items related to the key topics (Gram staining, culture media, biochemical tests, and antimicrobial susceptibility) within the domains of knowledge, skills, and confidence. The overall score for each topic (shown in bold) was based on students' holistic self-rating of their competence in that area. For example, the response to 'Gram stain – overall' captured the student's comprehensive perception of their knowledge across the entire Gram stain workflow, including the procedure, execution, and result interpretation.

Therefore, statistical comparisons were performed using these overall scores for the four primary topics (Gram staining, media, biochemical tests, and susceptibility), rather than the individual sub-components (e.g., specific aspects like interpreting Gram stain results or the staining process itself).

Table 2. Self-reported scores in the knowledge domain

Knowledge Domain	Learning Outcome	Post-Wetlab N = 20 Mean (SD)	Post-VUMIE™ N = 39 Mean (SD)	Baseline N = 124 Mean (SD)	Endpoint N = 35 Mean (SD)
Gram Stain	Process	4.2 (0.77)	4.0 (0.99)	3.6 (0.99)	4.5 (0.56)
	Interpret	4.2 (0.79)	4.4 (0.79)	3.5 (1.00)	4.5 (0.56)
	Perform	4.0 (0.83)	3.8 (1.03)	3.5 (1.03)	4.4 (0.60)
	Overall	*_4.0 (0.83)_ **	**4.0 (0.92)** **	3.4 (1.04)	**4.4 (0.61)****** $^{\#\Delta}$
Culture Media	Types	3.9 (0.71)	4.1 (0.76)	3.2 (0.96)	4.3 (0.63)
	Interpret	3.8 (0.63)	4.1 (0.77)	3.1 (0.95)	4.3 (0.66)
	Choice	3.7 (0.73)	3.9 (0.81)	3.1 (0.98)	4.1 (0.87)
	Overall	*_3.7 (0.73)_ **	**4.0 (0.79)**** **	3.2 (0.97)	**4.2 (0.65)****** $^{\#}$
Biochemical Tests	Type	3.8 (0.89)	4.1 (0.74)	3.1 (0.89)	4.3 (0.53)
	Interpret	3.6 (0.99)	4.1 (0.72)	3.0 (0.89)	4.3 (0.57)
	Choice	3.7 (1.04)	4.0 (0.78)	3.0 (0.91)	4.2 (0.63)

	Overall	3.7 (0.93) **	4.1 (0.76)** **	3.0 (0.92)	4.2 (0.60)**** #
Antimicrobial Susceptibility	Determine	3.9 (0.72)	4.1 (0.81)	3.0 (1.02)	4.4 (0.61)
	Interpret	3.9 (0.67)	4.0 (0.78)	3.0 (1.00)	4.4 (0.60)
	Perform	3.9 (0.72)	4.1 (0.76)	2.9 (1.00)	4.3 (0.63)
	Overall	3.9 (0.72)** **	4.1 (0.77)** **	3.0 (1.01)	4.3 (0.63)**** #

*p < 0.05 (versus baseline)
**p < 0.01 (versus baseline)
****p < 0.0001 (versus baseline)
#p < 0.05 (versus post-wetlab)
Δ= p < 0.05 (versus post-VUMIE™)

Table 3. Self-reported scores in the skills domain

Skills Domain	Learning Outcome	Post-VUMIE™ N = 39 Mean (SD)	Post-Wetlab N = 20 Mean (SD)	Endpoint N = 35 Mean (SD)	Baseline N = 124 Mean (SD)
Culture Media	Choice	4.0 (0.77)	3.7 (0.92)	4.1 (0.49)	3.1 (0.89)
	Interpret	4.0 (0.81)	3.9 (0.64)	4.2 (0.49)	3.2 (0.91)
	Overall	4.0 (0.81)** **	3.7 (0.88) **	4.2 (0.55)**** #	3.1 (0.91)
Gram Stain	Perform	3.7 (1.02)	3.9 (0.72)	4.4 (0.36)	3.6 (0.95)
	Interpret	4.3 (0.80)	4.1 (0.51)	4.6 (0.25)	3.6 (0.96)
	Overall	*3.9 (0.89) **	3.9 (0.64)	4.5 (0.26)**** ###ΔΔ	3.5 (0.97)
Antimicrobial Susceptibility	Perform	4.0 (0.78)	3.8 (0.69)	4.4 (0.42)	3.0 (0.90)
	Interpret	4.1 (0.75)	3.8 (0.63)	4.4 (0.48)	3.0 (0.93)
	Overall	4.0 (0.76)** **	3.8 (0.63)** **	4.4 (0.48)**** ##Δ	3.0 (0.89)
Biochemical Tests	Perform	4.0 (0.83)	3.7 (0.80)	4.2 (0.41)	3.2 (0.91)
	Interpret	4.0 (0.79)	3.7 (0.73)	4.3 (0.37)	3.2 (0.91)
	Overall	4.0 (0.79)** **	3.7 (0.73) **	4.2 (0.42)**** ##	3.2 (0.90)

*p < 0.05 (versus baseline)
**p < 0.01 (versus baseline)
****p < 0.0001 (versus baseline)
*p < 0.05 (versus post-wetlab)
**p < 0.01 (versus post-wetlab)
Δp < 0.05 (versus post-VUMIE™)
ΔΔp < 0.01 (versus post-VUMIE™)

Table 4. Self-reported scores in the confidence domain

Confidence Domain	Learning Outcome	Post-VUMIE™ N = 39 Mean (SD)	Post-Wetlab N = 20 Mean (SD)	Endpoint N = 35 Mean (SD)	Baseline N = 124 Mean (SD)
Culture Media	Choice	3.9 (0.79)	3.6 (0.94)	4.1 (0.48)	3.0 (0.91)
	Interpret	4.1 (0.79)	3.8 (0.83)	4.2 (0.48)	3.2 (0.95)
	Overall	3.9 (0.79)** **	3.7 (0.86) **	4.1 (0.48)****	3.1 (0.91)
Gram Stain	Perform	3.7 (1.08)	3.7 (1.00)	4.3 (0.37)	3.4 (0.98)
	Interpret	4.2 (0.80)	3.9 (0.85)	4.5 (0.26)	3.4 (0.98)
	Overall	3.9 (0.85) **	*3.8 (0.83) **	4.4 (0.37)**** ##ΔΔ	3.4 (0.97)
Antimicrobial Susceptibility	Perform	4.0 (0.78)	3.9 (0.59)	4.3 (0.46)	3.1 (0.96)
	Interpret	4.1 (0.76)	3.9 (0.59)	4.4 (0.36)	3.1 (0.96)
	Overall	3.9 (0.76)** **	3.9 (0.59)* **	4.3 (0.46)**** #Δ	3.1 (0.96)
Biochemical Tests	Perform	3.9 (0.82)	3.7 (0.86)	4.3 (0.37)	3.1 (0.95)

Interpret	4.0 (0.75)	3.7 (0.86)	4.3 (0.38)	3.1 (0.94)
Overall	**4.0 (0.82)** ****	**3.7 (0.86) ****	**4.2 (0.42)****** #	3.1 (0.95)

*p < 0.05 (versus baseline)
** p < 0.01 (versus baseline)
*** p < 0.001 (versus baseline)
**** p < 0.0001 (versus baseline)
*p < 0.05 (versus post-wetlab)
**p < 0.01 (versus post-wetlab)
Δp < 0.05 (versus post-VUMIE™)
ΔΔp < 0.01 (versus post-VUMIE™)

Technology acceptance

To assess students' attitudes toward technology before introducing VUMIE™, a technology acceptance section was included in the baseline survey. Among the respondents (n = 124), attitudes were predominantly positive: more than 90% (113 students) indicated they were willing or very willing to incorporate technology into their learning in general. Likewise, over 85% (107 students) considered access to a virtual microbiology training tool to be somewhat or very useful. However, only about 46% (57 students) felt that a virtual microbiology program would serve as a somewhat or very useful replacement for a traditional hands-on microbiology laboratory.

Results of multiple-choice knowledge questions

Each survey contained four identical multiple-choice questions. The post-intervention scores for these questions were higher in the VUMIE™ group compared to the wetlab group. The baseline scores were the lowest, while the highest scores were recorded at the endpoint.

Learning outcomes

Both the VUMIE™ simulation and wetlab interventions resulted in significant improvements in mean scores across knowledge, skills, and confidence when compared to baseline. As demonstrated in **Tables 2, 3, and 4**, VUMIE™ led to higher post-intervention scores for knowledge, skills, and confidence than the wetlab. However, there was no statistically significant difference between the two interventions, suggesting that the learning outcomes of the VUMIE™ simulation are comparable to those of the traditional wetlab. The results of the multiple-choice knowledge questions also showed that VUMIE™ produced better scores after the intervention, with the highest scores recorded at the endpoint, as shown in **Figure 2**. Furthermore, significant differences were found when comparing endpoint scores to those from the post-wetlab assessment in all three domains—knowledge, skills, and confidence. This indicates that completing both VUMIE™ and the wetlab contributed to enhanced student learning outcomes. Therefore, engaging in both activities is likely more beneficial for student development than participating in just one of them. Among the individual topics assessed in the surveys, the highest mean scores were recorded for interpreting Gram stains across all domains. These results are consistent with previous research suggesting that virtual simulations can produce similar educational outcomes to traditional teaching methods [15, 17, 22, 23]. Given the disruptions caused by the COVID-19 pandemic, which have hindered some students from completing practical laboratory work, simulations like VUMIE™ that offer comparable results to in-person education could help continue teaching essential content that would typically require a physical lab. This would enable students to progress through their courses without delays. Additionally, several studies have highlighted the importance of simulations during the pandemic and underscored the value of international collaboration to provide alternative educational methods, ensuring pharmacy students can still achieve the required learning outcomes despite challenges in accessing traditional learning environments [24, 25].

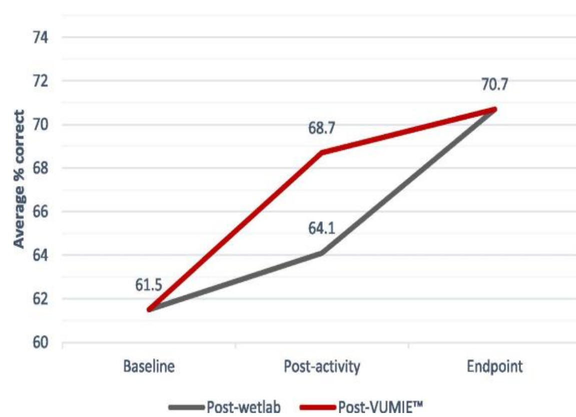

Figure 2. Displays the average percentage of correct answers for multiple-choice knowledge questions.

The use of virtual simulations offers significant benefits, particularly for students who can repeatedly practice processes and skills that would typically be limited in a traditional wetlab due to time, cost, supervision, and consumables constraints. The study found that the wetlab did not show statistically significant improvement from baseline regarding Gram stain skills, whereas the VUMIE™ simulation did. This suggests that students may not feel they fully mastered Gram staining in the wetlab, given that the skills can only be performed once due to time and material restrictions. In contrast, the virtual simulation supports deliberate practice, where learners engage in targeted activities to improve their skills, and can be utilized in mastery learning models, where students repeatedly engage in the learning process until they reach a specific goal [26, 27]. These concepts are especially relevant for simulations teaching procedural skills, such as VUMIE™, which guides students through aseptic techniques for microbiological testing [28]. The simulation offers consistent experiences for each student, making it useful as a preparatory tool before wetlab sessions, which may enhance both performance and safety during live laboratory exercises. Similar findings have been noted in other virtual lab experiences, particularly regarding increased confidence and more efficient completion of tasks [29, 30].

Traditional wetlab sessions provide feedback from demonstrators, but students typically had to wait until the following week to receive confirmation of their aseptic technique's success, relying on whether bacterial growth was observed on the plates. On the other hand, VUMIE™ offers immediate feedback, along with the ability to generate a lab report, allowing students to identify mistakes during the activity. Timely feedback is a crucial element of effective learning, as it fosters reflective thinking and helps learners improve based on prior performance [14, 28].

The "anytime, anywhere" access to virtual learning tools has been coined as "simulation on-demand" or "distributed simulation," though the latter term was originally associated with high-fidelity physical setups [28]. Once the VUMIE™ program is downloaded, students can use it anywhere with an internet connection. This flexibility also serves as a viable alternative for students unable to attend wetlab sessions in person. Learning outcomes showed no significant difference between the VUMIE™ and wetlab experiences, suggesting that VUMIE™ can be a viable option for students unable to participate in traditional lab activities.

In addition to physical safety, the virtual environment allows students to perform tasks without fear of negative consequences, such as making errors in a wetlab. Feeling psychologically safe is linked to better learning outcomes, as students are more likely to view mistakes as learning opportunities instead of failures [31, 32].

Not every virtual lab or simulation activity guarantees successful learning outcomes. Technology-mediated lab activities should be carefully designed, based on sound teaching theories and aligned with curriculum goals [33, 34]. When simulations are used as mere "add-ons" to existing course content, without being directly tied to learning objectives, their effectiveness diminishes [35, 36]. The VUMIE™ software has proven to be an effective tool for teaching microbiology to second-year Bachelor of Pharmacy students. However, like many commercial simulation products, it has limitations, such as its inability to demonstrate the Gram staining or agar plate streaking processes. While commercial products often fulfill many educational objectives, they may not address all the required learning goals. Educators aware of these limitations can usually supplement teaching to ensure learning outcomes are met. Another consideration for future iterations could be a version of the software that allows for modifications by the educator or institution.

Another factor to consider is technology acceptance. The study showed overwhelmingly positive self-reported technology acceptance. Most participants expressed a willingness to use technology regularly and found the availability of a virtual microbiology tool to be somewhat or very useful. The Technology Acceptance Model suggests that perceived usefulness and ease of use are key predictors of users' intentions to adopt a simulation or computer-based activity [37]. When integrating a simulation into the curriculum, educators must account for students' willingness to use technology and design activities suited to their needs.

Several factors should be noted when reflecting on the implications of this research. The VUMIE™ program was accessible from the students' first workshop and could be accessed anywhere with an internet connection. However, due to privacy concerns, there was no way to track how frequently students logged in or how often they repeated simulations, though such data could be valuable in explaining learning outcomes. Ethical guidelines at the institution required that participation in surveys be voluntary, which resulted in uneven group sizes. A 50% response rate for the post-activity survey, compared to the baseline, is typical for such voluntary surveys [38]. Furthermore, ethical restrictions meant that participants were responsible for entering their own codes, which may have led to inaccuracies after the baseline survey. Analyzing paired data and ensuring consistent group sizes for each survey response set would have been beneficial and should be considered in future studies. Despite these limitations, the findings provide valuable insights for educators. Additionally, this study measured short-term learning outcomes (approximately 8 weeks), and further research could explore long-term retention using the program compared to the wetlab. Future studies might also examine the timing of simulation use (such as just-in-time simulation) to assess its impact on learning outcomes.

Conclusion

The results of our study suggest that the VUMIE™ virtual clinical microbiology simulation program offers similar educational benefits as traditional wetlab activities in terms of student learning outcomes. The simulation provides a safe environment, both physically and psychologically, while also allowing students to repeat tasks, facilitating deliberate practice. This highlights the potential of virtual learning tools to serve as a substitute for in-person lab or clinical instruction, particularly in a global context where live, face-to-face teaching is becoming less frequent.

However, while the study shows that virtual simulations can produce outcomes comparable to traditional wetlabs, the research team does not believe these findings are enough to fully replace in-person laboratory experiences for pharmacy students. Instead, we propose that virtual simulations could serve as an effective pre-laboratory training tool to enhance skill development through deliberate practice and provide a standardized method of assessment in clinical microbiology education.

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Ethics Statement: None

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