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Research Article

Learning in Forensic Chemistry Education: Impact on Criminology Students' Competence and Readiness

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ABSTRACT

This study explored how e-learning influences the development of forensic chemistry skills and professional preparedness among criminology students in the Philippines. A convergent parallel mixed-methods design was utilized, incorporating a quantitative survey with 300 participants and qualitative interviews with students enrolled in a forensic chemistry course. The survey instrument, adapted from existing measures, was subjected to content validation and pilot testing, showing high internal consistency (α=0.86). Quantitative data were analyzed using descriptive statistics, correlations, and regression analyses, whereas qualitative data were analyzed using thematic analysis. The findings indicated that students had favorable views of e-learning in forensic chemistry, valued multimedia resources, and recognized both challenges and opportunities. A strong positive correlation (ρ=0.754, p=0.001) was identified between perceptions of e-learning and readiness to use e-learning tools, with readiness significantly influencing positive perceptions (R=0.708+0.806). Qualitative themes such as enrichment, utilization, enhancement, resources, and foundation underscored the advantages and disadvantages of e-learning in forensic chemistry education. The study concludes that well-crafted e-learning platforms can effectively connect theoretical knowledge with practical skills, improving students' comprehension and critical thinking. However, the absence of hands-on laboratory experience remains a significant limitation. The findings suggest that a blended learning approach, which combines e-learning with traditional practical training, is crucial for a thorough forensic chemistry education. Future research should broaden the study's scope, conduct longitudinal studies, and investigate hybrid learning models to enhance the effectiveness of e-learning in forensic chemistry education.

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Background

Forensic chemistry has become a crucial component of criminology and criminal investigations, with technological advancements allowing scientific measurements outside traditional laboratories (Kloosterman et al., 2015). The increasing significance of forensic science underscores the necessity of innovative educational strategies to prepare future experts in this field. E-learning has proven to be a valuable asset in science-related fields, including forensic chemistry. The Cyber Sleuth Science Lab (CSSL) is a virtual educational platform that integrates educational theory, gender-inclusive practices, and practical problem-solving to impart digital forensics skills (Casey et al., 2023). Utilizing case-based learning through e-learning platforms has boosted students' motivation and performance in forensic chemistry courses (Magwilang, 2022) by enhancing their critical thinking and problem-solving abilities. Incorporating forensic intelligence programs into academic curricula can offer graduates a more comprehensive understanding of forensic intelligence beyond courtroom applications (Morelato et al., 2023). E-learning in forensic chemistry education aids in thorough criminal trace analysis (Crispino et al., 2014) by employing real-case scenarios to foster proactive attitudes and prepare students for evolving challenges in crime and policing. The combination of e-learning and forensic chemistry education in criminology programs can improve students' learning and critical thinking skills. Case-based learning through e-learning platforms encourages critical thinking and problem-solving among forensic chemistry students (Magwilang, 2022), resulting in increased motivation and success.

E-learning platforms, such as the Cyber Sleuth Science Lab, illustrate the capability to merge educational theories with hands-on problem-solving in the realm of digital forensic education (Casey et al., 2023), thereby empowering underrepresented youth with knowledge of digital forensics. Nonetheless, the successful application of these methods hinges on effective interdisciplinary communication (Macassa and McGrath, 2024). While e-learning holds promise for forensic chemistry education, gaps remain in the research concerning its efficacy for criminology students. Many current studies on educational interventions are based on small sample sizes, which restricts the generalizability of their conclusions (Chan et al., 2021). Future research should prioritize large-scale studies across various institutions to evaluate the effectiveness of e-learning in cultivating forensic chemistry skills among students. This study investigated the influence of e-learning on the development of forensic chemistry skills and professional preparedness of criminology students. The research questions centered on students' views regarding e-learning's role in enhancing their forensic chemistry knowledge and investigative skills, the obstacles faced during the learning process, and the impact of e-learning on the utilization of digital tools in forensic investigations and practices. These questions are vital for understanding how e-learning can effectively equip future criminologists with the digital aspects of forensic investigations. The findings have the potential to significantly influence curriculum development and teaching methods in criminology programs, thereby enhancing the preparation of future criminologists to meet the field's evolving demands. By exploring the convergence of e-learning, forensic chemistry, and professional readiness, this study offers valuable insights for educators and institutions seeking to optimize criminology training for the digital age.

Literature Review

E-learning has become a crucial part of science education, especially in fields such as forensic science and chemistry. It offers a blend of opportunities and challenges, particularly in the field of higher education. On the positive side, e-learning provides several benefits to students. For example, platforms can boost

student engagement and motivation by incorporating interactive elements, such as virtual labs and simulations. These tools help students visualize complex concepts and apply their theoretical knowledge to practical scenarios. Take virtual labs in forensic chemistry, for instance—they can mimic real-world crime scene investigations, allowing students to refine their skills without the usual constraints and risks of physical labs. This approach can lead to enhanced learning outcomes and better prepare students for real-world applications (Yan and Pourdavood, 2024). Moreover, e-learning broadens access to educational resources, aiding students from diverse backgrounds. It helps remove geographical barriers and supports lifelong learning, which is crucial in rapidly changing fields such as forensic science (Masuudi et al., 2024). However, there are challenges. A major concern is maintaining student engagement and addressing reduced social interaction compared to traditional classrooms. Both faculty and students have raised concerns about the lack of personal interaction, which can affect the effectiveness of online learning (Yan and Pourdavood 2024). Additionally, technological limitations, such as inadequate digital infrastructure and limited access to necessary technology, can present challenges, especially in under-resourced educational settings (Ramulumo et al., 2024). Initiatives such as the Cyber Sleuth Science Lab (CSSL) show promise in teaching forensic chemistry through e-learning. The CSSL uses a virtual learning environment that integrates pedagogical theory, gamification, and real-world problem-solving to teach digital forensics. It has been successful in enhancing students' knowledge and skills for real-world applications and increasing their interest in careers related to digital forensics and cybersecurity. Gender-inclusive teaching strategies within CSSL have been particularly effective in engaging underrepresented groups, such as girls, without negatively affecting boys' engagement (Casey et al., 2023). Overall, the impact of e-learning on student engagement, motivation, and achievement in forensic chemistry is generally positive when it is implemented correctly. Programs that incorporate collaborative assessments and robust support systems can significantly enhance students' sense of community, responsibility, and motivation, leading to improved academic outcomes (Mphahlele, 2024). Despite these challenges, strategically integrating technology and collaborating with industries can further enhance the quality and effectiveness of e-learning in forensic science and chemistry education (Priddis and Vandenberg, 2018).

Many studies have explored how e-learning can improve critical thinking and problem-solving skills in forensic science education. A significant initiative in this field is the Cyber Sleuth Science Lab (CSSL), which combines digital forensic science with practical problem-solving. This project uses educational theory, gender-inclusive teaching, gamification, and computational thinking to engage students, especially those from underrepresented groups and girls, in addressing technology-related issues. By simulating real-world scenarios, students gain skills that are directly applicable to professional environments (Casey et al. 2023). Extended reality (XR) environments further enhance this by offering immersive online learning experiences. These virtual labs mimic actual investigations, allowing students to familiarize themselves with the tools and techniques used in forensic practices. Although developing these environments can be expensive, they provide significant benefits in terms of student engagement and skill development (Pringle et al., 2022). A major challenge in e-learning forensic chemistry is the lack of hands-on laboratory experience. Virtual and XR resources help address this by providing complementary learning experiences that reinforce knowledge and allow students to interact with equipment asynchronously. However, implementing these resources involves overcoming technical challenges such as Internet connectivity and platform proficiency (Pringle et al., 2022). Best practices in e-learning for forensic chemistry emphasize content that is both pedagogically sound and technologically supported. An online continuing education model highlights the importance of needs assessment and the careful selection of delivery methods, which has proven effective in engaging a global audience (Gluodenis, 2021). Regarding percep-

tions of e-learning in forensic chemistry, students generally have positive experiences with blended learning because of its flexibility, although some still prefer in-person learning for better concentration. The success of online platforms largely depends on instructors' communication skills and student engagement, which shape perceptions of their effectiveness (Khalaf et al., 2023). However, instructors often encounter challenges in blended learning. Past negative experiences can influence current practices, leading many to favor face-to-face interactions and view online teaching as less effective, prompting them to focus more on in-person support (Youde, 2020). Blended learning has been shown to positively impact student engagement and the development of soft skills. Formats that combine online and face-to-face elements can enhance engagement and reduce cognitive load, but their success depends on aligning online content with the teaching process (Oshima et al., 2024; Pisoni, 2019). Looking forward, there is potential for developing blended flipped learning models that emphasize peer interaction and content. These models should include off-campus learning opportunities with external tutors to enhance their competence and professional development (Wang et al., 2024).

Methodology

Research Design

In this study, a convergent parallel mixed-methods design was employed, integrating both quantitative and qualitative approaches to investigate the effects of e-learning in forensic chemistry education. The quantitative component consisted of a structured survey aimed at evaluating the perceptions, readiness, and challenges associated with e-learning tools. The qualitative component involved semi-structured interviews and focus group discussions to obtain in-depth insights into students' experiences and perspectives. This methodology was chosen to ensure data triangulation, thereby enhancing the validity and comprehensiveness of our findings. By merging numerical analysis with thematic interpretation, this study provides a thorough assessment of how e-learning influences both academic competencies and professional readiness.

Sampling and Participants

The study focused on Bachelor of Science in Criminology students taking Forensic Chemistry at a state college in the Philippines, with an estimated total of 1,300 students enrolled in the program. By applying Slovin's formula with a 5% margin of error, the minimum required sample size was calculated as 1,200. A purposive sampling method was used, targeting students familiar with e-learning platforms such as Learning Management Systems (LMS), Google Meet, YouTube, and virtual laboratory tools. Of these, 300 students participated in the quantitative survey, and 10 students were chosen from this group for qualitative interviews and discussions. To provide context for the results, participant demographics, such as age, year level, and gender, were documented.

Instruments

The primary instrument employed in this study was a survey crafted by the researchers to assess attitudes toward e-learning in the context of forensic chemistry education. This survey drew on existing frameworks related to technology readiness and digital learning, as recommended by Hao (2016), Hung et al. (2010), and Islam (2019). It comprised various sections, with questions rated on a scale from 1 (Strongly Disagree) to 5 (Strongly Agree). The survey inquired about the role of e-learning in enhancing students' understanding of forensic chemistry, their confidence in using digital tools, and the obstacles they encounter online. Experts evaluated the survey to ensure clarity and precision, and a small group of criminology students tested it to refine the wording. The survey demonstrated high reliability, with a Cronbach's alpha of 0.86. Additionally, a semi-structured interview guide was utilized to delve deeper into students' experiences and complement the survey findings.

Data Collection Procedures

Data were collected using both digital and physical methods. The survey was distributed online using Google Forms and in hard copy for students with limited Internet connectivity. Semi-structured interviews and optional focus group discussions were held either in person or through online platforms such as Google Meet,

based on the availability of participants. Before participating, students received informed consent forms that explained the study's goals, the voluntary nature of their participation, confidentiality protocols, and their right to withdraw at any point. The university's research ethics committee granted ethical approval, and all data were anonymized and securely stored to ensure the participants' privacy.

Data Analysis Techniques

Quantitative data were analyzed using descriptive statistics (frequency, mean, and standard deviation) to summarize student perceptions, as well as correlational analysis (Spearman's rho) and regression analysis to determine the relationship between perceptions of e-learning and readiness to use digital tools. Qualitative data were processed through thematic analysis, which involved coding responses, identifying recurring themes, and interpreting findings in relation to research questions. To ensure rigor, NVivo software and manual coding methods were employed, allowing for triangulation between qualitative and quantitative results.

Result and Discussion

Table 1. Cronbach's Alpha Ability Values for the Questionnaire Items.

Items	Number of Items	Cronbach's alpha Values
Total	11	0.936

Cronbach's alpha is a well-established measure used to assess the internal consistency reliability of scales and questionnaires in research, indicating how well the items in a test evaluate a single construct. In response to your question about the Cronbach's alpha value for a set of 11 items with an overall alpha of 0.936, this reflects a high degree of internal consistency, confirming the reliability of the questionnaire (Izah et al., 2024; Izah et al., 2023). Cronbach's alpha is especially beneficial in educational settings, as it verifies the reliability of tools used to evaluate student skills and preparedness, such as forensic chemistry for criminologists. A high Cronbach's alpha (generally above 0.7) is considered a sign of good internal consistency and indicates that the items consistently measure a single latent construct across various administrations (Izah et al., 2023; Trinchera et al., 2018). The substantial Cronbach's alpha value of 0.936 demonstrates strong internal consistency for the questionnaire items, implying that they effectively measure the construct of competence and readiness in forensic chemistry. This high reliability ensures that the questionnaire yields consistent and repeatable results, which is crucial for equipping future criminologists through effective e-learning.

Table 2. Profile of Respondents by Age

Age	**Frequency**	**Percentage**
18 – 20 years old	150	50.00%
21 – 23 years old	132	44.00%
24 – 26 years old	17	5.67%
27 years old and above	1	0.33%
Average		100%

Table 2 highlights important insights into how students perceive e-learning in forensic chemistry. Most participants were aged between 18 and 23 years, were male, and were in their second year of study. Students generally held positive opinions about e-learning, particularly appreciating multimedia resources. They recognized both the challenges and opportunities it presents, with the strongest consensus being that e-learning offers excellent value in terms of cost and quality. The respondents showed a willingness to use e-

learning tools, especially in their future careers. There was a strong positive correlation between students' perceptions of e-learning and their readiness to use e-learning tools. Additionally, regression analysis revealed that the willingness to use e-learning tools significantly impacted students' positive perceptions of e-learning in forensic chemistry. Overall, the findings indicate that students generally view e-learning in forensic chemistry favorably, acknowledge its potential benefits and challenges, and feel equipped to use e-learning tools in their studies and future professional endeavors.

Table 3. Profile of Respondents by Sex

Sex	**Frequency**	**Percentage**
Male	182	60.67%
Female	112	37.33%
Prefer not to say	6	2.00%
Average		100%

Figure 3 illustrates that the analysis of the gender distribution among the 300 survey respondents showed a clear dominance of male participants. Specifically, 182 individuals (60.67 %) were male, accounting for the majority of the sample. Female participants were the second largest group, with 112 individuals (37.33 %). A small portion of the respondents, six (2%), opted not to disclose their gender. This gender breakdown offers valuable insights into the survey's demographic composition, highlighting a notable disparity in representation between male and female respondents and recognizing those who chose not to specify their gender.

Table 4. Perceptions of E-Learning in Forensic Chemistry

Indicator	Weighted Mean	Interpretation	Standard Deviation
E-learning helps me understand forensic chemistry concepts better.	3.83	Agree	0.90
Multimedia resources (videos, animations) are helpful in my learning.	3.89	Agree	1.00
I feel confident studying forensic chemistry through e-learning.	3.62	Agree	1.04
I prefer learning forensic chemistry through digital tools.	3.65	Agree	1.04
Average	3.75	Agree	

Table 4 illustrates students' favorable views on e-learning in the context of forensic chemistry. The average weighted mean of 3.75 suggests that students concur with the effectiveness of e-learning for this subject (Gyamfi & Sukseemuang, 2017; Khalil & Al-Harbi, 2022). Students particularly appreciated multimedia resources, which received the highest weighted mean of 3.89 (Mezil et al. 2020). This finding is consistent with studies indicating that animated videos boost student engagement in science education (Mezil et al., 2020). Although students agreed that e-learning facilitates the understanding of forensic chemistry concepts (3.83), their confidence in learning through e-learning was somewhat lower (3.62) (Ibrahim et al., 2021; Jiang et al., 2022). This suggests that while students acknowledge the advantages of e-learning, there are still adaptation challenges (Roick et al., 2023). The data reflect a generally positive reception of e-learning in forensic chemistry education, although standard deviations around 1.00 reveal varied student perceptions. This highlights the importance of accommodating diverse learning styles and enhancing online platforms to boost students' confidence (Mezil et al. 2020; Roick et al. 2023).

Table 5. Challenges and Opportunities in Using E-Learning

Indicator	Weighted Mean	Interpretation	Standard Deviation
I experience internet connectivity issues when using e-learning.	3.83	Agree	0.97
Some forensic concepts are hard to understand without hands-on labs.	3.95	Agree	0.93
E-learning allows me to learn at my own pace.	3.79	Agree	0.87
I find it easier to access learning materials through e-learning.	3.77	Agree	0.90
Average	3.84	Agree	

Table 5 presents a statistical analysis that sheds light on both the difficulties and advantages of e-learning in forensic chemistry education (Stern, 2017). The average weighted mean of 3.84 indicates that the students generally agreed with the statements. One major challenge identified is internet connectivity issues, with a weighted mean of 3.83 (Jafar et al., 2023), which aligns with other studies highlighting this as a significant technical obstacle (Alsahou et al., 2022). The most significant challenge was grasping forensic concepts without direct laboratory experience, which received the highest weighted mean of 3.95, emphasizing the critical role of practical skills in forensic education (Alsahou et al., 2022; Forde and O' Brien, 2022). Students acknowledged that e-learning supports self-paced learning (weighted mean = 3.79) and provides easier access to materials (weighted mean = 3.77), reinforcing the opportunities noted in other studies (Forde & Obrien, 2022). This is consistent with the learner-centered advantages of e-learning (Alzahrani 2020). Although e-learning in forensic chemistry faces challenges related to technical issues and the absence of hands-on experience, it offers flexible learning and better access to study materials than traditional learning. Institutions should address connectivity problems and consider ways to incorporate practical components into online forensic education (Forde & Obrien 2022; Hayat et al. 2021).

Table 6. Readiness to Apply E-Learning Tools in Forensic Chemistry

Indicator	Weighted Mean	Interpretation	Standard Deviation
I am ready to use digital tools in future forensic-related work.	3.80	Agree	0.89
I can confidently use simulations or virtual labs in learning.	3.71	Agree	0.86
1I believe digital learning tools enhance professional preparedness.	3.80	Agree	0.87
Average	3.77	Agree	

Table 6 presents a statistical evaluation that reveals generally favorable readiness levels for integrating e-learning tools into forensic chemistry education. The weighted averages for the three indicators ranged from 3.71 to 3.80, corresponding to an "Agree" interpretation on the scale. This indicates that students largely agree that they are equipped to utilize digital tools in future forensic endeavors, can confidently participate in simulations and virtual labs, and believe that digital learning enhances their professional readiness (COBANOGLU & COBANOGLU, 2021; Mehran et al., 2017). The standard deviations, which ranged from 0.86 to 0.89, suggest relatively uniform responses among participants, indicating a general agreement on readiness for e-learning (Coskun et al., 2018; Kalghatgi et al.,

2023) Interestingly, while students express readiness for e-learning tools, some studies have identified a preference for face-to-face instruction over fully online learning in certain situations. For example, one study found that students were generally hesitant to enroll in fully online courses, highlighting the need for digital literacy training before implementing such courses (Mehran et al., 2017). In summary, the data indicate a moderate-to-high level of readiness among forensic chemistry students to apply e-learning tools in their education and careers. However, institutions should consider offering additional support and training to improve students' comfort and effectiveness with online learning methods (COBANOGLU & COBANOGLU, 2021; Coskun et al., 2018; Mehran et al., 2017).

Table 7. Correlation Between Perceptions of E-Learning and Readiness to Apply E-Learning Tools

Relationship	ρ	Kind of Relationship	p	Decision
Perceptions of E-Learning in Forensic Chemistry → Readiness to Apply E-Learning Tools in Practice	0.754	Very Strong Relationship	0.001	Significant

Table 7 The analysis results using Spearman's rank correlation coefficient reveal a strong positive association (ρ = 0.754) between perceptions of E-Learning in Forensic Chemistry and the readiness to utilize E-Learning tools in practice. The p-value (p = 0.001), being below 0.05, indicates that this relationship is statistically significant, leading to rejection of the null hypothesis (Fitriawan et al., 2023; Zine et al., 2023). Notably, these results are consistent with the findings of similar studies in other disciplines. For example, a study on nursing students identified a strong positive correlation between online learning self-efficacy and readiness for online learning (Rho=0.708, P=0.001) (Fitriawan et al., 2023). Furthermore, research involving economics students showed that ability and .

Table 6. Perceived Benefits of Using Lesson Exemplars

Perceived Benefits of Lesson Exemplars	Mean (M)	SD	Interpretation
The exemplar saves time in lesson preparation	4.47	0.52	Strongly Agree
The exemplar provides a clear benchmark for lesson quality	4.20	0.68	Agree
The exemplar enhances my confidence in teaching delivery	4.27	0.59	Agree
Overall Mean	4.31	0.60	Highly Useful

Table 6 The dimension of benefits received the highest rating (M = 4.31, SD = 0.60), with teachers strongly agreeing that exemplars saved time in lesson preparation (M = 4.47, SD = 0.52). They also acknowledged that exemplars provided a clear benchmark for lesson quality (M = 4.20, SD = 0.68) and enhanced their confidence in teaching delivery (M = 4.27, SD = 0.59). This aligns with the findings of Jiménez and Errabo (2024), who highlighted that lesson exemplars serve as effective reference tools to help standardize teaching practices while ensuring curriculum alignment. These results underscore the practical value of exemplars in reducing teachers' workloads and improving instructional consistency knowledge were the most critical factors affecting their e-learning readiness (Zine et al., 2023). In summary, the strong correlation between perceptions of e-learning and readiness to apply e-learning tools in Forensic Chemistry practice suggests that positive views of e-learning are associated with a greater willingness to implement these tools. This relationship highlights the importance of promoting positive attitudes towards e-learning to enhance its practical application in specialized fields such as Forensic Chemistry (Fitriawan et al., 2023; Nurtjahjanti et al., 2021; Zine et al., 2023).

Table 8. Regression Analysis Regression Analysis between Perceptions of E-Learning in Forensic Chemistry to the Readiness to Apply E-Learning Tools in Practice

	B	T	Sig.
(Constant)	.708	4.368	.001
Readiness to Apply E-Learning Tools in Practice	.806	19.143	.001

Dependent Variable: Perceptions of E-Learning in Forensic Chemistry Regression analysis examining the link between perceptions of e-learning in forensic chemistry and the readiness to utilize e-learning tools showed a significant and positive correlation. The model equation, (R = 0.708 + 0.806a), suggests that perceptions of e-learning rise by 0.806 units for each unit increase in readiness, indicating that readiness is a strong predictor of perception. This connection is supported by numerous studies that highlight the importance of readiness in determining the effectiveness and perception of e-learning systems. For example, research stresses the need to evaluate and improve readiness levels before implementing e-learning or m-learning systems, as users' perceptions greatly affect their willingness and readiness to use these systems (Ramadiani et al., 2020). Another study pointed out that digital readiness, including the availability of technological equipment and digital skills, directly affects students' socio-emotional perceptions and overall engagement in digital learning environments (Händel et al., 2020). Furthermore, the impact of readiness is echoed in research on digital transformation in education, indicating that factors such as computer anxiety and digital readiness significantly influence students' engagement and academic performance during e-learning experiences (Althubaiti et al., 2022). These findings collectively highlight the crucial role that readiness plays in shaping perceptions of e-learning and in determining the successful application and integration of such tools in educational practices.

Interview Results

The qualitative data gathered through interviews and focus group discussions revealed five central themes: Enrichment, Utilization, Enhancement, Resources, and Foundation. These themes reflect how criminology students perceived and experienced e-learning in forensic chemistry, highlighting both opportunities and challenges.

Enrichment

Students consistently described their learning experiences in forensic chemistry as enriching, pointing to the unique blend of theory and application. They found the course engaging and stimulating, especially when it was facilitated by dynamic teaching approaches. One student explained, “Forensic chemistry is very interesting and unique compared to other subjects, especially when our professor makes it fun and interactive.” Many emphasized how the subject sharpened their critical thinking and problem-solving skills, which they considered essential for their future as criminology professionals. This resonates with Magwilang (2022), who argued that case-based e-learning approaches can increase motivation and achievement in forensic chemistry.

Utilization

The level of students’ use of e-learning platforms varied significantly, showing that the utilization was not uniform across respondents. Some students admitted that they had not used e-learning tools extensively, while others relied on platforms such as YouTube, Google Classroom, and Coursera. As one participant shared, “Sometimes I just use Google or YouTube when the questions are really hard.” Others mentioned anticipating further integration, saying that their professor had announced that more e-learning activities would soon be introduced. This variation reflects what Ramadiani et al. (2020) highlighted: that readiness and access

strongly influence how effectively e-learning is adopted by students.

Enhancement

A common theme across the interviews was that e-learning enhanced the students' understanding of forensic chemistry concepts. Participants noted that online lectures, recorded sessions, quizzes, and digital simulations allowed them to revisit difficult topics at their own pace and convenience. For example, one student commented, "E-learning helped me understand how different chemicals are applied in forensic cases, especially when I could rewatch video demonstrations." Others, however, acknowledged limitations, particularly when studying in noisy home environments that hindered focus. This duality mirrors the findings of Ibrahim et al. (2021) and Roick et al. (2023), who noted that while e-learning supports comprehension, distractions and adaptation challenges can reduce its effectiveness.

Resources

Students also identified a wide range of e-learning resources that supported their study. Platforms such as Google Meet, LMS, Google Classroom, YouTube and ChatGPT were frequently mentioned. One participant explained, "YouTube videos helped me understand how forensic tests are done when we couldn't do them in the lab, while Google Classroom kept me updated with lessons and assignments." Some highlighted collaborative tools, such as discussion forums, encouraged peer-to-peer learning. These findings align with those of Mezil et al. (2020), who reported that multimedia resources, such as animations and videos, significantly increase engagement in science education.

Foundation

Finally, many students acknowledged that e-learning provided a foundation in forensic theories and techniques but was insufficient to fully prepare them for real-world forensic investigation. One respondent shared, "E-learning helps with theory, but it's just the basis—it can't replace the hands-on experience needed in actual crime scene work." While online learning provided knowledge in areas such as DNA analysis, chromatography, and evidence handling, students stressed that laboratory practice and field application are indispensable. This perspective reflects the findings of Forde and O'Brien (2022), who noted that while digital resources strengthen conceptual knowledge, the absence of physical laboratories limits the transfer of skills into practice.

Synthesis of the Interview Discussion

According to the interview results, students found that learning forensic chemistry through e-learning was a beneficial experience that enhanced their comprehension and provided access to a wide range of resources. However, the effectiveness of e-learning largely depends on how students interact with these tools and the support they receive in accessing reliable platforms. Although e-learning offers a strong theoretical foundation, its lack of hands-on practice means that it cannot fully replace traditional lab-based education. These insights suggest that a blended learning approach, combining digital tools with practical training, may be the most effective way to prepare criminology students for the demands of real-world forensic work. Students view e-learning in forensic chemistry as valuable, appreciating its capacity to deepen understanding and offer diverse resources, similar to the findings in biochemistry and molecular biology education, where virtual platforms enhanced engagement and learning experiences (Doluweera et al., 2023; Govindarajan & Rajaragupathy, 2021). The success of e-learning is heavily reliant on student engagement and the support they receive, including training to boost digital literacy and access to trustworthy platforms, as noted by faculty perceptions and systematic reviews of virtual lab use (Chudaeva & Soliman, 2024; Tatenov et al., 2023). Despite these benefits, e-learning cannot completely replace traditional lab-based education in forensic chemistry because of its inherent inability to provide the hands-on practical experience necessary for skill development, as evidenced by the limitations noted in virtual labs for physiology, engineering, and chemistry courses(Schnieder et al., 2022; Zhang et al., 2021). Innovative methods such as gamified virtual labs and blended

learning may boost engagement and conceptual understanding; however, they remain supplementary rather than replacements for physical laboratory work(Sanzana et al., 2023; Schnieder et al., 2022). Therefore, combining e-learning with hands-on practice is essential for comprehensive education in forensic chemistry.

Conclusion

This study demonstrates that e-learning significantly enhances criminology students' understanding and competence in forensic chemistry by providing accessible multimedia resources and flexible learning opportunities. Students generally hold positive perceptions of e-learning and exhibit readiness to apply digital tools in their future forensic work, with a strong correlation between these perceptions and readiness levels. However, challenges such as Internet connectivity issues and the lack of hands-on laboratory experience remain critical limitations that hinder the full effectiveness of e-learning in this field. The qualitative findings emphasize that while e-learning enriches theoretical knowledge and critical thinking skills, it cannot entirely substitute practical and lab-based training. Therefore, integrating e-learning with traditional hands-on approaches through blended learning models is essential for comprehensive forensic chemistry education that adequately prepares students for real-world professional requirements.

Limitations and Recommendation

This study is limited by challenges such as internet connectivity issues and the inability of e-learning to fully replicate hands-on laboratory experiences, which are critical for mastering practical forensic chemistry. The reliance on self-reported data and focus on a single institution may also affect the generalizability of the findings. To address these limitations, future research should expand to multiple institutions and consider longitudinal designs to better assess the long-term impact of e-learning on students. It is recommended that forensic chemistry education adopt a blended learning approach that integrates e-learning with traditional practical training to enhance both theoretical understanding and hands-on competence. Additionally, improving digital infrastructure and providing targeted support to boost students' digital literacy will further optimize the effectiveness of e-learning in the field.

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