

Effectiveness, Challenges, and Future Preferences of Online Lab Classes During Covid-19: A Study on The University Students of Science Faculty in Mymensingh

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ABSTRACT

The COVID-19 pandemic pressured the sudden adoption of online education, a problem exacerbated by the students of science faculties who are required to work with their hands. This research involved a comparison of the experiences of 137 students out of 8,628 students of Jatiya Kabi Kazi Nazrul Islam University (51) and Bangladesh Agricultural University (86) by using a descriptive and exploratory design with semi-structured interviews and questionnaires. The lack of lab facilities (54.2%), unreliable internet (37.7%), and lack of devices are the most frequent (8.1%), but more frequent among rural learners (77.4%), with an intermediate level of satisfaction. Most students are indifferent towards the long-term effects in the future, and more than half of them want to keep taking the online theory courses in the future. The regression analysis indicated that negative effects were on technical disruptions ($\beta = -0.271$, $p = 0.002$), and the access to the tools ($\beta = 0.368$) and institutional support ($\beta = 0.169$) had positive effects. Instructional effect ($r = 0.501$, $p < 0.001$) was observed as a result of these barriers. This work underscores that SDG-4-compliant measures that enable digital equality, virtual laboratories, and powerful instructor services are of value.

JEL Classifications: I23, I21, O33, D83, I18

Keywords: Effectiveness, Obstacles, COVID-19, Online-Lab-Class

INTRODUCTION

Coronavirus Disease 2019 (COVID-19) is a very transmissible respiratory disease caused by SARS-CoV-2, first discovered in Wuhan, China. It is transmitted through respiratory droplets and contaminated surfaces, leading to symptoms such as fever, cough, breathing difficulties, fatigue, and sore throat. Severe cases may lead to pneumonia and

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ARDS, both of which are fatal. Social distancing, wearing of masks, hand washing, lockdowns, and vaccination have been used in setting up key measures that have helped in the control of the spread (WHO, 2020). The pandemic affected the world's health, food systems, and employment greatly, pushing tens of millions into extreme poverty and causing a rise in undernourishment among up to 132 million people. Disrupted supply chains, unsafe working environments, and limited access to protection pose a considerable threat to farmers, agricultural workers, and migrant Labourers (World Bank, 2020). The inoculation of COVID-19 has prevented at least 14.4 million infections around the globe in the initial year, yet vaccination coverage is imbalanced, and poorer nations lag in this area (WB, 2023).

COVID-19 has brought a big challenge to Bangladesh. The virus was found on March 8, 2020, and by September 2023, the Department of Health reported 2,043,657 infections and 29,465 deaths (BSS, 2023). Numerous areas have been affected by the pandemic, among them: health, the economy, education, and social life. There were capacity and resource constraints in the healthcare system, and the economy was hit by setbacks in farming, production, and services. Lockdowns were then announced on March 26, 2020, and again on April 5, 2021, lowering production and trade locally, leading to decreased exports, especially in the ready-made garment industry, and a reduction in remittances (MIF, 2020). There was a loss of many informal workers and day labourers, which led to a decrease in family income and consumption of food (Jahan et al., 2021). Nonetheless, in 2020, agriculture, industry, and services made up 12.7%, 29.6%, and 52.8% of GDP, respectively, with a workforce of 38%, 22%, and 41%, respectively, and stimulus measures helped to recover the economy (Jahan et al., 2021). Schools and universities closed, moving to distance learning, creating digital disparities and exposing them to child labour, dropping out of school, and social injustices. Efforts by the government, like Smart Bangladesh, are aimed at merging online and physical education to make the country competitive in the global scene and to ensure that access to education is fair (BSS, 2023).

The COVID-19 pandemic has gravely affected the Bangladesh education system, leading to significant shutdowns of educational establishments and reduced effectiveness of online learning. Many students were excluded from the process due to network problems, a lack of devices, high data costs, and inadequately trained teachers. Even after students have completed online classes, exams, and presentations, there are still concerns about their job market readiness. Approximately 3.7 million children have been out of school since early 2020, and approximately 7.9 million students are currently experiencing learning loss. According to PPRC and BIGD surveys, 30% of secondary-level students experience educational disruption, while 43% struggle with mental health issues. University students also suffered significant psychological consequences, with 85% affected and female students disproportionately affected (Swapan, 2021; Hashan, 2020). Online education faced challenges such as limited access, slow internet, high costs, and students and teachers lacking technical skills (Dutta et al., 2020; Mahmud et al., 2021). This study focuses on Science Faculty students in Mymensingh and investigates challenges in online labs, pedagogy, equity, and student well-being to inform policies, improve educational quality, and strengthen resilience to future disruption. Of the 137 students, 46% were neutral, and 35.1% were satisfied with the online labs, while 46% believed that practical experience was

essential. 56.7% relied on mobile devices, whereas 78.1% were plagued by technical issues. Lack of lab equipment (54.2%) and living in a rural area (77.4%) were the main obstacles. Interest in future enrolment was mixed (likely 42.3%).

AIM AND OBJECTIVE OF THE STUDY

- I. To evaluate the effectiveness of online lab classes during the COVID-19 pandemic among university students of the Science Faculty in Mymensingh.
- II. To identify the key obstacles and challenges faced by students in participating in online lab classes during the COVID-19 pandemic.
- III. To explore students' perceptions, attitudes, and future preferences regarding the continuation of online lab classes post-pandemic

Hypothesis (H1): Lab classes during the COVID-19 pandemic significantly affect the effectiveness of learning among university students of the Science Faculty.

RATIONALE OF THE STUDY

This study emphasises the importance of sustaining higher education in Bangladesh during the COVID-19 pandemic using technology-based online programmes. Nevertheless, certain obstacles have been pointed out, especially among students of science faculties when their courses are necessitated to be studied in the laboratory (Kabir, 2020). Even though online practical classes were provided, there were positive and negative reports among the students (Saifullah et al., 2022; Siddique, 2022). In practice, the research presents the perception and barriers of learning and quality issues, and the advantages and disadvantages of online practical classes (Rabbi et al., 2022). The results can guide policymakers and officials to develop effective policies concerning online education. This study is a contribution to the existing literature, which provides the framework for further studies on technology-assisted education in Bangladesh and other developing nations (Begum et al., 2020). This paper examines the effects of online practical classes on science faculty students in Bangladesh during COVID-19 on learning challenges, student perceptions, and issues of quality of education. It can provide useful information about bettering technology-assisted learning, besides providing theoretical information to policy-makers to better practical education online, thus adding to the literature and providing guidance to research in developing countries in the future.

REVIEW OF LITERATURE

The reviewed literature in this study helps to understand the gaps, accumulate expertise, and conduct research on different points of view of online laboratory classes during the pandemic. It targets the student body of science faculty at BAU and JKKNIU and puts special emphasis on effectiveness, challenges in technology, and practical implementation. In Bangladesh, there have been only a few studies; however, the global literature sources offer numerous insights on enhancing online practical education (Combes, 2023).

There have been a number of studies examining the impacts of the COVID-19 pandemic on higher education and online learning. Mahdy (2020) observed research and students in the field of veterinary medicine and found that 96.7% experienced a considerable

academic derailment. The average score of online education was 5.1 ± 2.4 , and practical sections scored 3.6 ± 2.6 , which indicated that it was not easy to integrate practical training. This study also had such recommendations as interactive learning, real-world simulations, brief content, and 3D virtual tools. Islam et al. (2020) determined the main obstacles to online learning in Bangladesh: network difficulties, lack of facilities, poor student-teacher communication, and social-psychological drivers; 30.7% of the interviewees were located in rural regions where poor internet access is commonly accompanied by poor-quality mobile access. Hossain et al. (2021) state that half of the university students in Bangladesh were not only feeling depressed but also anxious a year into the pandemic, which is why psychological assistance as well as financial security and simplified education curricula should be prioritised. To benefit students, parents, and administrators, Iyer et al. (2020) recommended that US dental colleges keep and proceed with study activities through telecommuting. These articles point out the difficulties and possible ways to make online learning during a crisis effective. Many studies in Bangladesh, as well as many other countries across the globe, reveal that the COVID-19 pandemic considerably affected higher education, specifically online learning.

Nevertheless, the cross-sectional survey in Bangladesh reported that 61.48% of students in universities had been highly disrupted in their studies, and 47.84% showed significant concerns about their mental health during the pandemic. Universities helped students to attend online classes and had some financial and mental support (69.62%), but female students could score higher on knowledge and practice (Rahman et al., 2021). Indeed, a qualitative case study conducted at Rajshahi University discovered that online education applications such as Zoom, Facebook, and Google Classroom are not enough to satisfy the technical, professional, and specialised needs of higher education. The study cautioned that relying too heavily on online classes could result in session jams and have negative consequences for education, the economy, governance, and social stability (Mollah et al., 2020). It was found that effective online learning requires communication and social support, and teaching presence, social presence, and prompt response of the instructor play a vital role in creating positive student experiences (Gorsky and Blau, 2009). In March 2020, surveys of engineering students found that 30% could not manage work-life balance, 55% were demotivated, and 50% did not have a private study space. Logistical, technological, privacy, security, and practical training challenges were identified, and the study recommended strategies to address tool and technology gaps to improve learning outcomes (Asgari et al., 2021).

Thematic analyses revealed key themes such as educational impact, time management, challenges encountered, and future preferences, with preclinical students preferring online learning despite economic and network challenges (Khalil et al., 2020). Other studies identified successful online instruction factors such as well-designed content, motivated interaction, instructor support, online learning communities, and technological advancement (Sun, 2016). Topic modelling analyses identified scientific disciplines, support systems, and mental health as critical areas impacted by the pandemic (Vijayan, 2021). Case studies and meta-analyses have shown that resilient and adaptive teaching practices, rather than rigid pedagogical frameworks, improve outcomes, with blended learning outperforming strictly online or face-to-face instruction (Peimani et al., 2021; Means et al., 2013).

The students indicated that they felt more comfortable with learning activities in the physical classroom rather than with online competitive skills and resources in the midst of stress (Chakraborty et al., 2020). A crucial barrier in India and Ethiopia was institutional unpreparedness and digital divides, such as the lack of faculty training (Kummitha et al., 2021). Online photovoice methodology has proposed the following critical facilitators: technology, internet, communication, emotion, and financial resources, and barriers, including lack of technology, internet, learning settings, and interaction, which were mapped at ecological system levels, reflecting the interactions of individual, microsystem, exosystem, and macrosystem factors. Altogether, these works prove that online education ensured continuity in the time of COVID-19, but technical issues as well as socio-economic status, mental health, and absence of practical learning are considerable challenges that require adaptive, resilient, and resource-sensitive teaching methods.

The perceptions of online education among students have been studied on a worldwide level, and the studies by Mahdy (2020), Islam et al. (2020), Hossain et al. (2021), and Iyer et al. (2020) concern student satisfaction and the aspects that contribute to it. Nonetheless, there is a certain gap in the literature regarding the perception of science faculty students and their satisfaction with the online education systems in Bangladesh. Although Islam et al. (2020) investigated the issue of online classes during the COVID-19 period in Bangladesh, the effectiveness of online education among students studied in Bangladesh Agricultural University (BAU) and Jatiya Kabi Kazi Nazrul Islam University (JKKNIU) is yet to be investigated. Recommendations for improving online education include enhancing technological infrastructure, ensuring equal opportunity, improving internet access, validating e-exams, and conducting further objective studies.

Research on COVID-19's effectiveness in online education has primarily focused on lecture-based learning, mental health, and virtual platform difficulties. Bangladesh studies have mainly addressed connectivity concerns and psychological stress, while international studies have analysed medical, engineering, and dental education issues. However, the usefulness of online laboratory courses for science students remains unexplored, with no study specifically examining their opinions and preferences.

Research gap

While many studies have investigated online learning during the COVID-19 pandemic in Bangladesh (Islam et al., 2020; Hossain et al., 2021; Dutta and Smita, 2020), most have considered online classes and online lectures and did not study OL in the science learning disciplines and science laboratory education, wherein the laboratory practical element is a need to achieve learning outcomes. The experience of teaching science faculty students in an online laboratory has also received less attention in the international literature, with focus mainly dedicated to medical and dental students' experience of taking online exams or to engineering students' experience of studying in an online lab (Mahdy, 2020; Iyer et al., 2020; Asgari et al., 2021). Past studies have likewise also concentrated on satisfaction and difficulties, separately neglecting to completely examine how these variables add up to the effectiveness of online lab classes together with socio-economic variables, technological hindrances, and institutional differences. Moreover, Islam et al. (2020) explored the challenges with online classes in general in Bangladesh, but there is no present study that has found comparative evidence between Bangladesh Agricultural University (BAU) and

Jatiya Kabi Kazi Nazrul Islam University (JKKNIU), or that has especially assessed the opinions and preferences of the science students towards online laboratory courses. To solve this issue, this study has been undertaken, employing the Community of Inquiry (CoI) framework and Technology Acceptance Model (TAM), to explore the factors affecting the effective use of online laboratories and barriers among science faculty students of Mymensingh in an attempt to offer empirical support for future education policy and practice in Bangladesh.

THEORETICAL FRAMEWORK

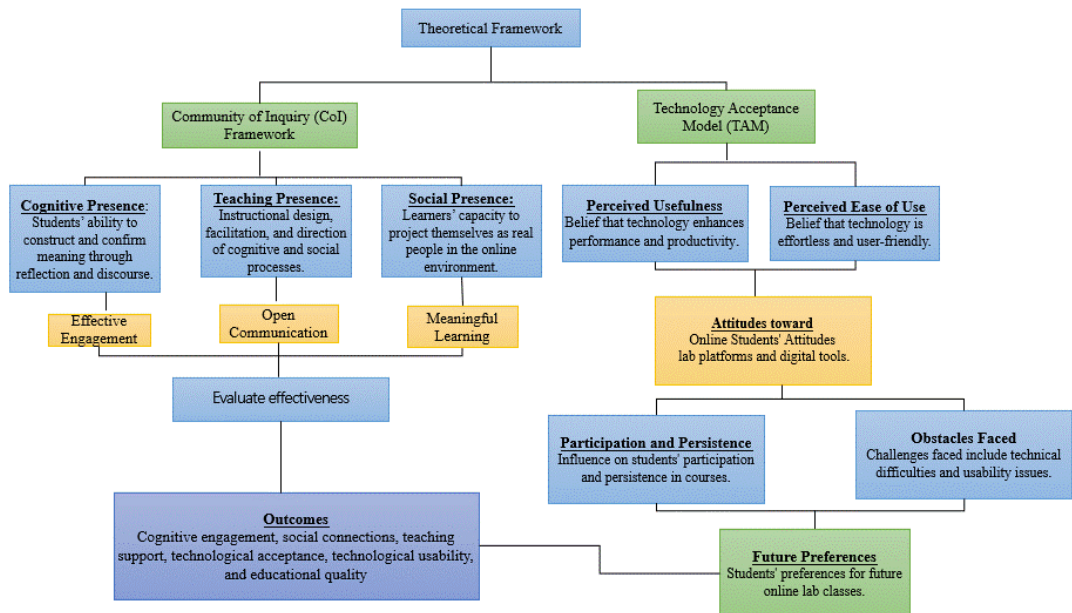
The theoretical framework explores the available theories to inform the research arguments, to demonstrate relevance, to have a systematic basis for a thesis, dissertation, or research paper, and to ensure that there is coherence and academic rigour (Sarah Vinz, 2022).

The Community of Inquiry (CoI) Framework and the Technology Acceptance Model (TAM)

CoI Framework, created by Garrison et al. (2000), focuses on efficient online learning in terms of social and cognitive presence as well as teaching presence. Social presence enables students to connect on an emotional level and openly communicate, cognitive presence encourages understanding because of reflection and discourse, and teaching presence facilitates design and facilitation, balancing social and cognitive factors and ensuring meaningful learning results (CoI, 2021; Martin et al., 2022; Harris et al., 2021).

Technology Acceptance Model (TAM) by Davis (1989) is used to understand the concept of technology acceptance in the context of perceived usefulness (PU) and ease of use (PEOU) to influence attitudes and behavioural intentions and direct actual use. Although it is extensively used, TAM has been accused of not taking into consideration social, organisational, and emotional variables, which represent a diminutive part of technology-use variability (Taherdoost, 2018).

CoI framework and TAM (Davis, 1989; Garrison et al., 1999) are good theoretical bases through which the effectiveness, challenges, and future preferences of online lab classes for science faculty students in Mymensingh can be studied. The CoI framework focuses on the mutual interaction between teaching presence, cognitive presence, and social presence as the requirements of the establishment of meaningful learning experience in online mode. Within the framework of science labs, teaching presence provides the appropriate instructional design and facilitation, cognitive presence provides the means of problem-solving and experimentation through digital modes, and social presence provides the facilitation of collaboration and peer support over distance. Moreover, the TAM accentuates the influence of perceived usefulness (PU) and perceived ease of use (PEOU) of students on their attitudes towards online lab technologies. When students consider online labs as helpful in mastering the skills, as well as convenient to utilise, the likelihood of students agreeing to them and planning to use them at the end of the pandemic increases. A combination of all these theories elucidates the dynamics of learning and technology adoption in online labs.

FIGURE 1. THEORETICAL FRAMEWORK

Source: Author Construct, 2025

TABLE 1. QUESTIONNAIRE MAPPING TABLE WITH RELEVANT FINDINGS

Framework	Construct	Questionnaire Items & Text
Community of Inquiry (CoI)	Teaching Presence	Sec 2, Q6: Access to online support/tutoring (teacher/classmate) — Yes/No
Community of Inquiry (CoI)	Social Presence	Sec 3, Q8: Felt isolated from peers — Yes/No/Sometimes Sec 4, Q7: Rating of support & resources available (Excellent–Poor)
Community of Inquiry (CoI)	Cognitive Presence	Sec 2, Q1 (1.1): Satisfaction with online lab experience (1–5) Sec 2, Q4: Did online labs replace hands-on experience? Sec 2, Q11: Satisfaction with virtual tools/software (1–5) Sec 3, Q10: Quality of online lab materials Sec 3, Q11: Adequately prepared for future coursework/career?
Technology Acceptance Model (TAM)	Perceived Usefulness	Sec 2, Q2: Access to necessary equipment/materials Sec 2, Q9: Should online labs continue post-pandemic? Sec 4, Q3: Belief that online labs provide quality education Sec 4, Q5: Importance of availability of online lab classes
Technology Acceptance Model (TAM)	Perceived Ease of Use	Sec 2, Q3: Frequency of technical issues Sec 4, Q8: Role of technology in effectiveness

**Percentages and statistics are drawn from Tables 1–7 and the accompanying narrative of "Effectiveness, Challenges, and Future Preferences of Online Lab Classes During Covid-19" (N = 137; BAU n = 86, JKKNIU n = 51).*

METHODOLOGY

This paper adopted a descriptive and exploratory research design to investigate the effectiveness and difficulties of online laboratory classes by science faculty students to learn during the COVID-19 pandemic in Mymensingh, Bangladesh. The use of a quantitative approach was mainly done to ensure a deep knowledge of the phenomenon. The primary method employed in the research was a social survey, though some other types of methods like survey interviews, in-depth interviews, and empirical observation were also employed to elucidate the analysis. A semi-structured questionnaire to gather primary data about respondents was developed. Researchers collected information from science faculty students of Bangladesh Agricultural University (BAU) and Jatiya Kabi Kazi Nazrul Islam University (JKKNIU) by using a semi-structured questionnaire from January 2025 to March 2025. We sent questionnaires directly to the eligible candidates, and filled forms were collected following informed consent, where both open-ended and structured answers could be provided. Primary and secondary data sources were used to gather data. Primary data were sampled with the help of students, and secondary data were acquired based on the organisational reports, academic books, peer-reviewed journal articles, online databases, newspapers, and similar empirical investigations to give background information. The target population was science faculty students studying at Jatiya Kabi Kazi Nazrul Islam University (JKKNIU) and Bangladesh Agricultural University (BAU) with a population of about 8628. Among them, we identified 51 respondents from JKKNIU and 86 from BAU; 137 sample students who took online laboratory classes during the pandemic were identified using convenience sampling. Convenience sampling was used in the present study as it would enable the researcher to select science faculty students that were readily available who did agree to participate in the study. In this study, the population of science faculty students was not possible due to the non-availability of a complete sampling frame of all science faculty students in Mymensingh, as it was a study among university students. Furthermore, due to time, resource, and participant limitations, probability sampling was not feasible. Hence, the respondents who met the study criteria who had been easily accessible were chosen for data gathering. Convenience sampling cannot be considered scientists' real sampling method to represent the analysed population; however, it is considered appropriate in social science studies when access to the target population is limited and is widely used as a sampling method. We computed the sample size using the Social Science Statistics sample size calculator. Here is the sample size formula,

$$n = \frac{Z^2 \cdot p(1 - p) \cdot N}{E^2(N - 1) + Z^2 \cdot p(1 - p)}$$

Confidence Level 95% (Z= 1.96)

Estimated Proportion, p= 0.1

Population Size, N= 8628

Margin of Error 5% ($E = 0.05$)

Sample size, $n \approx 137$

The parameters were 95% confidence, a population size of 8628, a proportion of 0.1, a confidence interval of 5, and a precision level of 5%, which gave a statistically valid sample. The individual student was used as the basis of analysis.

Pilot testing and reliability

To ensure relevance of the activities for the children in the target population, we conducted a pilot study involving 30 children who were not part of the final survey. To test the elements of the questionnaire for their clarity, wording, sequence, and relevance, the pilot test was conducted. Several minor corrections to the questionnaire were made based on participants' feedback as a whole to make the questionnaire more comprehensible and consistent.

Cronbach's alpha coefficient was used to determine internal consistency reliability of the questionnaire. Overall, the questionnaire showed fair reliability (Cronbach's $\alpha = 0.82$). The Cronbach's alpha values were calculated for all the constructs used in this study, the results of which were satisfactory internal consistency for social science research with values above 0.70 for the Effectiveness of Online Laboratory Classes (10 items; $\alpha = 0.84$), Obstacles to Online Laboratory Classes (8 items; $\alpha = 0.79$), and Future Perspective (6 items; $\alpha = 0.81$).

Researchers processed and analysed the data with the help of different statistical methods: descriptive and inferential analysis, classification, tabulation, frequency distribution, and percentages. The Statistical Package of the Social Sciences (SPSS) version 22 was used to conduct the analysis, thereby being accurate and reliability. This paradigm of research gave rigour and flexibility in the ways of exploring the numerous aspects of the experience of the students using online labs.

One hundred and fifty (150) student questionnaires were emailed to the eligible students. Out of the total questionnaires, 142 questionnaires were received with a 94.7% response rate. There were 137 questionnaires for final processing, after excluding five that had incomplete questionnaires.

TABLE 2. DISTRIBUTION, RETURN, EXCLUSION, AND FINAL ANALYSIS OF STUDENT QUESTIONNAIRES

Description	Number
Questionnaires distributed	150
Questionnaires returned	142
Incomplete questionnaires excluded	5
Valid questionnaires analysed	137
Final response rate	94.7%

Ethical considerations

All participants admitted were given information on the topic of the study, the voluntary nature of participation, confidentiality of the information they provide, and the

possibility of refusal or withdrawal from the study ad libitum, without any negative consequences. All participants gave written informed consent prior to data collection. Going no further, no personally identifiable information was collected, and all data collected were only used for academic research purposes.

FINDINGS AND ANALYSIS OF THE STUDY

The research concluded that during COVID-19, online lab classes enhanced flexibility and accessibility but had poor internet, lack of interaction, and did not have hands-on practice, decreasing student engagement and learning outcomes.

Demographic background of the respondents

Table 3 illustrates the socio-economic status of the selected population. Collected data shows that the 23-25 age group, with 67.2%, is higher than the other age groups. The sample size is almost equally distributed between males and females, who mainly belong to the 10500-20000 income group. A subgroup analysis was performed to compare students' perceptions between Bangladesh Agricultural University (BAU, n=86) and Jatiya Kabi Kazi Nazrul Islam University (JKKNIU, n=51).

TABLE 3. DEMOGRAPHIC PROFILE OF THE RESPONDENTS

Variables		Institution					
		BAU			JKKNIU		
		n	Per cent (%)	n	Per cent (%)	Total n	% of total
Gender	Male	44	32.1	24	17.5	68	49.6
	Female	42	30.7	27	19.7	69	50.4
	Total	86	62.8	51	37.2	137	100
Age	18-22	9	6.6	4	2.9	13	9.5
	23-25	53	38.7	39	28.5	92	67.2
	26-28	18	13.1	5	3.6	23	16.7
	29-32	6	4.4	3	2.2	9	6.6
	Total	86	62.8	51	37.2	137	100
Income	0-10000	25	18.2	10	7.3	35	25.5
	10500-20000	26	19	12	8.8	38	27.7
	21000-30000	23	16.8	9	6.6	32	23.4
	31000-40000	6	4.4	7	5.1	13	9.5
	41000-50000	6	4.4	13	9.5	19	13.9
	Total	86	62.8	51	37.3	137	100

Source: Field Survey, 2025

Student perspectives on online lab effectiveness

Table 04 demonstrates the perceptions of BAU and JKKNIU respondents regarding online science laboratory, resources, support, and readiness for a career in terms of their resources, support and satisfaction.

TABLE 4. SATISFACTION AND PERCEIVED EFFECTIVENESS OF ONLINE LABS

Variables			Standard Deviation	Institution					
				BAU		JKKNIU		Total n	% of total
				n	%	n	%		
Satisfaction with Online Science Lab Courses	Not at all	0.79460	15	10.9	9	6.6	24	17.5	
	Satisfied		29	21.2	19	13.9	48	35.1	
	Neutral		41	29.9	22	16.1	63	46	
	Very satisfied		0	0	1	0.7	1	0.7	
	Extremely satisfied		1	0.7	0	0	1	0.7	
	Total		86	62.7	51	37.3	137	100	
Replacement of Hands-on Lab Experience	Yes, completely	0.72317	13	9.5	8	5.8	21	15.3	
	Yes, to some extent		35	25.5	18	13.1	53	38.7	
	No, not at all		38	27.7	25	18.2	63	46	
	Total		86	62.7	51	37.1	137	100	
Access to Online Support/Tutoring	Yes	0.46577	59	43.1	35	25.5	94	68.6	
	No		27	19.7	16	11.7	43	31.4	
	Total		86	62.8	51	37.2	137	100	
Satisfaction with Virtual Tools & Software	Not at all	1.01608	7	5.1	4	2.9	11	8	
	Satisfied		19	13.9	8	5.8	27	19.7	
	Neutral		27	19.7	20	14.6	47	34.3	
	Very satisfied		27	19.7	19	13.9	46	33.6	
	Extremely satisfied		6	4.4	0	0	6	4.4	
	Total		86	62.8	51	37.2	137	100	

Source: Field Survey, 2025

The mixed students' perceptions towards online courses associated with science laboratories are shown in Table 4. The majority response was most likely at the neutral

(46.0%) or satisfied (35.1%) level, with only 1.4% indicating very satisfied/excellent level of satisfaction. Almost half (46.0%) agreed that online labs could not take the place of hands-on experience, while 38.7% agreed that it could be partially replaced. Majority got on-line support (68.6%). The virtual tools generally were more satisfying; 33.6% were very satisfied, while 34.3% were neutral.

TABLE 5. INSTRUCTIONAL QUALITY AND TECHNOLOGICAL INTEGRATION

Variables			Standard Deviations	Institution				Total n	% of total
				BAU		JKKNIU			
				n	%	n	%		
Average Lab Classes per Week	1	1.02904		7	5.1	8	5.8	15	10.9
	2-3			40	29.2	22	16.1	62	45.3
	5			11	8	8	5.8	19	13.9
	6 more			28	20.4	13	9.5	41	29.9
	Total			86	62.7	51	37.2	137	100
Quality of Online Lab Materials	Excellent	0.85524		3	2.2	3	2.2	6	4.4
	Good			40	29.2	25	18.2	65	47.4
	Fair			21	15.3	17	12.4	38	27.7
	Poor			22	16.1	6	4.4	28	20.5
	Total			86	62.8	51	37.2	137	100
Importance & Availability of lab Support Resources	Excellent	0.94128		8	5.8	3	2.2	11	8
	Good			33	24.1	31	22.6	64	46.7
	Fair			18	13.1	11	8	29	21.2
	Poor			27	19.7	6	4.4	33	24.1
	Total			86	62.7	51	37.2	137	100
Role of Technology in Online Lab Effectiveness	Very important	0.76043		13	9.5	13	9.5	26	19
	Important			59	43.1	29	21.2	88	64.2
	Neutral			9	6.6	4	2.9	13	9.5
	Not important			5	3.6	5	3.6	10	7.3
	Total			86	62.8	51	37.2	137	100

Source: Field Survey, 2025

According to Table 5, the majority of the students attended 2 - 3 online lab classes (45.3%), while 29.9% of students attended six or more lab classes online per week. In

general, the quality of the lab materials available online was rated mostly good (47.4%), with 20.5% rating it as poor. Likewise, the overall ratings for lab support and resources were good (46.7%). Some students regarded the use of technology as important; 64.2% labelled it as important and 19.0% very important about the overall effectiveness of online labs.

The obstacles of the online lab classes for students

Table 6 explores obstacles encountered by BAU and JKKNIU students in online labs, including technical, device access, isolation and infrastructure barriers, and future willingness to be enrolled.

TABLE 6. TECHNICAL CHALLENGES AND SOCIO-SPATIAL BARRIERS

Variables		Standard Deviations	Institution					
			BAU		JKKNIU		Total n	% of total
			n	Per cent (%)	n	Per cent (%)		
Frequency of Technical Issues	Never	1.01650	1	0.7	3	2.2	4	2.9
	Rarely		15	10.9	11	8	26	19
	Occasionally		37	27	24	17.5	61	44.5
	Frequently		16	11.7	10	7.3	26	19
	Always		17	12.4	3	2.2	20	14.6
	Total		86	62.7	51	37.2	137	100
Availability of Devices	Laptop	0.48706	49	20.4	36	15	85	35.4
	Computer		6	2.5	6	2.5	12	5
	Mobile		86	35.8	50	20.8	136	56.7
	Tab		3	1.2	4	1.7	7	2.9
	Total		144	59.9	96	40	240	100
Living Area During Pandemic	Rural area	0.41996	67	48.9	39	28.5	106	77.4
	Urban area		19	13.9	12	8.8	31	22.6
	Total		86	62.8	51	37.3	137	100

Source: Field Survey, 2025

Table 6 presents the main technical and socio-spatial obstacles to online lab learning. Occasionally (44.5%) and rarely (19.0%) were the most common answers for problems with technical issues, while frequently (19.0%) and always (14.6%) were less common problems. The mobile phone was the most frequently used device (56.7%), followed by laptops (35.4%). During the pandemic, 77.4% of students were from a rural area, suggesting the location and device dependency had a significant impact on the opportunity students had for effective participation in the science laboratories online.

TABLE 7. STUDENT ENGAGEMENT AND STRUCTURAL OBSTACLES

Variables		Standard Deviations	Institution					
			BAU		JKKNIU		Total n	% of total
			n	Per cent (%)	n	Per cent (%)		
Obstacles in Online Lab Participation	Network	0.47883	55	23.3	34	14.4	89	37.7
	Device		16	6.8	3	1.3	19	8.1
	Lab Instrument		83	35.2	45	19.1	128	54.2
	Total		154	65.3	82	34.8	236	100
Access to Lab Facilities During the Pandemic	Yes	0.32235	7	5.1	9	6.6	16	11.7
	No		79	57.7	42	30.6	121	88.3
	Total		86	62.8	51	37.2	137	100
Feeling of Isolation with Peers During COVID-19	Yes	0.80467	43	31.4	23	16.8	66	48.2
	No		27	19.7	13	9.5	40	29.2
	Sometimes		16	11.7	15	10.9	31	22.6
	Total		86	62.8	51	37.2	137	100

Source: Field Survey, 2025

Online participation in lab experiences had significant challenges related to engagement and structure in addition (Table 7). The most frequently reported obstacle was not having lab instruments (54.2%), followed by network-related problems (37.7%), and device-related problems (8.1%). Physical lab facilities were very restricted, with 88.3% reporting that NO access was available during the pandemic. Peer isolation also stood out; 48.2% said they felt isolated and 22.6% sometimes for the entire population, overall.

The future perception of the respondents

Table 8 presents the attitudes of BAU and JKKNIU students towards online labs and theory classes, their continuation after the pandemic, their adoption, and their motivations regarding possible effects on traditional education. Findings revealed that BAU students were more in favour of continuing online theory classes (35.8%) compared to JKKNIU students (19%). Regarding the perceived long-term impact on traditional education, positive perceptions were slightly higher among BAU respondents (16.8%) than those from JKKNIU (13.9%).

TABLE 8. THE FUTURE PERCEPTION OF THE STUDENTS

Variables			Institution				Total (n)	% of total
			BAU		JKKNIU			
			n	Per cent (%)	n	Per cent (%)		
Continuation of Online Theory Class Post- Pandemic	Yes	49	35.8	26	19	75	54.7	
	No	30	21.9	19	13.9	49	35.8	
	Not sure	7	5.1	6	4.4	13	9.5	
	Total	86	62.8	51	37.3	137	100	
Factors Influencing Attention to Online Labs	Personal interest in the subject	38	20	18	9.5	56	29.5	
	Academic requirements	69	36.3	42	22.1	111	58.4	
	Recommendations from instructors	8	4.2	7	3.7	15	7.9	
	Availability of online lab classes	4	2.1	4	2.1	8	4.2	
	Total	119	62.6	71	37.4	190	100	
Perception of Long- Term Impact on Traditional Education	Positive	23	16.8	19	13.9	42	30.7	
	Neutral	41	29.9	25	18.3	66	48.2	
	Negative	22	16.1	7	5	29	21.1	
	Total	86	62.8	51	37.2	137	100	
Likelihood of Future Enrolment in Online Labs	Very likely	12	8.8	12	8.8	24	17.5	
	Likely	16	11.7	18	13.1	34	24.8	
	Neutral	31	22.6	14	10.2	45	32.8	
	Unlikely	16	11.7	6	4.4	22	16.1	
	Very unlikely	11	8	1	0.7	12	8.8	
	Total	86	62.8	51	37.2	137	100	

Source: Field Survey, 2025

Table 8 indicates that there is a practically equal split between those in favour of continuing online theory classes after the pandemic (54.7 yes, 38.8 no), and BAU students are also somewhat more favourable (35.8 no, 19 JKKNIU no) and 9.5 Not). The extent of online lab familiarity is: 49.6 are somewhat familiar, 23.4 very familiar, 27.0 unfamiliar more or less. The most significant drivers of engagement are academic requirements (58.4) and personal interest (29.5), with peer or instructor recommendations (7.9) and accessibility to it (4.2) being supportive. The attitudes towards the long-term consequences on traditional

education are primarily neutral (48.2), and 30.7% and 21.1% positive and negative, respectively. Future enrolment intentions are mixed, with 42.3% likely, 32.8% neutral, and 25% unlikely, indicating apprehension over practical, technical, and quality concerns.

THE EFFECTIVENESS AND OBSTACLES OF ONLINE LAB CLASSES DURING COVID-19

The table shows how the statistical model predicted variability in perceived instructional effectiveness, highlighting how challenges influenced students' overall learning experiences in the COVID-19 pandemic online education context.

Regression assumptions (multicollinearity and heteroscedasticity)

The basic assumptions, such as multicollinearity and heteroscedasticity, were carefully tested within the linear regression equation models. Various parameters of multicollinearity, such as Variance Inflation Factor (VIF) and Tolerance, were used to assess it. All VIFs were below the conservative value of 5, showing minimal multicollinearity of all the independent variables as presented in Table 06. Additionally, the assumption of homoscedasticity (constant variance) was assessed by checking the residual scatter plots, and it was found that the errors were randomly distributed around the regression line, which met the assumption of homoscedasticity.

TABLE 9. EFFECTIVENESS AND OBSTACLES IN ONLINE LAB CLASSES DURING COVID-19

Effectiveness			Obstacles		
Model	R ²	Adjusted R ²	Model	R ²	Adjusted R ²
1	0.322	0.251	1	0.739	0.711
ANOVA			ANOVA		
Sig. Value		0.000	Sig. Value		0.000

Source: Field Survey, 2025

The findings of Table 05 indicate that the model of effectiveness was statistically significant (the adjusted $R^2 = 0.251$ with a value of $R^2 = 0.322$) and that about 25% of the perceived effectiveness variance was explained using the predictors. In comparison, the obstacles model presented a greater R^2 of 0.739 and adjusted R^2 of 0.711, indicating that 71.9% of the variability in the challenges experienced by students was explained, which is also significant ($p < 0.001$). The results of these findings indicate that obstacles have greater predictive capacity in determining the online lab experiences of the students. The effect size for the regression models was determined using the Coefficient of Determination (R^2). For the Effectiveness model, the R^2 was 0.322, suggesting the predictors explained 32.2% of the variance. The Obstacles model showed a significantly higher effect size with an R^2 of 0.739, explaining 73.9% of the variability in student challenges.

Therefore, the analysis of the coefficients, Table 06, will study the effects that socio-economic variables, technical disturbances, and the circumstances of online education have

on students' perceived effectiveness of online labs and the barriers to it. Notable predictors have been identified, and they indicate which variable influenced students the greatest extent throughout the COVID-19 pandemic.

TABLE 10. DETERMINANTS OF EFFECTIVENESS AND OBSTACLES IN ONLINE LAB CLASSES DURING COVID-19

Independent variables	Coefficients									
	Dependent Variables									
	Effectiveness					Obstacles				
	β	t	Sig.	Collinearity Statistics		β	t	Sig.	Collinearity Statistics	
			(p)	Tol	VIF			(p)	Tol	VIF
Educational Institution	-0.122	-1.548	0.124	0.892	1.121	-0.173	-3.546	0.001	0.892	1.121
Respondents Education	-0.109	-1.185	0.238	0.653	1.532	-0.034	-0.600	0.550	0.653	1.532
Father's Education	0.099	0.729	0.467	0.296	3.380	0.137	1.614	0.109	0.296	3.380
Mother's Education	0.197	1.433	0.154	0.292	3.429	-0.030	-0.350	0.727	0.292	3.429
Father's Occupation	-0.003	-0.034	0.973	0.752	1.329	-0.015	-0.287	0.774	0.752	1.329
Mother's Occupation	0.030	0.340	0.735	0.690	1.449	0.039	0.707	0.481	0.690	1.449
Family Income	-0.230	-1.760	0.081	0.324	3.089	-0.080	-0.992	0.323	0.324	3.089
Area	-0.123	-1.461	0.147	0.776	1.289	0.165	3.160	0.002	0.776	1.289
Technical Disruptions	0.271	3.170	0.002	0.753	1.328	0.712	13.409	0.000	0.753	1.328
Online Support	0.169	1.942	0.054	0.728	1.373	0.072	1.333	0.185	0.728	1.373
Virtual Isolation	0.180	2.225	0.028	0.845	1.183	0.468	9.343	0.000	0.845	1.183
Access Online Tools	0.368	4.063	0.000	0.671	1.491	0.216	3.833	0.000	0.671	1.491
Online Lab Experience	0.059	0.648	0.518	0.671	1.490	-0.209	-3.724	0.000	0.671	1.490

NB: *Statistically significant at $p < .05$

Source: Field Survey, 2025

Table 10: To be effective, essential predictors were technical disruptions ($\beta = 0.271$, $p = 0.002$), virtual isolation ($\beta = 0.180$, $p = 0.028$), and the availability of online tools ($\beta = 0.368$, p less than 0.001): these factors significantly influence student perceptions. Family income and educational institution had marginal effects. As far as impediments go, technical disruptions ($\beta = 0.712$, $p < 0.001$), on-line isolation ($\beta = 0.468$, $p < 0.001$), on-line lab experience ($\beta = -0.209$, $p < 0.001$), area of residence ($\beta = 0.165$, $p = 0.002$) and availability of online tools ($\beta = 0.216$, $p < 0.001$) played significant roles in the No multicollinearity problems were detected through collinearity statistics ($VIF < 5$).

The association between obstacles and the effectiveness of online science lab classes

Table 11 uses chi-square and Spearman's rho to investigate the relationship between barriers and online science lab effectiveness, focusing on how technical issues, limited support, and resource shortages affected student performance.

TABLE 11. BARRIERS AND EFFECTIVENESS IN ONLINE SCIENCE LABS

Variables	Values	Frequency	(%)	(χ^2)	Correlation (Spearman's rho)
Obstacles	Low	11	8.0	$p < .001$ $v = .374$	$P < .001$ $r = .501^{**}$
	Moderate	48	35.1		
	High	78	56.9		
	Total	137	100		
Effectiveness	Low	53	38.7		
	Moderate	46	33.6		
	High	38	27.7		
	Total	137	100		

NB: *Statistically significant at $p < .05$

Source: Field Survey, 2025

In Table 11, the chi-square test indicates that there is a significant relationship between obstacles and effectiveness ($p < .001$, $v = .374$), which means that there is a strong correlation between high obstacles and effectiveness. Spearman rho correlation ($r = .501$, $p < .001$) also shows that there was a strong positive correlation, such that the higher the obstacles, the lower the effectiveness. Descriptive results indicate that the majority of the students show high obstacles (56.9%) and low effectiveness (38.7%). On the other hand, a few students had low obstacles (8.0%), and this resulted in higher effectiveness. The results present the paramount importance of reducing technical and resource-related barriers to enhance the students' performance in virtual science lab learning. Further, the association of obstacles with effectiveness was indicated with Cramer's V (.374) and Spearman's rho (.501) as representing moderate to strong effect sizes.

HYPOTHESIS (H1) TESTING AND ACCEPTANCE STATEMENT

Hypothesis testing (H1): It is hypothesised that online lab classes during the COVID-19 pandemic have a significant impact on the effectiveness of learning for students in the science faculty in the field of science. A regression analysis was conducted (Table 06) and showed that the critical predictors were included as follows: technical disruptions ($\beta = 0.271$, $p = 0.002$) and access to online tools ($\beta = 0.368$, $p < 0.001$), which were statistically significant. Overall model and individual key predictors were found to have p-values < 0.05 , which formally backs the research hypothesis (H1) while rejecting the null hypothesis (H0).

DISCUSSION OF THE STUDY

The paper discusses the perceptions of online science laboratories courses in BAU and JKKNIU among students and their views in terms of effectiveness, barriers, opportunities, and socio-economic and technological factors. Through the Technology Acceptance Model (TAM) and Community of Inquiry (CoI), it defines cognitive, teaching, and social presence, perceived usefulness, and ease of use as significant elements in the process of engagement, persistence, and attitude development. Based on the interpretation of the findings as reflected in the Community of Inquiry (CoI) framework, the TP appeared to be moderately supportive of the environment but not effective for learning. The relevance of online support/tutoring with different criteria for learning was also far too low (68.6%), although it was marginally correlated with the learning effectiveness ($p = 0.054$; $\beta = 0.169$). Social Presence was in sharp contrast, however, as a significant challenge. The incidence of feeling isolated was nearly half of the respondents, this had a significant effect on the perceived effectiveness of learning ($\beta = 0.180$, $p = 0.028$) and significantly increased the perceived obstacle to learning ($\beta = 0.468$, $p < 0.001$). Weak social interaction in the virtual environment is also highlighted by the limited quality of the support that was available, presenting: Only 8% gave "Excellent" and around 45% gave "Fair" and "Poor". Likewise, the pupils' satisfaction with regard to the use of the online laboratory was low; only 1.4% felt very satisfied, while 46% considered that online labs completely substituted hands-on experience in the laboratory, and 59.1% deemed that they were inadequate for preparing them for future courses and jobs. The learning effectiveness regression model ($R^2 = 0.322$, Adjusted $R^2 = 0.251$, and $p < 0.001$) indicates that the variation of learning effectiveness can be explained by one-fourth to one-third of technical, institutional, and socio-demographic factors, and other pedagogical factors can explain the rest.

There were also a few results that were explained by the Technology Acceptance Model (TAM), which consisted of four aspects regarding perceived usefulness and perceived ease of use. Students expressed mixed feelings about the value of using online labs, with a slight majority—57.7 per cent—saying they were at least making their materials and equipment available. As in TAM, access had a positive significant effect on learning effectiveness ($\beta = 0.368$, $p < 0.001$), while at the same time learning obstacles were significantly adversely affected by the lack of access ($\beta = 0.216$, $p < 0.001$). Perceived ease of use was the most influential, with technical problems occurring in 97% of the students, with technical disruptions having a significantly negative impact on learning effectiveness $\beta = 0.271$, $p = 0.002$ while technical problems had a significantly positive impact on perceived obstacles to learning $\beta = 0.712$, $p < 0.001$. Furthermore, obstacles and learning effectiveness

are strongly correlated ($\chi^2 = 55.09$, $p < 0.001$; Spearman's $r = 0.501$, $p < 0.001$), which shows that the technical problems and poor laboratory facilities hurt their perception of usefulness and cognitive participation. Overall, the results of the two analyses suggest that the study hypothesis is upheld; there is a strong relationship indicating that the different measures of online laboratory learning were negatively affected by COVID-19, where social interaction and technical issues appear to be the most important factors. These results indicate that the improvement of the digital infrastructure, laboratory technologies, and chances of academic interaction would be the most effective and meaningful method to improve the quality and efficiency of online laboratory education.

Gender was evenly represented (49.6% male, 50.4% female), with participants aged between 23 and 25 years, who were senior undergraduates or postgraduates and mostly belonged to Muslim families (65.7%). Fathers were mostly farmers (35.8%) or non-government workers (33.6%), and the mothers were mainly homemakers (86.9%). Rural and socio-economic disadvantages are manifested by low family income, low educational attainment, especially by mothers (51.1% primary level), which affect access, perceptions, and barriers to online lab learning (Islam et al., 2020).

The online lab classes enjoy moderate satisfaction, with the majority of the students expressing neutral (46%) or somewhat (35.1%) satisfaction, and only 1.4% expressing high satisfaction. Though 57.7% said that they had access to equipment and materials, nearly half of them said that they had a shortage of adequate resources. In particular, 59.1% indicated that online labs did not prepare them for future study or careers, which shows the disconnect between virtual and real-life learning. These results are consistent with Mahdy (2020) and Asgari et al. (2021), who concluded that practical disciplines were more disadvantaged when it comes to online transitioning, even with enhanced online teaching technologies. The most reported barriers were absence of lab instruments (54.2%), network problems (37.7%), and scarcity of devices (8.1%); those in rural areas were overrepresented (77.4%). Technical problems (44.5% occasionally; 14.6% always) were also an impediment to participation. In addition, 48.2% of the respondents felt left out by their peers, and issues of dwindling standards of education (20.5%) and lack of interaction between them (16.8%) were also a concern. These observations are consistent with Islam et al. (2020) and Doyumgac et al. (2020), who found an unstable network, inappropriate facilities, and socio-economic problems to be the main issues of online learning in Bangladesh and other related problems.

The willingness to continue online theory classes was accompanied by the unwillingness to take online lab-based courses, so the overall attitude of students related to the future of online labs is rather mixed. Very likely and likely to re-enrol were 17.5% and 24.8%, respectively, whereas 32.8% were neutral. The degree of participation was also chiefly motivated by scholastic needs (58.4%) and not personal interest (29.5%). Almost half of the respondents (48.2%) did not know the long-term effects of online education, whereas 30.7% linked it to being positive. The results resemble those collected by Khalil et al. (2020), who identified that the students tended to appreciate online courses as supplementary but not as an alternative to the in-person labs. The results of regression analysis indicated that the socio-economic context of parental education, occupation, and family income did not significantly affect effectiveness, whereas technical disruptions, online support, and access to digital tools were those that had the most impact on

effectiveness. There were technical disruptions, which decreased effectiveness ($p < 0.002$, $\beta = 0.271$) and increased obstacles ($p < 0.000$, $\beta = 0.712$). Likewise, access to online tools ($\beta = 0.368$ on effectiveness) and access to support ($\beta = 0.169$) had a positive effect on outcomes. This trend makes sense with respect to Gorsky and Blau (2009) and Sun (2016), who have emphasised the fact that successful online learning can be achieved with a good technological framework, based on support and interactive design, as opposed to the socio-economic status of the learners.

A strong association between obstacles and effectiveness was confirmed, with chi-square ($p < .001$, $v = .374$) and Spearman ($r = .501$, $p < .001$) showing that higher obstacles were associated with lower effectiveness. The rate of high obstacles was most frequent (56.9%), and the rate of low effectiveness was simultaneous (38.7%). Conversely, learners who faced fewer barriers were more satisfied and saw more value in online labs. These findings also corroborate with previous ones by Doyumgac et al. (2020), who indicated that low levels of technology and internet connectivity greatly lower educational achievements, and Mahdy (2020), who discovered that practical subjects seem to be the worst affected in online mode because of limited resources. The general discussion has shown that although students did not discount the importance of technology use and enjoyed the advantages of being able to study during the COVID-19 period, their satisfaction level was medium, and the barriers were high. Lack of equipment, unreliable internet, and the inability to communicate caused constant problems, which restrained the ability of online labs to substitute for practical experiments. The future intention to enrol was low and was motivated more by the need to complete studies than by the desire to do so. This is in line with other studies conducted in Bangladesh by Mollah et al. (2020), indicating that the online learning process is effective during emergencies, yet infeasible in the long-term technical and professional training. H_1 is accepted, and H_0 rejected for regression, correlation, and chi-square analyses, as all results are statistically significant ($p < 0.05$).

However, this study tries to examine every aspect which are related to the effectiveness and obstacles of online lab classes during COVID-19 for the students, but cannot cover all causes due to some limitations like time and funding. There is a possibility that future researchers conduct to other universities in Bangladesh, regional comparisons, inter-university comparisons, gender-specific effects, and post-pandemic status on online lab classes based on this study to arrive at more inclusive, equitable, and policy-oriented methods of enhancing the quality of education of the students.

LIMITATIONS OF THE STUDY

There are certain limitations which are worth noting in this study.

- One limitation is that the convenience sampling method may have resulted in selection bias and the findings may not be generalisable.
- Second, the data are taken from a cross-sectional design, which provides a snapshot of students' perceptions at a single point in time and is not amenable to making causal inferences.
- Third, the study used self-reported data, and there is a potential for recall bias and social desirability bias.

- Fourth, the current study only sampled two universities from Bangladesh; so, the findings might not represent the students from the other public or private universities in Bangladesh.
- Lastly, the research also failed to include a comparison group or follow-up over time, thereby minimising the comparisons that could be made with changes in students' perceptions over time.

FUTURE RESEARCH AGENDA

Because of the limited scope of the study, 137 students were randomly selected from 2 public universities (BAU & JKKNUIU) using convenience sampling; future studies should include students from more than 2 public and private universities throughout Bangladesh to ensure the broader applicability of results. Since the present design was cross sectional future studies are needed to investigate the students' perception and learning outcomes change over time, with the shift from Blended pedagogy to post-pandemic Blended pedagogy in the institution. A range of comparative studies across disciplines of science, engineering, medicine, and agriculture would elucidate science education in an online context beyond the context of science faculty like the current research paper. Results of this study should also be extended to research gender differences, digital inequality, and psychological factors in online laboratory learning, with the results related to socio-economic factors (such as low level of education and rurality) in the present study. Finally, to complete this study, blended laboratory learning and emerging technologies like virtual reality (VR), augmented reality (AR), and artificial intelligence (AI) in science teaching and learning should be advanced and investigated in future research.

CONCLUSION AND PRACTICAL APPLICATION

The COVID-19 pandemic has accelerated online science lab adoption in Bangladesh, but challenges outweigh opportunities. The findings, guided by CoI and TAM, reveal low engagement, technical barriers, and decreased effectiveness. Prior research confirms that without adequate infrastructure, online labs cannot achieve the desired results (Mahdy, 2020; Islam et al., 2020; Hossain et al., 2021).

However, the research establishment revealed that the respondents were nearly equally men (49.6%) and women (50.4%), of an age mainly between 23-25 (67.2%), having rural, economically varied dispositions, with low family income (25.5% below 10000BDT) and parental education as low as 51.1% of the mothers were at the primary level. There was only limited online lab satisfaction; 46% remained neutral, and 35.1% were somewhat satisfied. The most notable barriers were a lack of lab equipment (54.2%), network issues (37.7%), and equipment shortage (8.1%). Perceptions were divided in the future, with only 42.3 per cent likely to re-enrol.

Furthermore, regression modelling revealed an inverse relationship between effectiveness and technical disruptions ($\beta = 0.493$, $p < 0.001$), with a positive correlation between efficiency and access to digital tools ($\beta = 0.266$) and online support ($\beta = 0.191$), all of which were significant ($p < 0.001$). The significance of chi-square ($p < 0.001$, $v = 0.374$)

and Spearman correlation ($r = 0.501$, $p < 0.001$) supported the idea that greater obstacles were associated with lesser effectiveness. It points out that the resolution of technical obstacles and better access are even more important when compared to the demographic trends in online lab-based learning performance improvement.

In this study, it is evident that policies that promote SDG 4 (Quality Education) are important in terms of ensuring equal access to digital learning devices and infrastructure. Strategies should aim at levelling the digital divide, where rural and low-income students are provided with devices, reliable access, and support in technology matters. In conclusion, the study conclusion is that although online learning in the laboratory might be flexible, it has limitations with regard to its effectiveness because of technological limitations and resource limitations. Improved digital access, support, and infrastructure can decrease these barriers, thereby facilitating an increase in student engagement, satisfaction, and learning outcomes, especially in rural and low-resource settings.

The research highlights that online science laboratories are handy in times of COVID-19, but technology, pedagogy, and infrastructure should be enhanced. Universities like BAU and JKKNIU are encouraged to invest in virtual labs, cheap internet, loans of devices, hybrid models, peer collaboration, as well as faculty-student training to enhance engagement, social presence, and perceptions, and also offer realistic institutional and policy practice.

Policy Level Actions:

- Promote affordable high-speed internet access in rural areas for reliable connectivity.
- Offer low-cost laptops on loan and tablets to bridge the digital divide.
- Align digital education policies with SDG 4 for equitable access for underserved students.

Institutional Level Actions:

- Implement blended learning models, which combine online theory with limited in-person lab sessions.
- Encourage faculty to use simulation experiments, peer collaboration tools, and active learning strategies to increase engagement.
- Organise regular workshops to teach students and faculty how to effectively use digital learning platforms.

PRACTICAL RECOMMENDATIONS

Based on the findings, several recommendations are made for practice.

- Subsidising at least 80% of students in low-income and rural communities to gain access to high-speed internet links in public universities should be encouraged, as problems with the internet were reported among 37.7% of students identifying network issues as a constraint in this study and 77.4% of students living in rural areas.

- Virtual laboratory platforms that include interactive simulations and digital laboratory resources across all science departments need to be created within 2 years (54.2%), and access to online tools is the most powerful positive predictor of effectiveness ($\beta = 0.368$, $p < 0.001$).
- At least two training workshops per semester should be conducted at each faculty to enhance students' and teachers' digital competency and effective use of the lab technologies that are presented online to solve the technical disruptions, which were the strongest predictor of the obstacles identified in this study ($\beta = 0.712$, $p < 0.001$).
- The universities should adopt blended learning in the lab environment by combining online learning with face-to-face learning in the laboratory for better learning outcomes and student motivation, as 46% of respondents felt that there would be no replacement for hands-on learning in the lab if it were for an online course.
- Technical issues were an issue for 78.1% of students, and 68.6% of students had online technical support/tutoring, so 5% of students during online learning in the laboratory should have a dedicated technical support unit that can provide prompt technical assistance during students' laboratory sessions and could reduce interruptions due to technical issues.

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