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Introduction to Gel Electrophoresis Lab - Virtual Simulation in Biotechnology Course

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Abstract

Gel electrophoresis is a fundamental technique in molecular biology used to separate DNA fragments by size. However, limitations in laboratory facilities often hinder its implementation. This study aims to analyze students' understanding of the operating principles of gel electrophoresis, the functions of its main components, and their ability to interpret DNA separation results through a virtual practicum on the LabXchange platform. The study employed a descriptive qualitative approach with 63 fifth-semester students from the Biology Education Program. Data were collected through observations during the simulation, analysis of DNA band patterns generated by the virtual experiment, and students' responses in the worksheet. The findings indicate that the virtual simulation effectively visualizes the DNA migration process, enabling students to understand the roles of agarose gel, buffer, and electrical current in fragment separation. Students identified the relationship between fragment size and migration distance and evaluated the expected results based on electrophoresis theory. Thus, the virtual laboratory practicum proved to be an effective alternative learning method for enhancing conceptual understanding and analytical skills in gel electrophoresis.

Keywords: DNA; Gel Electrophoresis; Labxchange Simulation; Molecular Biology Learning; Virtual laboratory

INTRODUCTION

The 21st century demands increasingly rapid advances in science and technology across various aspects of life, including education. Technological developments serve not only as tools but also as essential elements that transform how people learn, work, and interact. In the context of learning, technology integration is necessary to facilitate students' access to information, develop higher-order thinking skills, and prepare them for increasingly complex global challenges. (Rahyuni et al., 2021;.Harahap & Solihin, 2025). Therefore, 21st-century learning must be designed to be more innovative, interactive, and relevant to students' needs in the digital age (Adawiyah et al., 2023). Technological developments, globalization, and social dynamics in today's era require universities to provide relevant and adaptive learning experiences for students (Yatimah et al., 2018). In science education, practical activities are essential components that not only strengthen understanding of theoretical concepts but also develop the scientific skills necessary in biology and biotechnology (Solihin, Apriliani, et al., 2025). However, many study programs face limitations in laboratory infrastructure, including insufficient availability of tools and materials to support all types of practical work. This condition can reduce the quality of learning and hinder students' achievement of competencies (Solihin, Bae, et al., 2025)

Previous research and reports have generally focused on the importance of hands-on lab work in physical laboratories, but have not addressed effective alternatives when laboratory facilities are not optimally accessible. In this context, virtual labs offer an innovative solution that bridges these limitations by enabling students to conduct experiments safely, in a structured, interactive manner, without requiring access to a physical laboratory (Byukusenge & Tarmo, 2022). The use of virtual laboratories in learning is strongly recommended, as it can overcome the limitations of physical laboratory facilities and infrastructure (Byukusenge & Tarmo, 2022). Virtual labs enable students to conduct simulated experiments, deepen their understanding of scientific concepts, and develop practical skills without technical barriers or safety risks (Mercado & Picardal, 2023). Furthermore, virtual labs offer flexibility in time and space, enabling interactive, iterative learning that reinforces understanding (Scherp & Meier, 2016). Thus, the implementation of virtual labs not only complements conventional practicums but also provides an innovative solution that ensures optimal learning quality despite limited laboratory facilities (Maryuningsih et al., 2019). One online platform that supports the implementation of virtual practicals is LabXchange, which provides a comprehensive guide to various types of science experiments (Lisa et al., 2022) This platform enables students to systematically simulate practical experiments, ranging from basic concepts to complex procedures, including DNA electrophoresis.*LabXchange* provides step-by-step guidance, interactive materials, and practical experiences that simulate real-world laboratory conditions. Using this platform is crucial, particularly in the context of limited laboratory resources, as it enables students to deepen their understanding of scientific concepts and develop practical skills (Subotin et al., 2021). Modern biotechnology is a branch of science that uses principles of biology, chemistry, and engineering to manipulate biological cells, tissues, or molecules to produce products, processes, or solutions of value to humans, industry, and the environment. This field encompasses a range of advanced techniques, including genetic engineering, tissue culture, recombinant protein production, and molecular analysis, enabling innovation in health, agriculture, and bioproduction (Azizah & Aloysius, 2021)

*Gel electrophoresis*is a laboratory technique used to separate biomolecules, such as DNA, RNA, and proteins, based on differences in their size, shape, and electrical charge. The basic principle of this technique is the migration of charged molecules through a gel matrix under an electric field; smaller or more compact molecules move faster through the gel's pores than larger or more complex molecules. Factors affecting separation include the gel concentration and type, the buffer composition and pH, the applied voltage, and the electrophoresis time. During this process, molecules are bound or stained with specific dyes for visualization, enabling high-precision analysis of the relative sizes and structural differences between fragments. This mechanism makes gel electrophoresis a highly sensitive technique and enables its adaptation to a wide range of biomolecule sizes and types (Kharki & Berrada, 2021). This practicum aims to examine the fundamental principles and operational stages of gel electrophoresis and to evaluate the benefits of virtual labs in practicum settings. *Gel electrophoresis and practical simulations to virtually* visualize and understand DNA separation.

RESEARCH METHODS

This study employs a qualitative descriptive approach with a virtual practicum-based learning design to describe students' conceptual understanding and analytical skills in gel electrophoresis practica using virtual simulations on the LabXchange platform. The research subjects were 63 fifth-semester students of the Biology Education Study Program at UIN Syarif Hidayatullah Jakarta, selected through purposive sampling, who had studied the basic concepts of DNA and molecular biotechnology.

Data collection was conducted through three main techniques, namely: 1) Observation of practicum activities, to observe student involvement, accuracy in following simulation procedures, and the ability to identify the stages of electrophoresis work. 2) Student worksheets (virtual LKM), which contain analytical questions related to the working principles of electrophoresis, component functions, and interpretation of DNA banding patterns. 3) Documentation of simulation results, in the form of screenshots of DNA banding patterns from virtual practicum results, which are analyzed based on their conformity to electrophoresis theory. Data analysis was conducted qualitatively and descriptively through the stages of data reduction, data presentation, and conclusion drawing.(Damayanti et al., 2022). Data from observations, student worksheet answers, and simulation documentation were analyzed by grouping student responses according to indicators of understanding of gel electrophoresis, including the direction of DNA migration, the relationship between fragment size and migration distance, and the interpretation of the quality of DNA separation.(Dewi et al., 2018).

RESULTS AND DISCUSSION

The subjects of this study were 63 Biology Education students in their fifth semester of Biotechnology. Subject selection was based on the suitability of the course material to the topic of the virtual-based gel electrophoresis practicum. Subject characteristics indicate that most students have not had direct experience with gel electrophoresis in a physical laboratory. This condition makes the virtual practicum a relevant learning alternative to assess students' understanding of the concepts and procedures of gel electrophoresis. The results of the virtual gel electrophoresis research conducted through simulation on the LabXchange platform are as follows:

Table 1. Results of Observations of Student Activities During Virtual Practicum

No	Observation Indicators	Number of Students (n=63)	Percentage (%)
1	Follow the practical stages according to procedures	56	88,9
2	Determine the correct direction of DNA migration	54	85,7
3	Explain the function of agarose gel	52	82,5
4	Explain the function of the electrophoresis buffer	50	79,4
5	Explaining the role of electric current	51	81,0

Based on Table 1, the results of observations of 63 students generally indicate a high level of achievement in the implementation of the electrophoresis practicum. A total of 56 students (88.9%) were able to follow the practicum stages according to the procedure, indicating that the majority of students had a good understanding of the practicum workflow. In addition, 54 students (85.7%) correctly determined the direction of DNA migration, indicating a strong knowledge of the basic principles of electrophoresis.

Regarding conceptual understanding, 52 students (82.5%) explained the function of agarose gel, whereas 50 students (79.4%) explained the function of the electrophoresis buffer. These percentages indicate that most students understand the roles of the main components in electrophoresis, although a small number still require conceptual reinforcement. Meanwhile, 51 students (81.0%) were able to explain the role of electric current, which indicates a good understanding of the DNA separation mechanism. Overall, these data suggest that the practicum was implemented effectively and supported students' conceptual understanding.

Table 2. Results of Analysis of Student Worksheet Answers (Virtual LKM)

No	Conceptual Understanding Aspects	Understanding Category	Number of Students
1	The working principle of gel electrophoresis	Good	48
2	Relationship between fragment size and migration distance	Good	50
3	Interpretation of DNA banding patterns	Pretty good	47
4	Identify the ideal results of electrophoresis	Good	45

Based on conceptual understanding data, the majority of students were in the good category in understanding the working principles of gel electrophoresis, the relationship between fragment size and migration distance, and identifying ideal electrophoresis results. The number of students with a good understanding of these aspects ranged from 45 to 50 students. Meanwhile, their knowledge of DNA banding pattern interpretation was in the fair–good category, indicating that strengthening of the analysis of results is still needed. In general, students demonstrated an adequate conceptual understanding of electrophoresis.

Table 3. DNA Banding Pattern Analysis from Virtual Simulation Results

No	DNA Band Analysis Criteria	Observation result
1	Direction of DNA migration	Towards the positive electrode
2	Small DNA fragments	Migrate further
3	Large DNA fragments	Migrating slower
4	DNA band sharpness	Clear and separate visibility
5	Conformity with electrophoresis theory	In accordance

Based on observations of DNA banding patterns, DNA migration appears to be toward the positive electrode, consistent with DNA's negative charge. Smaller DNA fragments migrate farther than larger, slower-moving fragments. DNA bands appear clear and well-separated, indicating optimal electrophoresis. Overall, the observations align with electrophoresis theory.

Table 4. Level of Conformity of Student Results with Ideal Results

No	Suitability Category	Number of Students	Percentage (%)
1	Very suitable	26	41,3
2	In accordance	21	33,3
3	Not suitable	16	25,4
	Total	63	100

Based on data on the suitability of the practicum results to the theory among 63 students, 26 students (41.3%) were in the very suitable category, indicating a strong ability to relate the electrophoresis practicum results to the theoretical concepts studied. Furthermore, 21 students (33.3%) were in the suitable category, indicating that most students correctly understood and interpreted the practicum results, although there were still minor limitations.

Meanwhile, 16 students (25.4%) were in the less appropriate category, indicating difficulties in understanding the relationship between observation results and DNA electrophoresis theory. Differences may influence this condition through variations in mastery of basic concepts, analytical skills, or practical experience. Overall, the majority of students (74.6%) demonstrated good to excellent agreement between the results of the practical and the theory; thus, it can be concluded that the implementation of the practical was effective in supporting students' conceptual understanding.

Table 5. Student Perceptions of the LabXchange Virtual Practicum

No	Statement	Agree (%)	Disagree (%)
1	A virtual lab makes it easier to understand the concept of electrophoresis	87,3	12,7
2	Easy-to-use simulation	84,1	15,9
3	Assisting in analyzing practical results	85,7	14,3
4	Suitable as an alternative to laboratory practicals	88,9	11,1

Based on questionnaire results assessing students' perceptions of virtual lab use, the majority of respondents agreed with all statements. 87.3% of students stated that the virtual lab facilitated understanding of electrophoresis concepts, while 84.1% found the simulations easy to use. Furthermore, 85.7% of respondents reported that the virtual lab assisted in analyzing laboratory results, and 88.9% considered it a suitable alternative to conventional laboratory facilities.

The relatively low percentage of disagreement (11.1–15.9%) indicates that a small proportion of students still face challenges in using or understanding the simulation. Overall, these data suggest that students received the virtual lab well and that it has strong potential as an effective learning medium for electrophoresis practica.

This discussion presents the results of gel electrophoresis simulations conducted on the LabXchange platform. The analysis focuses on the migration patterns of DNA bands, the relationship between fragment size and their movement speed in the gel matrix, and the degree of agreement between the simulation results and the theoretical principles of electrophoresis. The simulation results are then compared with students' predictions to assess the consistency of conceptual understanding, particularly with respect to migration direction and differences in the distance traveled by DNA fragments.(Maryuningsih et al., 2019).

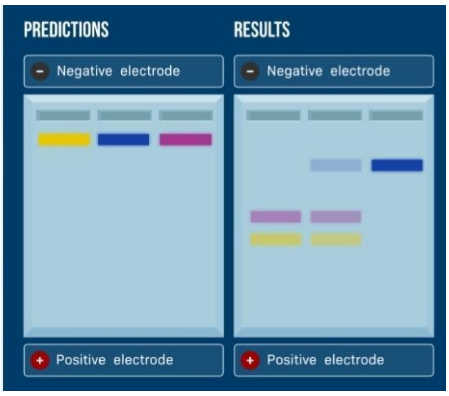

Figure 1. Predictions and Results from the Practicum: Gel *Electrophoresis*

Based on observations, DNA strands appear to migrate toward the positive electrode during electrophoresis. This occurs because DNA molecules contain negatively charged phosphate groups, which are attracted to the positive pole when an electric current is applied. The electrical charge on DNA is the primary factor determining the direction of molecular migration in an agarose gel. This demonstrates that the LabXchange simulation adequately illustrates the basic principles of electrophoresis. Observations show that small DNA bands migrate farther than larger bands. The size of DNA molecules affects migration speed because agarose gel acts as a filter that retains larger molecules more strongly. Small fragments pass through the gel's pores more readily and therefore migrate more quickly toward the positive electrode. This relationship between fragment size and migration distance demonstrates the effectiveness of the principle of molecular separation in electrophoresis. The resulting DNA banding pattern is clearly visible, although the intensity and thickness vary across lanes. The theory can explain this: variations in band thickness indicate differences in DNA concentration across samples. The greater the amount of DNA introduced into the gel well, the thicker the bands formed. Thus, this simulation can visually represent differences in DNA concentration.

During electrophoresis, the DNA bands did not overlap between lanes, indicating that the buffer system was functioning correctly. According to Maryuningsih et al., (2019) The buffer maintains pH stability, preserves a negative charge, and prevents DNA degradation during the process. This stability also prevents changes in the direction of molecular motion due to ionic fluctuations. Therefore, the simulation results indicate that the electrophoresis environment is ideal. According to Scherp & Meier, (2016) This practicum activity facilitates students' development of scientific process skills, such as asking questions, identifying problems, formulating hypotheses, compiling work steps, conducting experiments, and conducting observations and simulations. In the virtual gel electrophoresis practicum, this process is observed when students examine how the size of DNA fragments affects migration patterns in the gel. Students first identify the problem as differences in DNA migration distance, then formulate an initial assumption (hypothesis) that smaller fragments will migrate farther than larger fragments. Next, through simulations on the virtual platform, students follow the experimental procedure, beginning with sample preparation and selection.

According to (2024), the use of virtual labs has a significant positive impact because it provides interactive, easily accessible, and representative practical experience even without physical laboratory facilities. The advantage of the LabXchange platform in gel electrophoresis practice is its presentation, which includes systematic conceptual explanations and displays of ideal results at each stage of the procedure. This feature helps students understand not only the step-by-step procedure but also the expected results when electrophoresis is performed correctly. By visualizing ideal results such as neat DNA migration patterns, band separation according to fragment size, and stable gel conditions, students can compare their observations during the simulation with the expected standards. This allows students to identify errors, improve conceptual understanding, and enhance analytical skills regarding the working principles of electrophoresis.

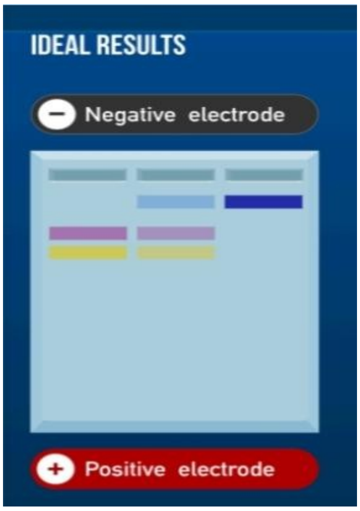

Figure 2. Ideal results of the Electrophoresis practicum

The DNA banding pattern in ideal results indicates stable, neat, and consistent fragment separation, characterized by parallel band positions, proportional migration distances, and uniform thickness. This condition suggests that all electrophoresis parameters, including agarose concentration, applied voltage, run time, and electrophoresis technique, have been met.

Loading. The sample is in an optimal state, allowing DNA fragments to migrate according to their size without experiencing distortion, diffusion, or overlap. Thus, these ideal results indicate the success of the electrophoresis process in efficiently and accurately separating DNA fragments (Maryuningsih et al., 2019). Virtual labs play an essential role in enhancing Higher Order Thinking Skills (HOTS) by providing an interactive, flexible learning environment that enables students to explore independently. Through simulations that replicate real-life experimental conditions, students are required to analyze each step of the procedure, predict outcomes, evaluate discrepancies between ideal and observed patterns, and critically interpret data. This process encourages higher-order thinking skills such as analysis, evaluation, and conceptual synthesis, which are often difficult to achieve in conventional labs due to time and equipment constraints. Furthermore, virtual labs allow students to repeat experiments without the risk of equipment damage or material waste, allowing them to deepen their understanding and correct errors reflectively. Thus, the use of virtual labs not only provides a safe, standardized laboratory experience but also effectively stimulates the development of students' HOTS (Makiyah, 2019).

According to Zahra Firdaus (2022), virtual labs provide an interactive learning experience in which students can participate directly at every stage of the practicum through responsive, easy-to-understand simulations. This interactivity allows students to conduct experiments, try various options, and see the consequences of each action in real time. Furthermore, the virtual platform is equipped with guidance features, such as step-by-step instructions, conceptual explanations, and automatic feedback, that help students understand the process more effectively. This combination of interactivity and guidance allows students not only to follow procedures passively but also to develop a stronger conceptual understanding by evaluating decisions made during the simulation. Thus, virtual labs are an effective tool for supporting independent learning while providing necessary guidance throughout the experimental process.

According to Evi Suryanti (2019), Student perceptions of the use of the Virtual Laboratory were generally positive, primarily because the platform was considered capable of providing a clear, focused, and easy-to-follow practicum experience even without physical laboratory facilities. Students found the interactive simulation interface easier to understand the experimental workflow, visualize the process, and connect theory to practice more concretely. Furthermore, the guidance, concept explanation, and automatic feedback features provided a sense of confidence, allowing them to learn without the fear of making risky mistakes, as they would in a real laboratory. Virtual laboratories were also considered to enhance time efficiency, learning flexibility, and practicum accessibility, allowing students to repeat specific steps until they fully grasp the concept. Overall, students viewed virtual labs as an effective and relevant learning tool that supports both practical and conceptual understanding, particularly in biotechnology-based courses and molecular laboratories.

According to et al. (2022), virtual laboratories provide significant protection against risks that usually arise in real laboratories, such as direct contact with electric current, the use of chemical buffers, or potential damage to sensitive electrophoresis equipment. In gel electrophoresis practica, students can learn all stages, from gel preparation and sample loading to operation of the power supply, without encountering physical hazards or procedural errors that could damage the equipment. Furthermore, the virtual platform automatically records DNA migration results in clear banding patterns, allowing students to observe, store, and analyze the data electronically. This digital documentation facilitates students' review of DNA fragment movement or comparison of results with theory, without the risk of data loss. Thus, the use of a virtual laboratory not only improves safety but also enhances observational accuracy and conceptual understanding in gel electrophoresis laboratories.

CONCLUSION

The virtual gel electrophoresis lab on the LabXchange platform successfully met all established learning objectives. Students understood the basic principles of electrophoresis, including DNA charge, migration direction, and the effect of fragment size on separation distance. Furthermore, students were able to identify the function of each principal component, such as agarose gel, sodium borate buffer, and*power supply*, and how these components work together to create optimal separation conditions. Virtual simulations also allow students to directly observe DNA banding patterns and compare them to ideal results, improving their data analysis and interpretation skills. Overall, the use of virtual laboratories has proven effective in supporting learning in molecular biology, particularly when physical laboratory facilities are limited.

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