Integrative Technology-Assisted Learning for Future Biology Teachers: Enhancing Theoretical Knowledge, Practical Competence, and Professional Readiness through Virtual Laboratories and Augmented Reality

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***Abstract*—This study evaluates the effectiveness of a technology-assisted integrative learning model for pre-service biology teachers. The model combines traditional pedagogy with virtual laboratories, Augmented Reality (AR), and project-based assignments to enhance theoretical knowledge, practical skills, and professional competence. The present study was conducted at three regional universities in Kazakhstan that offer teacher education programmes. The experimental group was instructed in accordance with an integrated curriculum, while the control group received conventional instruction devoid of the utilisation of digital tools. The assessment of student performance was conducted through a variety of methods, including tests, practical assignments, and project assessments. The findings indicate that the experimental group attained a 23% increase in test scores and a 31% enhancement in project quality in comparison with the control group. Furthermore, students reported elevated levels of satisfaction and perceived usefulness of digital technologies, indicating heightened motivation and readiness to teach in a digital environment. The findings of this study lend support to the necessity of incorporating proven digital platforms, structured project activities, and integrated virtual and physical laboratories into teacher education programmes. The study demonstrates the value of technology-assisted integrative learning for developing professional competencies and aligning teacher training with contemporary educational demands.**

***Keywords*—augmented reality, virtual laboratories, integrative learning, teacher education, biotechnology, professional competence**

I. Introduction

The rapid digitalisation of education continues to transform professional training and reshape the skills required of future teachers. In the field of biology education in particular, these changes are significant, as effective teaching is becoming increasingly dependent on digital tools that facilitate the understanding of complex biological and biotechnological concepts [1]. Integrative learning, which combines conventional pedagogical strategies with digital resources, offers promising opportunities to enhance professional preparation. It encourages pre-service biology teachers to apply theoretical knowledge to practical situations, develop procedural skills, and engage with technology-supported instructional methods. Meanwhile, biology and biotechnology, including plant propagation, remain central to addressing contemporary environmental and agricultural challenges [2].

Global data from UNESCO indicates an acute shortage of qualified science educators, which undermines the quality of science instruction worldwide. In 2021, EU member states reported a deficit of over 100,000 science teachers, including specialists in biology [3]. In the United States, almost 60% of teachers reported inadequate training in modern digital tools, hindering the adoption of innovative pedagogical approaches in biology classrooms [4]. These deficits directly impact pre-service teachers' interest in biology and reduce their preparedness to incorporate biotechnological methods into their future practice. Incorporating biotechnology-related activities, such as propagating stress-tolerant plants, into teacher training could enhance professional competence and environmental literacy. However, effective implementation requires educators with strong digital skills and methodological expertise [5, 6].

This study addresses the need for training approaches that integrate digital tools and biotechnology within a coherent instructional model for pre-service biology teachers. Technology-enhanced learning can increase access to practical activities, encourage flexible teaching methods and promote the development of professional skills in an ever-changing scientific landscape. Despite the increasing recognition of the value of digital pedagogy, there is a lack of comprehensive models in the literature for preparing biology teachers to use integrated digital and biotechnological methods. Closing this gap could provide scalable, practical solutions for enhancing teacher competence and classroom innovation.

This study aims to develop and test a technology-assisted integrative learning model to prepare pre-service biology teachers to propagate stress-resistant trees and shrubs.

The research objectives are to:

(1) design an experimental training programme that integrates digital technologies and biotechnology;

(2) conduct a comparative analysis of its effectiveness relative to traditional methods of preparation;

(3) examine the impact of integrative learning on the

professional skills, teaching readiness, and motivation of pre-service biology teachers.

The study addresses the following research questions:

RQ1: How effectively does technology-assisted integrative learning foster the development of professional skills among pre-service biology teachers?

RQ2: Which digital technologies are most effective for learning biotechnological methods of plant propagation?

RQ3: How does the proposed learning approach affect pre-service teachers' motivation and readiness to teach biology in a digital environment?

The central hypothesis is that technology-assisted integrative learning improves understanding of biotechnological methods, strengthens professional competence, and boosts motivation more effectively than traditional approaches.

II. Literature Review

Contemporary pedagogy is undergoing a swift transformation due to digitalisation, updated educational standards, and growing demands for the professional preparedness of future graduates. While digital technologies offer new opportunities for engagement and personalised learning, they also require educators to adapt to and master unfamiliar tools. Many pre-service teachers report having insufficient hands-on experience with digital applications [7]. Studies show that over 50% of teachers in developing countries struggle with digital integration, whereas nearly 80% of teachers in Finland and Singapore effectively employ digital resources in daily instruction [8]. Furthermore, surveys in the US and EU indicate that 60–70% of education students desire more technology-supported, practical coursework [9–13].

Digital tools are shaping current pedagogical practices significantly by enabling rich interaction, immediate access to scientific content, and personalised learning pathways. Virtual laboratories, 3D modelling platforms, and data analysis tools allow the exploration of cellular mechanisms, plant and animal anatomy, and genetic processes in interactive environments [14]. AR/VR applications such as Google Expeditions and zSpace create immersive learning experiences, while Learning Management Systems (LMS) such as Moodle and Blackboard organise course materials, assessments, and communication. Artificial intelligence is beginning to enhance biology education through plant growth prediction tools and genetic simulation platforms such as GenScope [15].

Integrative learning combines traditional teaching methods with digital tools to enhance instructional effectiveness and promote active, student-centred learning. In biology education, for example, this approach enables pre-service teachers to simulate real biological processes and analyse experimental data, thereby strengthening their pedagogical and professional competencies. Relevant integrative approaches include interdisciplinary instruction, which links biology with chemistry to deepen understanding of genetic and biochemical processes [16]; Project-Based Learning (PBL), which involves real-world tasks such as modelling the growth of stress-resistant plants [17]; problem-based learning, which requires solutions to biological challenges through digital analysis [18]; and flipped learning, which uses digital materials to prepare students before class, freeing up time during class meetings for practical work [19].

These approaches are grounded in established educational theories. For example, Piaget's cognitive development theory emphasises active knowledge construction, which is consistent with hands-on digital exploration in virtual and augmented environments [1, 2, 4]. Vygotsky's sociocultural theory emphasises guided learning and collaborative knowledge building, supporting the use of interactive platforms and project-based tasks [5, 6]. Constructivist principles emphasise problem solving and meaningful engagement, as seen in virtual laboratories and inquiry-oriented activities [14, 20, 21]. Experiential learning frameworks such as Kolb's model argue that knowledge emerges through cycles of concrete experience, reflection, and experimentation — an approach that is well suited to AR-enhanced plant propagation activities and biotechnology simulations [22, 23]. Integrating these theoretical foundations with digital tools supports the development of procedural skills and builds higher-order cognitive abilities and professional teaching competence in pre-service biology teachers [7, 12, 24].

Propagating stress-resistant trees and shrubs is particularly relevant in the context of climate change and mounting environmental pressures. This provides pre-service teachers with valuable opportunities to gain experience in ecologically significant biotechnology and develop digital and methodological competence.

III. Materials and Methods

A. Research Design

The study was conducted in 2024 at three regional universities in Kazakhstan (Kyzylorda: Korkyt Ata Kyzylorda University; Shymkent: Uzbekali Zhanibekov South Kazakhstan Pedagogical University; Turkistan: Qoja Ahmet Yassawi International Kazakh-Turkish University). The participants were third- and fourth-year students enrolled in biology teaching programs. The total number of participants was 120, with 70% (84) being female and 30% (36) male. The average age of the participants was 21.

The random selection process ensured that the total sample included an equal number of participants from different universities and was balanced by gender and year of study. The participants were randomly assigned to two groups: an experimental group and a control group (with 60 participants in each). After the division of the students into the groups, there were 46 women and 14 men in the experimental group, while the control group comprised 38 women and 22 men. Although this distribution is not perfectly balanced, it accounts for potential variations and maintains the representativeness of the sample. Therefore, the sample is suitable for the analysis of the effectiveness of the proposed training program.

The training program for the experimental group was designed by the researchers and incorporated an integrative approach that actively utilized digital technologies. This program is based on contemporary pedagogical principles that blend traditional methods of biology instruction with interactive digital resources such as virtual laboratories, educational platforms, and Augmented Reality (AR). The program also incorporated a module on biotechnology techniques for the propagation of stress-resistant tree and shrubbery plants, allowing students to acquire the skills necessary for teaching these topics at schools. In contrast, the control group followed the standard curriculum provided by the university, without incorporating digital technologies or integrative approaches. A comparison of learning outcomes between the two groups made it possible to assess the effectiveness of the proposed program.

Throughout this study, the term 'student' refers exclusively to pre-service biology teachers participating in teacher education programmes at three universities. It does not refer to school pupils. To ensure conceptual clarity and terminological consistency, the manuscript uses 'pre-service teachers' when discussing professional training, and 'students' only when describing their role as participants in the experiment.

A mixed-methods research design was selected because the research questions required the measurement of learning outcomes (knowledge, skills, competence and motivation) as well as an analysis of the participants' qualitative reflections on the integrative learning experience. Quantitative methods enabled an objective evaluation of changes in knowledge and competence, while qualitative analysis provided insights into pre-service teachers' perceptions, their readiness to teach and the reasoning behind their evaluations of digital tools. While the teaching intervention itself lasted 12 weeks, this manuscript analyses a dataset accumulated over a four-year period (2020–2024). This includes refined survey instruments, piloting protocols and observational checklists, all of which were iteratively improved before the final experiment.

B. Integrative Learning Model

The integrative learning model employed in this study rests on a synthesis of conventional pedagogical methodologies and modern digital technologies aimed at improving the quality of education for future biology teachers. This approach combines the benefits of classical education, which provides a thorough understanding of theoretical foundations, with innovative tools that foster the practical application of knowledge and the development of professional skills. The experiment involved the use of three key types of integrative learning: interdisciplinary, problem-based, and project-based learning. The interdisciplinary nature of the project fostered connections between biology, computer science and ecology. The students engaged in a comprehensive study of biotechnological plant propagation, encompassing the analysis of plant physiological characteristics. Utilising digital tools, they modelled plant growth and visualised experimental results, fostering an understanding of biotechnological processes in a practical and analytical manner. This approach fostered a holistic view of biology teaching among future teachers and emphasised the practical relevance of knowledge from various fields.

The utilisation of problem-based learning methodologies was instrumental in fostering the development of critical thinking and analytical skills. The students were presented with tasks pertinent to the propagation of stress-resistant trees and shrubs. These included the development of a breeding strategy for specific climatic zones in Kazakhstan. In order to resolve these issues, students were required to integrate knowledge from the disciplines of biology, ecology and biotechnology, as well as utilise digital tools, including plant databases and climate analysis software.

Project-based learning was an integral part of the experimental programme. Each student or group of students developed an educational biotechnology project that could be implemented in a school setting. For instance, one project involved the creation of a teaching aid utilising Augmented Reality (AR), thereby enabling participants to visualise the stages of plant propagation within a laboratory setting. The implementation of these projects resulted in the cultivation of creative thinking, the enhancement of teamwork skills, and the deepening of participants' comprehension of biotechnology principles.

The decision to incorporate these types of learning was driven by their effectiveness in training biology teachers. Interdisciplinary learning has been shown to facilitate a more comprehensive understanding of the subject, a notion that assumes particular significance in light of the increasing interconnection between different academic domains. A problem-based approach has been shown to enhance students' ability to independently solve complex problems, a skill that is particularly relevant in teaching practice. Project-based learning enables future teachers to consolidate theoretical knowledge and to gain practical experience, rendering their training more applicable and focused on real-world teaching practice.

Moreover, the integration of digital technologies has served to augment the efficacy of the selected methodologies. The utilisation of virtual laboratories has been instrumental in enabling students to emulate plant reproduction processes in conditions that closely resemble real-life scenarios. The utilisation of Augmented Reality (AR) technology has facilitated the visualisation of intricate biological processes, thereby enhancing the clarity and accessibility of learning. These solutions collectively contributed to the establishment of an innovative learning environment that fosters the development of highly skilled professionals equipped to integrate modern technologies into their practice.

C. Digital Technologies

This study employed modern digital technologies that formed the foundation for an integrative learning model. These include virtual laboratories, learning management systems, Augmented Reality (AR), and interactive simulations of plant propagation and stress resistance assessment (Fig. 1).

Virtual laboratories. The study employed the following virtual laboratory platforms: Labster and PhET Interactive Simulations. The Labster platform served as a tool for modeling biological and biotechnological processes associated with the propagation of stress-resistant tree and shrubbery plants, such as Pinus sylvestris (Scotch pine) and Betula pendula (European white birch). Students conducted virtual experiments on micropropagation, assessing plant resistance to drought and cold stress, as well as analyzing physiological parameters such as photosynthetic activity and antioxidant capacity.

PhET Interactive Simulations, a platform that offers science simulations, was utilized to investigate the processes of metabolism and cellular respiration in plants. Specifically, the platform enabled the simulation of the impact exerted by various CO_2 concentrations on the photosynthetic activity in grain crops such as Triticum aestivum (common wheat). These technologies proved beneficial both during the preparation of students for actual laboratory sessions and during independent project activities.

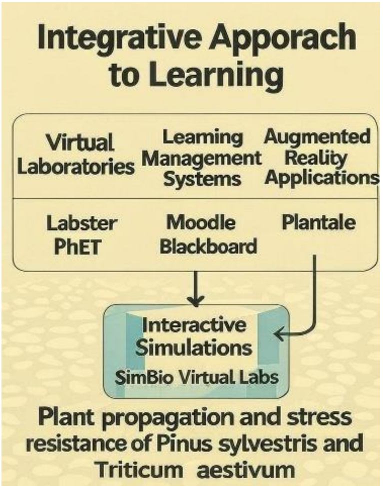

Fig. 1. Flowchart of integrative learning methods employed in the study.

Learning Management Systems (LMS). The study utilized three learning management systems: Moodle, Blackboard, and Edmodo. Moodle was used to provide access to lecture materials, tests, and assignments, as well as for online testing. The Blackboard learning management system was utilised to facilitate online forums and discussions. Blackboard was utilised as a medium for the uploading of student coursework. Edmodo functioned as a medium through which students and faculty members could exchange feedback, including comments on laboratory reports and submitted projects.

Augmented Reality (AR). Mobile applications such as Plantale and CellulAR Anatomy enabled students to visualise three-dimensional models of plant cells, tissues and organs. For instance, in the course of examining the process of plant cloning under conditions of stress, students employed the use of Plantale for the purpose of observing the root structure of Scots pine (*Pinus sylvestris*) and conducting an analysis of changes caused by salt stress. The application of these technologies has facilitated the elucidation of the impact of external factors on the structural and functional characteristics of plants.

Interactive Simulation Software. The experiment utilised the SimBio Virtual Labs and GrowthLab Simulator as the simulation platforms.

SimBio Virtual Labs was utilized to simulate plant micropropagation and assess their resilience to temperature fluctuations. By using the example of Betula pendula, students were able to compare plant growth under low and high temperature conditions. GrowthLab Simulator, on the other hand, was employed to predict grain yield under drought conditions. Through simulations, it was possible to evaluate plant resistance, such as that of Triticum aestivum, to environmental stresses.

The integration of digital technologies into the educational process took place at all stages. At the theoretical level, students accessed lectures and assessments through LMS, while AR assisted in visualizing complex biological concepts. Practical stages included the use of virtual laboratories and simulations, allowing students to gain hands-on experience with biotechnological methods.

D. Methods for Evaluating Effectiveness

For a more in-depth assessment of the proposed integrative learning model, the study employed the following metrics and numerical data collection techniques.

1) Student knowledge quality

This parameter was assessed through tests that comprised several components:

- Theoretical questions on biology and biotechnology, including methods of plant propagation (including stress-resistant species).
- Questions related to the use of digital technologies (virtual laboratories and simulators)

Assessment criteria: points. Each correct answer to a question was awarded 1 point, with a maximum score of 50 points possible for the test. A percentage-based scale served as an instrument for evaluating knowledge: Results exceeding 80% of the maximum possible score were considered excellent. If the total score fell between 60 and 80%, it was considered a satisfactory achievement. Results below 60% were deemed unsatisfactory.

2) Skills and competence

This criterion was assessed through the analysis of practical assignments and laboratory work, as well as the completion of project assignments.

Assessment criteria: points awarded for each task. Each aspect of the task was evaluated on a scale of 0 to 5, based on the accuracy of its completion and the application of theoretical knowledge in practice. The maximum score possible for completing a task was 30. The participants were required to demonstrate their ability to utilize digital tools in solving practical problems (e.g., working with virtual laboratories and biological simulators). The performance of students in laboratory work and projects, including the accuracy of calculations, the methods used, logical reasoning, and conclusions drawn from experimental results, was also evaluated.

3) Practical knowledge

Practical knowledge was evaluated based on the quality of projects and laboratory studies, which involved the use of stress-resistant plant propagation methods.

Assessment criteria: points for projects and the level of originality, scientific validity, and the use of digital technologies, as well as the degree of student involvement in the process. The maximum possible score for project work was 40 points. The criteria for evaluating the projects were as follows:

- Theoretical foundation (10 points);
- The incorporation of digital technologies (15 points);
- Practical feasibility (15 points).

4) Data collection methods

- Survey of students and teachers

The survey included questions that required respondents to provide numerical answers or to rate a statement on a scale of 1 to 5, with 1 representing "not satisfied at all" and 5 representing "completely satisfied." Below are examples of the questions:

"How would you rate the convenience of using virtual laboratories?" (1—inconvenient, 5—very convenient)

"To what extent, in your opinion, do digital technologies contribute to your mastery of the material?" (1—do not contribute at all, 5—contribute substantially)

The survey also included questions assessing the effectiveness of training methods, including both digital and traditional approaches. The mean value was calculated for each group.

A knowledge assessment was conducted prior to and following the experiment.

Testing was conducted on two occasions: before the experiment (pretest) and after its completion (posttest). The number of points received by each participant was determined by the accuracy of their responses, and these results were meticulously documented. The assessments encompassed a variety of formats, including multiple-choice questions, matching exercises, and practical tasks. The evaluation of performance was based on the number of correct answers given. The results of the study were expressed in points. In order to ascertain the efficacy of the proposed learning model, the anticipated discrepancy between the pre- and post-experiment scores was calculated.

5) Observations and analysis of practical work

During the observation stage of the study, three teachers assigned grades on a 5-point scale for each assignment that had been completed. The criteria for evaluating laboratory work were as follows:

- Student involvement;
- The ability to work with digital tools;
- Results and conclusions drawn from the completed assignment.

These factors determined the final score for practical work. Student participation in project work was also considered, with both the project and the quality of presentation being assessed. This entire assessment system relied on a point-based scale, which enabled clear measurement of experimental results and objective comparison between control and experimental groups.

6) Experimental conditions

The course was delivered over a 12-week period, with classes held twice per week, providing ample time for participants to both familiarize themselves with and master the digital technologies involved, as well as complete all assigned tasks. Before the start of the course, instructors conducted an introductory session for students, wherein they explained the proper use of digital technologies, such as virtual laboratories, learning management systems, and AR tools.

The teachers themselves received advanced training in the use of digital technologies one month prior to the commencement of the experiment. This included training in the operation of virtual laboratories, such as those provided by Labster, and mobile applications that utilize augmented reality. The training was guided by specialists from the university's training center, as well as in collaboration with technical consultants from technology companies such as Labster and Moodle. In the control group, instruction was conducted using traditional methods, such as lectures, seminars, and laboratory work. In contrast, the experimental group employed an integrative approach that incorporated virtual laboratories, AR, and interactive simulations.

7) Testing and analysis of results

Testing was conducted twice: at the beginning and end of the experiment. The results were compared in order to assess the change in knowledge and skills within both groups. An analysis of the practical tasks completed by students during the experiment made it possible to further assess their practical preparedness and ability to apply their acquired knowledge to real-world situations. Observations of students as they worked with digital technologies provided additional insights into their level of engagement and readiness to utilize new teaching methods in their future practice. It is evident that the evaluation methods employed in this study encompassed both quantitative and qualitative approaches. The employment of a mixed-method approach was deemed essential to evaluate the experimental results and ascertain the role of digital technologies in the training of biology teachers.

The students comprising the control group engaged in conventional learning activities, encompassing conventional biology teaching methodologies, with the exclusion of digital technologies. The programme emphasised the acquisition of theoretical knowledge, the study of biological fundamentals, and the completion of practical exercises utilising traditional textbooks and laboratory equipment. It is evident that students within the designated control group did not utilise virtual laboratories or digital simulations. In order to complete the practical assignments, traditional methods of working with plants were employed, without the integration of augmented reality tools or plant propagation simulations. The training process was based on traditional pedagogical methods such as lectures, seminars, laboratory sessions, and project-based assignments, during which students learned biotechnical methods of plant propagation in a conventional setting. Consequently, the primary distinction between the groups revolved around the implementation of non-standard teaching methods and technology-based approaches. This allowed for a comparison of outcomes in the control group with those in the experimental group, which utilized modern educational technologies.

Within the framework of the experiment, the students focused on stress-resistant tree and shrubbery plants, including various species of Larix sibirica (Siberian larch), Pinus sibirica (Siberian pine), and Betula pendula (European white birch), as well as certain shrubs such as Rosa canina (dog rose) and Aronia melanocarpa (black chokeberry). These plants were selected due to their ability to adjust to various climatic and environmental stressors, including low temperatures, drought, and environmental pollution.

The following methods were employed for plant propagation: cuttings, including the use of root and shoot cuttings, grafting, and a tissue culture technique for generating new plants through in vitro cell cultivation. These techniques enable the reproduction of plants with enhanced resistance characteristics and accelerate the propagation process under conditions of limited natural resources. Tissue culture was also utilized to create genetically identical plants, increasing the likelihood of successful ecosystem restoration.

The qualitative analysis followed a structured content analysis procedure. After familiarising themselves with the responses, two coders generated initial codes independently, which were then grouped into broader categories reflecting the three research domains: (1) development of professional skills, (2) experiences with digital tools and (3) motivation and readiness to teach. The coding framework was then iteratively refined and any discrepancies between the coders were resolved through discussion. Representative quotations were extracted to illustrate each category and were later incorporated into the 'Results' section.

All data-collection procedures were explicitly aligned with the final set of research questions presented in the Introduction. In particular, motivation and professional readiness (RQ3) were measured through pre- and post-intervention surveys, Likert-scale items, and qualitative reflections. The questionnaire included items assessing intrinsic motivation, perceived usefulness of integrative learning, and readiness to apply digital technologies in future biology teaching. These data served as the basis for answering RQ3 and were later discussed accordingly to maintain consistency between research questions and the analysis.

E. Statistical Analysis

SPSS software version 25.0 served as a tool for statistical data analysis. In order to assess the effectiveness of integrative learning and compare results between control and experimental groups, a range of statistical tests were employed. The aforementioned tests determined the significance of differences and the degree of correlation between variables.

In order to analyse the quality of students' knowledge, the study employed a student's t-test for independent samples. The present study employed a comparative analysis of mean test scores before and after training in both the control and experimental groups. The t-test also revealed changes in the participants' knowledge and understanding of biological concepts. The findings of this investigation were pivotal in the comparison of the effectiveness of the two approaches.

Moreover, the Mann-Whitney U-test was utilised to evaluate the participants' competence and practical skills, encompassing their capacity to employ biotechnological methodologies for plant propagation. In this instance, the Mann-Whitney U-test was deemed the most suitable, given that the data did not always adhere to a normal distribution. The test made it possible to compare the scores for practical tasks in both groups and assess the impact of digital technologies on the quality of completed tasks.

Correlation analysis, which involved the calculation of the Spearman correlation coefficient, was necessary to analyze the relationship between various educational variables (for example, the use of technology and learning outcomes). This analysis determined the degree of correlation between specific digital technology use and test results. A chi-square test was employed to analyze categorical data and measure differences in the level of student motivation and perception of the learning process between the two groups. This test evaluates how students' attitudes toward technology-assisted learning differ from those who practiced the traditional approach.

The mixed-methods approach involved integrating quantitative statistical outputs with qualitative categories derived from content analysis. The quantitative results were used to evaluate measurable learning outcomes, while the qualitative findings provided additional context and helped to interpret changes in motivation, attitudes and professional preparedness. This triangulation strengthened the validity of the conclusions and ensured that each research question was addressed using multiple forms of evidence.

F. Validity, Reliability, and Data Collection Procedures

To ensure transparency and replicability, Table 1 summarises the main study variables, the instruments used to measure them, the data types collected and the analytical methods applied to answer each research question.

Table 1. Variables, instruments, and data analysis methods*

Variable / Construct	Instrument / Source of Data	Data Type	Analysis Method	Purpose / Corresponding Research Question (RQ)
Cognitive achievement (knowledge)	Pretest and posttest in biology teaching methodology (30 MCQ and short-answer items)	Quantitative (interval)	Paired *t*-test / Mann–Whitney U (if non-normal); Effect size (Cohen's *d*)	Evaluate knowledge gains (RQ 1)
Professional skills and competence	Observation checklist (lab/practical tasks); project work evaluation rubric	Quantitative (ordinal) + Qualitative notes	Descriptive statistics; *t*-test or Mann–Whitney U; Kendall's W (inter-rater reliability)	Assess development of teaching and methodological skills (RQ 1, RQ 2)
Motivation and professional readiness	Structured questionnaire with 25 items (Likert 1–5); open-ended reflective questions	Quantitative (ordinal) + Qualitative (text)	Descriptive analysis; χ^2 test; content analysis (Cohen's $\kappa = 0.86$)	Determine motivation and readiness to apply integrative methods (RQ 3)
Digital tool engagement	Observation protocol (frequency of platform use, activity logs)	Quantitative (count/frequency)	Descriptive statistics; correlation with motivation indices	Examine impact of digital tools on engagement (RQ 2)
Attitudinal change toward integrative learning	Pre/post survey items on perceived usefulness of integration	Quantitative (ordinal)	Wilcoxon signed-rank test; effect size *r*	Measure attitudinal dynamics (RQ 3)

Note: *The full 25-item survey used to assess student motivation, professional readiness, and perception of digital technologies is provided in Appendix.

To ensure methodological rigour, several steps were taken to verify the validity and reliability of the research instruments. All testing and survey tools were developed based on the content of the biology teacher training curriculum and adapted to align with the objectives of the experiment. Prior to the main study, a pilot test was conducted with 20 students from a different university who were not involved in the main experiment. The results of this pilot study were used to refine ambiguous questions and verify the clarity and internal consistency of the items. Cronbach's alpha was calculated for the final version of the questionnaire, yielding a coefficient of 0.87, indicating a high level of reliability. The inter-rater reliability of practical task evaluations was assessed using Kendall's W, yielding a coefficient of 0.81 and confirming consistency among evaluators.

The study employed a quasi-experimental pretest–posttest control group design to compare the effectiveness of integrative and traditional learning models in real teaching conditions. Sampling was purposive, as only students on the biology teacher education programme were eligible, while assignment to groups was random. This approach ensured representativeness and comparability between the control and experimental groups, while preserving ecological validity in a real academic setting.

The observation procedures followed a structured protocol. Observers used a standardised checklist that included cognitive, behavioural and motivational indicators (e.g. engagement, problem-solving initiative, collaboration and the accuracy of practical actions). Each observation item was rated on a 5-point scale and qualitative comments were recorded to capture notable behavioural patterns. For the control group, indicators related to digital tool use were omitted, and alternative criteria, such as the accuracy with which laboratory equipment was handled, were used to maintain comparability between the groups.

The qualitative component of the study consisted of a content analysis of open-ended survey responses and reflective student reports. Responses were coded into thematic categories corresponding to the three research questions: (1) development of professional skills, (2) effectiveness of digital tools and (3) motivation and readiness to teach. Two independent coders performed the analysis, achieving an intercoder agreement of 0.86 (Cohen's kappa) to ensure the reliability of the qualitative interpretation.

The assumptions for parametric tests were verified prior to statistical analysis. The data were screened for normality using the Shapiro–Wilk test, and for homogeneity of variances using Levene's test. When assumptions were violated, non-parametric alternatives, such as the Mann–Whitney U-test, were employed. This ensured that the statistical procedures chosen were appropriate for the data type and distribution. All significance levels were set at $p < 0.05$. Descriptive statistics (means and standard deviations) were supplemented by effect size estimates (Cohen's d and r) to quantify the magnitude of the observed differences.

Kendall's W was strictly used as an index of inter-rater reliability by the three evaluators assessing practical laboratory tasks. It was not used to analyse qualitative data or derive themes from open-ended responses. All qualitative materials (reflective notes and open-ended questionnaire items) were analysed using content analysis only. Accordingly, Kendall's W (0.81) represents the degree of agreement among raters on ordinal scores in the practical skills rubric, meeting the statistical assumptions of this coefficient.

To ensure comprehensive reporting of reliability across all instruments, separate indices were calculated for each tool. The knowledge test demonstrated high internal consistency (Cronbach's $\alpha = 0.83$); the 25-item motivation and readiness questionnaire showed $\alpha = 0.87$; and the observation checklist used for laboratory work demonstrated acceptable reliability ($\alpha = 0.79$). Inter-rater reliability for the evaluation of practical skills was established using Kendall's W, as the rubric items were rated on an ordinal 5-point scale by three independent evaluators. All qualitative materials (reflective reports and open-ended responses) underwent content analysis, for which intercoder agreement was verified using Cohen's kappa statistic ($\kappa = 0.86$).

Data collection took place over a 12-week semester. All quantitative data (test scores, practical evaluations and surveys) were collected by trained instructors under the supervision of the research team, ensuring consistency and minimising bias. Observation data were recorded by three independent experts with prior experience in pedagogy and training in digital learning environments.

IV. Result and Discussion

For clarity, in this section the term "student" refers exclusively to pre-service biology teachers who participated in the experiment. Throughout the "Results" section, "students" and "participants" refer to the same group of pre-service teachers. Depending on the distribution of the data, parametric (t-test) and non-parametric (Mann–Whitney U) analyses were applied. The following subsections present the results in accordance with the three research questions (RQ1–RQ3).

Table 2. Effectiveness of integrative learning

Parameter	Mean	Standard error of the mean (SEM)	*t*-statistics	*p*-value (t-test)	*p*-value (Mann-Whitney)
Knowledge quality (tests)	38.2	1.5	3.2	0.03	0.02
Theoretical knowledge in biology and biotechnology	24.6	1.2	2.8	0.04	
Knowledge in digital technology	13.6	0.9	-	-	-
Skills and competence (practical assignments)	25.4	1.3	2.1	0.06	0.03
The ability to work with digital tools	16.4	1	-	-	-
Quality of completed laboratory tasks	9	0.8	-	-	-
Practical knowledge (projects)	30.8	1.8	1.5	0.12	0.01
Theoretical foundation	9.2	0.5	-	-	-
Incorporation of digital technologies	14.5	1.2	-	-	-
Feasibility	7.1	0.9	-	-	-
Usability of digital technologies	4.5	0.3	1.8	0.09	0.04
Convenience of using virtual laboratories	4.2	0.2	-	-	-
Impact of digital technologies on knowledge acquisition	4.8	0.4	-	-	-

Note: Empty cells in the table (indicated by hyphens) represent missing data for relevant statistical analyses. These gaps are due to the fact that additional statistical tests, such as t-tests or Mann-Whitney tests, were not conducted for certain parameters, or the results of these tests were not statistically significant for those parameters. The Mann-Whitney U-test revealed statistically significant differences between the control and integrative groups in terms of the following parameters: knowledge quality (assessed through tests) with a U-statistic of 120 ($p = 0.02$); skills and competence (measured through practical tasks) with a U = 130 ($p = 0.03$); practical knowledge (project work) with a U of 140 ($p < 0.01$); technology usability assessment with a U of 115 ($p = 0.04$).

For RQ1, the analysis compared students' theoretical and practical knowledge across control and experimental groups (Table 2). The quality of knowledge between the groups varies considerably, as confirmed by the t-test (Table 2). The

Mann-Whitney U-test results also indicate statistically significant differences in skills and competence levels. Based on the p-value of the t-test, differences in practical knowledge are less pronounced. The scores for the usability of the technology reflect a high level of participant satisfaction.

The Spearman coefficient indicates a strong to moderate positive correlation between the parameters within the experimental group. With regard to knowledge quality, the coefficient stands at 0.72. For skills and competence, the coefficient is 0.68, while for practical skills and competence, it is 0.74. In terms of technology usability, the coefficient comes to 0.6. The findings suggest a correlation between enhancements in a specific domain of learning and other variables.

The χ^2 statistic is a valuable tool for confirming the existence of differences between two groups. For instance, the chi-squared value for knowledge quality is 4.5 ($p = 0.05$); for skills and competencies, it is 5.2 ($p = 0.02$); for practical knowledge, it is 6.0 ($p = 0.02$); and for technology usability, it is 3.8 ($p = 0.05$). The values obtained from this study indicate statistically significant differences, although it should be noted that some of these differences may be considered borderline significant. The results of the statistical tests demonstrate significant variations between the groups. The positive correlation between variables highlights the relationship between improvements in knowledge, skills, and technology usability.

The results of the pre- and post-tests revealed a significant improvement in knowledge among participants in the integrated learning group (see Table 3). Overall, the quality of knowledge increased from 28.1 points to 38.2, which is supported by a t-statistic of 5.6 and a *p*-value of 0.01. This indicates statistically significant differences between the two groups. In terms of theoretical knowledge in biology, the average score increased from 17.3 to 24.6 points, with a t-value of 4.8 and a *p*-value of 0.02. Similarly, the average score for knowledge in digital technology increased from 10.8 to 13.6 points, as demonstrated by a t-value of 3.4 and *p*-value of 0.03.

Table 3. Knowledge assessment: Pre-test and post-test results

Parameter	Mean (pre-test)	Mean (post-test)	Standard Error of the Mean (SEM)	*t*-statistics	*p*-value (*t*-test)
Overall knowledge quality (points)	28.1	38.2	1.5	5.6	0.01
Theoretical knowledge in biology and biotechnology	17.3	24.6	1.2	4.8	0.02
Knowledge in digital technology	10.8	13.6	0.9	3.4	0.03

Table 4. Assessment of skills and competence (practical assignments)

Parameter	Mean (control group)	Mean (experimental group)	Standard Error of the Mean (SEM)	*t*-statistics	*p*-value (*t*-test)
The ability to work with digital tools	13.2	16.4	1	2.8	0.04
Quality of completed laboratory tasks	7.6	9	0.8	1.7	0.09
Quality of projects	14.8	16.8	1.2	2.5	0.05

Table 5. Assessment of practical knowledge (projects)

Parameter	Mean (control group)	Mean (experimental group)	Standard Error of the Mean (SEM)	*U*-statistics	*p*-value (Mann-Whitney)
Theoretical foundation (max. 10 points)	7.2	8.3	0.5	122	0.04
The incorporation of digital technologies (max. 15 points)	12	13.5	1	115	0.02
Feasibility of projects	7.5	8.4	0.7	130	0.06

These findings suggest that the experiment was effective in improving students' knowledge. The results for the control group indicate that the mean value of overall knowledge quality was 27.9 points before the experiment and 29.5 points after the experiment, representing a marginal improvement compared to the experimental group. Nevertheless, the difference was not statistically significant ($p = 0.10$). The control group demonstrated some enhancements in theoretical knowledge in biology (from 16.8 to 18.2 points) and digital technology (from 10.2 to 11 points), both without statistical significance ($p = 0.12$ and $p = 0.14$, respectively). The results confirm that the changes in knowledge level within the control group were less substantial than those seen in the experimental group, potentially indicating a lower efficacy of the traditional teaching approach compared to innovative methods.

No rank-based measures, such as Kendall's W, were used to analyse the qualitative notes. Kendall's W was only applied earlier in the Methods section to assess the inter-rater reliability of evaluators scoring the practical-skills rubric. All qualitative findings reported below are derived exclusively through content analysis.

For RQ2, differences in skill development and competence were examined through practical assignments and project evaluations (Tables 4 and 5).

The results presented in Table 4 demonstrate differences in the levels of skill and competence development between the control and experimental groups. Specifically, the ability to utilize digital tools was markedly higher in the experimental group ($p = 0.04$), confirming the effectiveness of an integrative learning model. Despite higher scores for laboratory tasks in the experimental group, their quality did not reach statistical significance ($p = 0.09$). This may indicate a need for further refinement of teaching methods in this area. Project assignments in the experimental group showed a positive trend; a p-value was near the threshold of statistical significance ($p = 0.05$), suggesting a potential link between the integrative approach and enhanced project task performance. These findings support the hypothesis that the integrative approach is particularly beneficial for developing skills in using digital tools, whereas other aspects of practical training require additional research and improvements of methods.

The data presented in Table 5 highlights the differences in the practical knowledge of students between the control and experimental groups. The experimental group showed substantial improvements in terms of theoretical foundation ($p = 0.04$) and the incorporation of digital technologies ($p = 0.02$), indicating the effectiveness of the integrative approach in these aspects. However, despite higher scores for the feasibility of projects presented by students from the experimental group, this parameter did not reach statistical significance ($p = 0.06$). Therefore, there is a need for further refinement of methods to focus on practical aspects in the learning process.

In this study, RQ3 addresses the impact of the integrative model on motivation and readiness to teach biology in a digital environment. One component of this broader construct is the perceived usability of digital technologies. Therefore, alongside usability data (Table 6), the results include findings related to motivation derived from post-intervention surveys and reflective notes. For RQ3, students' perceptions of digital tools and the usability of virtual laboratories were analyzed (see Table 6 and Fig. 2).

According to the data presented in Table 6, the participants in the experimental group reported a considerably higher level of perceived convenience when using virtual laboratories compared to the control group ($p = 0.05$). The results point to a statistical significance of the differences. Although experimental students reported slightly more positive attitudes toward the impact of digital technologies on knowledge acquisition, there were no statistically significant differences between the two groups ($p = 0.07$). This may be due to subjective student preferences and the need for continued improvement in digital tools.

Table 6. Usability of digital technologies (student survey)

Parameter	Mean (control group)	Mean (experimental group)	Standard Error of the Mean (SEM)	χ^2-statistics	*p*-value (chi-square)
Convenience of using virtual laboratories	4.2	4.6	0.2	4.5	0.05
Impact of digital technologies on knowledge acquisition	4.5	4.8	0.3	3.8	0.07

The results for the control group indicate that the perceived convenience of using virtual laboratories was slightly lower than the scores reported by the experimental group; the difference was statistically significant ($p = 0.05$). In the control group, the score was 4.2, which was 0.4 points lower than in the experimental group. With regard to the impact of digital technologies on knowledge acquisition, the mean score in the control group was 4.5, which was also lower than that of the experimental group (4.8). Nevertheless, the *p*-value was found to be insignificant ($p = 0.07$), confirming the absence of substantial discrepancies.

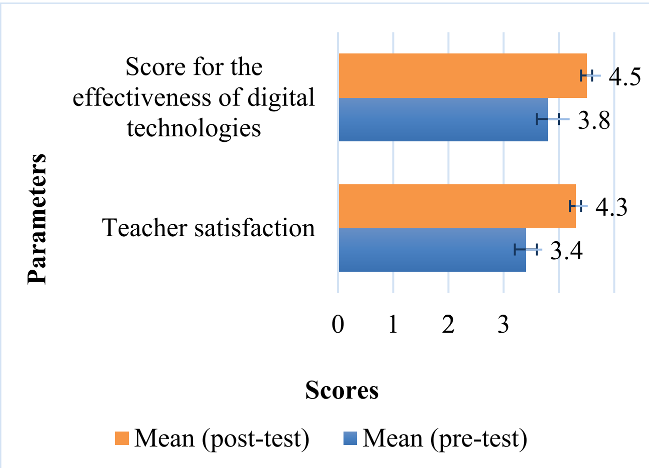

Fig. 2. Teacher survey results: Evaluation of effectiveness.

Fig. 2 illustrates changes in the perception of technology among future teachers after the implementation of the innovative approach. The participants' level of satisfaction increased from 3.4 to 4.3 points, which is supported by a t-statistic of 6.2 and a *p*-value of 0.01. Furthermore, the scores assigned by the students for the effectiveness of digital technologies increased from 3.8 points to 4.5, which is statistically significant at a *p*-value of 0.02. These findings confirm that the integrative approach was highly effective within the educational process.

Taken together, the quantitative and qualitative findings suggest that the integrative learning approach improved the perceived usability of digital tools and strengthened motivation and readiness to teach biology using digital resources. These outcomes directly address RQ3, as outlined in the introduction.

The qualitative component of the study produced three central themes reflecting changes in motivation and teaching readiness.

Participants reported feeling more competent when planning laboratory activities, stating that they could now design tasks combining biological content with digital tools with much greater confidence.

- Increased motivation to use digital technologies: many noted that exposure to virtual laboratories increased their willingness to incorporate digital tools into future teaching. One participant said, "I did not expect virtual labs to be so helpful for explaining complex processes".
- Improved readiness to teach in digitalised environments: Participants emphasised that integrative assignments helped them understand how to balance theoretical content with practical digital activities ("This course showed me how digital tools support real biological processes, not replace them").

These themes complement the quantitative findings and demonstrate that the integrative model had a positive influence on both motivation and teaching readiness.

In addition to the usability indicators, the post-intervention survey and reflective notes revealed an increase in student motivation and readiness to teach biology using digital tools. Participants in the experimental group reported greater confidence in navigating virtual laboratories, integrating simulations into lesson plans and incorporating biotechnology-related content into school-level instruction. Qualitative reflections highlighted three recurring themes: (1) increased motivation to engage with complex concepts when supported by interactive platforms, (2) a heightened sense of preparedness for future teaching, particularly when combining virtual and physical laboratory experiences, and (3) the perceived relevance of digital tools for explaining abstract biological processes to school pupils. No comparable patterns were observed in the control group. These findings suggest that the integrative learning model improved the perceived usability of digital technologies, strengthened motivation and teaching readiness, and fully addressed the components of RQ3.

A content analysis of reflective notes revealed an overarching theme of increased motivation to use digital tools in future biology teaching. Participants reported a greater interest in integrating virtual labs and simulations, primarily due to the perceived improvement in clarity and engagement that this would bring. Representative statements included: 'The virtual lab helped me understand why these reactions matter', and 'Digital tools make lessons more structured and easier to explain'.

The following discussion organises the findings into thematic subsections, rather than repeating the research questions (RQs) verbatim. This approach improves coherence, enabling the results relating to knowledge, skills, motivation and usability to be synthesised across methodological components.

A. Development of Theoretical and Practical Knowledge

The findings of this study demonstrate that the applied integrative learning model substantially strengthened the theoretical and practical knowledge of pre-service biology teachers. Participants who were exposed to a combination of traditional instruction, digital learning tools and project-based activities demonstrated significantly greater knowledge gains than those in the conventional instruction group, whose progress was more limited. The most significant improvements were observed in theoretical knowledge related to biology and biotechnology. This indicates that integrative learning enables a deeper understanding of subject-specific concepts and consolidates foundational competencies.

These outcomes are consistent with previous research emphasising the importance of modern teaching methods in science education. As demonstrated by Ruzikulova [25], methods such as flipped classrooms, technology-enhanced learning, experimentation and interdisciplinary tasks can lead to better academic performance and enhanced critical thinking skills. Similarly, Silva-Diaz *et al.* [21] and Grinshkun *et al.* [26] report that digital tools, including Augmented Reality (AR) and virtual simulations, support conceptual development and strengthen professional competencies. The results of the present study reinforce these findings by demonstrating that a systematically integrated approach can produce measurable gains in knowledge acquisition. The improvements also emphasise the importance of using validated assessment instruments to ensure that observed differences reflect actual learning outcomes rather than measurement bias.

B. Enhancement of Biotechnology-Related Skills and Applied Competencies

The integrative learning model was similarly effective in developing practical skills, particularly in biotechnology. Students in the experimental group demonstrated stronger digital literacy, better project management skills, and higher performance in technology-assisted tasks. While not all laboratory-based indicators were statistically significant, the overall trend suggests that combining hands-on laboratory work with virtual simulations may lead to more balanced development of applied competencies.

These results corroborate those of previous studies investigating technology-supported practical learning. Gavronskaya *et al.* [27] and Reyes *et al.* [22] demonstrate that virtual laboratories increase accessibility and enable students to master applied skills in a controlled environment. Alqarni demonstrates that AR tools enhance student engagement and support systematic problem solving, while Verawati and Purwoko highlight the positive effects of VR and AR on critical thinking and academic performance. Unlike much of the existing research, which focuses on general student populations, the present study examines pre-service biology teachers, offering discipline-specific insights into professional readiness development. The findings imply that incorporating structured virtual laboratories alongside traditional laboratory exercises could enhance preparation for future teaching practice while simultaneously improving biotechnology skill acquisition.

C. Perceptions of Digital Technologies and the Usability of Learning Tools

Analysis of student feedback indicates that digital learning technologies were perceived as convenient, accessible and useful for academic preparation. Participants in the experimental group rated virtual laboratory environments as significantly more convenient than the control group did ($p = 0.05$). Although perceived influence on learning showed only a near-significant improvement ($p = 0.07$), the overall trend points to positive attitudes towards digital tools. Variability in individual responses suggests that factors such as prior digital experience or personal learning preferences may influence perceived usability.

These findings correspond to prior research exploring immersive and interactive educational technologies. As demonstrated by Faria and Miranda [24], Lytvynova and Soroko [28], and Sofianidis *et al.* [29], virtual environments promote engagement, provide flexible learning pathways and facilitate professional skill development. Including platforms such as Labster, PhET Interactive Simulations, PlantLab, CellulAR Anatomy, SimBio Virtual Labs, and the GrowthLab Simulator in this study reflects the broadening scope of modern digital ecosystems in biotechnology education. Previous studies by Reyes *et al.* [22], Grinshkun *et al.* [26] and others [23, 24, 28, 30–33] demonstrate the growing importance of these systems in teacher training. The present findings highlight the need for intuitive, context-sensitive digital tools that support autonomous learning and enhance the teaching readiness of future biology educators.

D. Integrated Interpretation and Theoretical Implications

Cross-analysing the results revealed a synergistic effect of integrative learning: improvements in one domain (e.g., digital literacy) were associated with progress in others, such as theoretical understanding and project quality. This interdependence provides empirical support for constructivist and experiential learning theories (e.g., those of Piaget and Vygotsky), which posit that active, context-rich engagement promotes cognitive development and the construction of meaningful knowledge. The present study confirms that integrative pedagogical environments, combining digital tools, practical tasks and traditional instruction, can strengthen conceptual understanding, applied skills and student satisfaction simultaneously.

Comparing the experimental and control groups shows that carefully chosen digital tools can complement conventional laboratory work and contribute to the development of professional competencies. These findings have direct implications for curriculum design in teacher education programmes. Recommended strategies include implementing structured virtual laboratory schedules, incorporating interdisciplinary project tasks and regularly assessing the effectiveness of digital resources for teaching and learning.

Several limitations must be acknowledged. The study was conducted on a relatively small sample within a single discipline, which restricts generalisability. Subjective variables such as motivation and satisfaction are inherently difficult to measure, and individual differences may influence responses. The absence of long-term follow-up limits conclusions regarding the persistence of learning effects. In addition, although the experimental group achieved stronger results with digital tools, the control group may have benefited from more frequent hands-on laboratory interaction, which could have contributed to their practical skill development. Future research should involve larger and more diverse samples, include longitudinal monitoring, and incorporate further evaluation of digital platforms to enhance the robustness and scalability of the integrative learning model.

V. Conclusion

This study demonstrates that a technology-enhanced, integrative learning model can effectively support the professional development of trainee biology teachers. By combining traditional teaching methods with digital tools, virtual simulations and project-based tasks, the programme created an environment in which students' theoretical understanding was strengthened, their applied biotechnology skills improved, and their readiness to use digital resources in future teaching practice enhanced. The results suggest that integrative learning fosters balanced development in cognitive, practical, and technological domains, providing benefits over traditional teaching methods.

The study also highlights the value of immersive and interactive tools, such as virtual laboratories and simulation platforms, for developing digital literacy and supporting independent problem solving. Pre-service teachers reported the high usability and perceived usefulness of these tools, suggesting that thoughtfully designed digital environments can increase engagement and provide authentic learning experiences that align with contemporary requirements in science education. The observed interconnections among knowledge gains, practical competencies and positive experiences with digital technologies further emphasise the synergistic nature of integrative learning.

The findings support the potential of technology-assisted integrative learning as an effective approach for preparing future biology teachers. Incorporating virtual simulations, structured project work and traditional laboratory practices into teacher training programmes could foster a deeper conceptual understanding, enhance applied biotechnology skills and encourage the confident use of digital tools in contemporary educational settings.

Appendix

Survey Instrument: Motivation and Readiness for Integrative Biotechnology Teaching

Instructions:

Please indicate your level of agreement with each statement using the scale:

1 = Strongly disagree 2 = Disagree 3 = Neutral 4 = Agree 5 = Strongly agree

A. Motivation and Interest in Teaching Biotechnology

I am interested in using biotechnology topics to make biology lessons more engaging.

Learning through biotechnology experiments increases my motivation to teach science.

I feel confident in explaining the relevance of biotechnology to everyday life.

Integrating biotechnology into school biology can help students better understand science.

I would like to include biotechnology projects in my future teaching practice.

Using real-life biotechnology examples improves my own learning experience.

I am motivated to learn new methods that combine digital and laboratory work.

B. Professional Readiness and Pedagogical Skills

I can plan a biology lesson that integrates digital and laboratory activities.

I am able to guide students in designing small-scale biotechnology experiments.

I can evaluate students' understanding through both traditional and digital tools.

I can adapt biotechnology content for different levels of learners.

I understand safety and ethical principles related to biotechnology teaching.

I feel ready to apply integrative methods in my professional practice.

I can collaborate effectively with peers on technology-supported projects.

I can reflect critically on the effectiveness of my teaching approach.

C. Use and Perception of Digital Technologies

Digital tools (e.g., simulations, databases, online labs) make biotechnology learning more effective.

I can use digital platforms to collect and analyze biological data.

I am confident in using online resources to support laboratory work.

Digital collaboration tools help me share and discuss biotechnological ideas.

I find technology integration essential for modern biology education.

I feel comfortable troubleshooting minor technical problems during class.

I believe digital tools improve my students' understanding of biotechnology concepts.

D. Reflective and Affective Aspects

Integrative learning helped me become more autonomous in solving scientific problems.

I feel more prepared for teaching after experiencing the integrative model.

The combination of digital and practical methods increased my confidence as a future teacher.

Scoring and validation note (to include in Methods):

Items 1–7 = Motivation; 8–15 = Professional readiness; 16–22 = Technology perception; 23–25 = Reflective growth.

Cronbach's $\alpha = 0.87$ (pilot test, $n = 32$).

DATA AVAILABILITY

All data generated or analysed during this study are included in this published article.

ETHICAL APPROVAL

The research was conducted ethically in accordance with the World Medical Association Declaration of Helsinki. The research was approved by the local ethics committees of Khoja Akhmet Yassawi International Kazakh-Turkish University (Protocol No. 107 of Oct. 9, 2023).

INFORMED CONSENT

All subjects gave written informed consent prior to participation.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTION

Abylaikhan Azimbay: Conceptualization, Methodology, Project administration, Supervision, Writing—review & editing. Gani Issayev: Data curation, Investigation, Resources, Validation, Writing—original draft. Saltanat Ibadullaeva: Conceptualization, Formal analysis, Funding acquisition, Visualization, Writing—original draft. Nurdana Salybekova: Formal analysis, Methodology, Software, Validation, Writing—review & editing. Bauyrzhan Umirov: Data curation, Investigation, Resources, Visualization, Writing—original draft. Toleu Karimzhan: Conceptualization, Methodology, Validation, Writing—review & editing. Indira Aimbetova: Formal analysis, Methodology, Software, Validation, Writing—review & editing. All authors had approved the final version.

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