



APPLICATION OF MODERN EDUCATIONAL TECHNOLOGIES IN THE STUDY OF BIOLOGY IN TECHNICAL COLLEGES

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ABSTRACT

Digital technologies are increasingly used in biology education, yet evidence from vocational colleges in Central Asia remains limited. This study assessed the effectiveness of digitally enhanced biology instruction among 102 second-year students at Bishkek Technical College, Kyrgyzstan. A quasi-experimental design was applied, with 51 students receiving conventional instruction and 51 following a modified programme that incorporated incorporating multimedia presentations, online platforms, mobile applications, videos, and virtual laboratory simulations. Both groups completed theoretical tests, laboratory work, problem-analytical tasks, and a learning-satisfaction questionnaire. The experimental group achieved significantly higher laboratory scores than the control group (77.51 ± 13.08 vs. 67.45 ± 13.32 ; $t(100)=3.85$, $p=0.00021$, Cohen's $d=0.76$) and higher overall semester scores (73.34 ± 7.67 vs. 67.76 ± 6.65 ; $t(100)=3.93$, $p=0.00016$, $d=0.78$). Learning satisfaction was also higher in the experimental group (6.75 ± 1.97 vs. 5.45 ± 1.95 ; $t(100)=3.35$, $p=0.00114$, $d=0.66$), whereas differences in theoretical knowledge and problem-analytical performance were not statistically significant. Satisfaction positively correlated with academic performance ($r=0.31$, $p<0.05$). The study contributes empirical evidence that blended, low-cost digital instruction can strengthen practical biology skills, motivation, and vocationally relevant competences in resource-constrained technical colleges.

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Keywords: augmented reality; critical thinking; digital competences; multimedia technologies; online platforms

INTRODUCTION

Technical colleges play a key role in preparing students for careers in specialised fields by equipping them with the necessary skills and knowledge to develop competence in their chosen areas of specialisation. Biology is one of the fastest-growing fields of science due to advances in research and analytical methods. In the context of globalisation and the rapid development of digital technologies, technical colleges in Central Asia are facing the need to integrate innovative teaching methods that can ensure high-quality

education and meet the modern requirements of the labour market. The relevance of studying the effectiveness of modern educational technologies is driven by the need to adapt educational programmes to societal and labour-market needs, which requires graduates to have not only extensive theoretical knowledge but also practical skills. Sadiq (2020) addressed the changing role of the teacher in education, from being the sole carrier of knowledge to becoming a facilitator who supports students in acquiring knowledge. Thus, the problem of training teachers with new competences also arises.

Research in science education increasingly emphasises the transformation of teaching met-

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hods through digital technologies, with reviews of trends in mainland China calling for a deeper integration of computer-based and interactive methods to support collaboration and research skills (Zhang, 2021; Luo et al., 2023). In Kyrgyzstan specifically, vocational education is being gradually digitalised in line with broader education reforms (Narkoziev, 2017; Isaeva et al., 2023), yet biology remains a discipline in which the practical applications of technology are evolving faster than their uptake in technical-college classrooms. Because biology instruction relies heavily on the visualisation of invisible, microscopic, and dynamic processes, such as cellular structures, enzyme activity, and heredity, this study focused specifically on technologies with a demonstrated capacity to visualise and simulate these processes: multimedia presentations, online learning platforms, mobile applications, and virtual laboratory simulations (Alsharida et al., 2021; Jevons, 2022; Sangur et al., 2025).

Digital educational technologies offer new opportunities to enhance biology teaching by making abstract biological processes more visible, interactive, and accessible. This study intentionally chose multimedia presentations, online learning platforms, mobile applications, and virtual simulations. It was theoretically grounded in the Cognitive Theory of Multimedia Learning, according to which students learn more effectively when verbal and visual information are combined, when unnecessary cognitive load is reduced, and when learners actively select, organise, and integrate new information. In biology education, these principles are especially relevant because many topics, such as cell structure, enzyme activity, heredity, and physiological processes, are difficult to understand through verbal explanation alone. Therefore, multimedia and virtual simulations can support both conceptual understanding and the development of practical laboratory skills.

Previous studies have demonstrated the value of digital and mobile learning in science education, including biology, and some research has examined students' acceptance of online and mobile learning in Kyrgyzstan and the wider Central Asian context. However, these studies mainly focused on attitudes, preferences, or broader digitalisation processes rather than experimentally measured learning outcomes in vocational or technical colleges. Thus, the empirical gap addressed in this study concerns the limited evidence on whether digitally supported biology instruction improves theoretical knowledge, laboratory performance, problem-solving ability, and learning satisfaction among students in technical

college education in Central Asia. Accordingly, this study narrows its focus from digital technology in general to this specific set of visualisation- and simulation-based tools, testing their effect on measurable learning outcomes among technical-college biology students rather than on general attitudes toward digitalisation.

The purpose of this study was to compare conventional and digitally enhanced methods of teaching biology at a technical college in Kyrgyzstan. The study was guided by the following research questions: RQ1: Do students taught through digitally enhanced methods demonstrate higher theoretical knowledge scores than students taught through conventional methods? RQ2: Do multimedia resources, online platforms, and virtual simulations improve students' laboratory skills compared with conventional instruction? RQ3: Do digitally enhanced methods contribute to better problem-analytical performance in biology? RQ4: Does the use of digital teaching methods increase students' satisfaction with the learning process? RQ5: Is there a relationship between learning satisfaction and overall academic performance?

METHODS

The research employed a quantitative, quasi-experimental, comparative design with two non-randomised parallel groups: a control group and an experimental group. The research methods included a pedagogical intervention, comparative analysis of learning outcomes, curriculum-based theoretical testing, criterion-based assessment of laboratory work and problem-analytical tasks, and a questionnaire survey of students' learning satisfaction. Statistical methods included descriptive analysis using means, standard deviations, medians, frequencies, and percentages; independent-samples t-tests for between-group comparisons; Cohen's *d* for estimating effect sizes; and Pearson's correlation coefficient for examining the relationship between learning satisfaction and overall academic performance.

The study was conducted on a sample of 2nd-year students at the Bishkek Technical College who studied biology. The total number of students taking part in this study was 102, including 52 girls and 50 boys. The students were divided into two groups of 51 each, based on the average biology grades for the previous period of study. The distribution was made to ensure that the groups' average performance level for the previous period was the same. The selected educational institution was chosen as the basis for the study due to its accessibility, the availability of

the required number of students of the relevant profile, and the willingness of the administration to facilitate the experiment.

A formal pre-test was not conducted before the intervention. Initial equivalence of the control and experimental groups was ensured by using students' average biology grades from the previous period of study as a baseline indicator. Students were distributed between the groups so that the initial level of academic performance in biology was comparable. Thus, previous academic achievement was used as a practical baseline measure to reduce the risk of initial differences between the groups before the implementation of the intervention.

The use of a non-randomised quasi-experimental design without a formal pre-test reflects a common constraint of applied research in intact college groups, where randomly reassigning students to different teaching conditions was not administratively feasible within a single academic term. To offset this limitation, several controls were applied: both groups followed the same curriculum content and learning outcomes, were assessed with identical instruments and criterion-based rubrics on a shared 100-point scale, and were graded by the same teacher using fixed written criteria; group allocation was additionally based on documented prior academic performance so that the two groups entered the study with comparable average achievement. These measures reduce, but do not eliminate, the risk of confounding from unmeasured factors such as prior digital experience, motivation, or access to devices. This limitation is explicitly acknowledged, and a pre-test/post-test design is recommended for future research, as discussed in the Conclusions section.

All procedures involved in this study followed ethical standards. Before being involved in the data collection process, the study participants and their parents were informed about the purpose of the study, and their consent was obtained. Participant confidentiality was maintained by anonymising their responses during the data analysis. Participants were guaranteed the right to refuse to have their data processed during the study at any time without consequences. The study was conducted following the Code of Ethics of the American Sociological Association (2023). The European Commission (2021) guidelines on ethics and data protection were followed to protect the data.

Two groups were formed that were taught using different methodological approaches. Both groups studied the same content and completed

the same types of assignments: theoretical learning, laboratory work, and problem-analytical tasks. The control group studied according to a conventional curriculum without modern digital technologies; the forms of work included lectures, work with printed textbooks, and laboratory and problem-analytical tasks in the classical format. The experimental group worked with the same content, but using modern educational technologies, including multimedia presentations, online learning platforms and videos. In this group, the teacher acted as a facilitator, guiding students in their independent search and analysis of information.

The validity of the assessment instruments was ensured through their alignment with the biology curriculum studied by both groups during the semester. The theoretical test questions, laboratory assignments, and problem-analytical tasks corresponded to the learning outcomes of the course and reflected the same content taught to the control and experimental groups. Laboratory work and problem-analytical tasks were assessed using criterion-based rubrics. For laboratory work, the criteria included accuracy of performance, interpretation of results, adherence to instructions, and quality of reporting. For problem-analytical tasks, the criteria included depth of analysis, logical reasoning, application of biological knowledge, and clarity of explanation.

Inter-rater reliability was not calculated because the assessment was conducted by one teacher. To strengthen objectivity, the same written rubrics, fixed assessment criteria, and 100-point scale were applied to both groups. The assessment focused on task performance rather than on the teaching method used by the group. This procedure helped to ensure consistency in scoring and reduce the possible influence of subjective judgement.

Among the experimental learning technologies used were the Khan Academy and Coursera platforms, where students watched video tutorials and completed interactive exercises. To get acquainted with laboratory methods, the virtual laboratories PhET Interactive Simulations and Labxchange were used to simulate experiments. Classroom teaching was accompanied by multimedia presentations with diagrams, photographs, and video clips of biological processes. For example, within the framework of their laboratory work, students investigated the effect of temperature on catalase activity or cell structure using a virtual microscope.

A separate type of learning activity was solving problem-analytical tasks that required a formulated written answer, explanation of cause-and-effect relationships, and application of knowledge in new situations. For example: "Imagine that you are conducting an experiment to determine the effect of pH on the activity of an enzyme. What results do you expect to get and why?" This type of task helped to assess the students' ability to think systematically, logically, and critically, not just to reproduce knowledge.

The study was conducted from September to December 2024. The level of learning was monitored by testing at the end of the semester. Examples of test questions included: "What is the function of mitochondria in a cell?", "What do prokaryotes and eukaryotes have in common?", "What is plasmolysis?". The assessment of learning achievements was based on a 100-point system, with further grade conversion according to the Bologna system. At the final stage of the study, the average score for theoretical modules, laboratory work, and critical tasks was calculated for each participant. The assessment of laboratory works and problem-analytical tasks was conducted according to the criterion-level system using the assessment rubrics. For laboratory work, the accuracy of performance, interpretation of results, adherence to instructions, and quality of design were considered. Problem-analytical tasks were evaluated based on the depth of analysis, reasoning, ability to apply knowledge, and logical construction of the answer. This approach ensured the objectivity of the assessment and helped identify the level of critical thinking.

At the end of the study period, a questionnaire was conducted to assess the level of satisfaction with the learning process – students rated their attitude on a scale from 1 to 10. Within the survey, the scale from 1 to 10 was interpreted as follows: 1 meant complete dissatisfaction with the learning process, while 10 was the highest level of satisfaction, reflecting a high interest in the subject, convenience of teaching methods, and a positive attitude towards their results. The questionnaire included questions about interest in the subject, convenience of the technologies used, and self-satisfaction with the results.

The results of knowledge control and learning satisfaction were compared between the control and experimental groups. Descriptive statistics were calculated for all measured variables, including mean, standard deviation, median, frequencies, and percentages. Since the main comparison involved two independent groups, independent-samples t-tests were used to com-

pare mean scores for theoretical knowledge, laboratory work, problem-analytical tasks, overall semester performance, and learning satisfaction. The effect size was calculated using Cohen's *d*. The relationship between overall academic performance and learning satisfaction was examined using Pearson's correlation coefficient. Grade distributions were also presented using bar charts to visualise the number of students in each assessment category. ANOVA and the Mann–Whitney U test were not used in the final statistical reporting because the analysis focused on mean differences between two independent groups, and the results were reported as mean±standard deviation.

RESULTS AND DISCUSSION

The results are reported below for each assessed outcome, namely theoretical knowledge, laboratory work, problem-analytical tasks, and overall semester performance, followed by an analysis of learning satisfaction. In keeping with the distinction between findings and their interpretation, this section presents the observed group differences; the mechanisms that may underlie these differences are addressed in the Discussion.

According to the objectives of the study, at the end of the semester, the academic performance data was analysed, grouped by type of work. The analysis, based on the semester grades, demonstrated the effectiveness of modern teaching technologies in all types of work. The first type of work assessed was knowledge of the theoretical material on the topics studied. The students used multimedia presentations prepared by the teacher and had access to online platforms and mobile applications. All these sources enabled constant access to material, definitions, and better visualisation of biological objects and processes, which is especially significant in disciplines such as cytology and genetics, where students encounter many abstract concepts that are complex to visualise using conventional methods. The average score in the group with conventional teaching methods was 70.33 ± 13.57 points. The average score in the group using modern methods was 72.07 ± 13.16 points. The median was 70 and 73 points, respectively. As these results show, the average score did not differ significantly between the groups.

However, the test of factual knowledge of theoretical material demonstrated a different distribution of levels in the experimental and control groups (Figure 1).

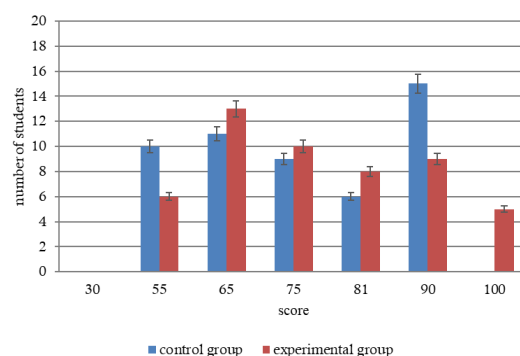


Figure 1. Distribution of the Results of the Assessment of Theoretical Material Knowledge by Students of the Studied Sample

No student in the control group received an A (91-100 points), whereas 5 in the experimental group did. The control group had more B grades (15 vs. 9), but the experimental group performed better. The experimental group had more students who got the highest mark (A), but the control group (30%) had the same number of students who passed the tests well. More pupils in the control group received D grades than in the experimental group, with C ratings practically identical. Multimedia low-level scores fell sharply. E scores were higher in the experimental group than the control. FX scores improved in the experimental group. No student in either group received an F grade.

The assessment findings are compared between groups and presented graphically in Figure 1.

More significant differences were found in the development of laboratory skills (Figure 2). In preparing for this type of work, online platforms were actively used, allowing students to become acquainted with the technique of performing work even without special equipment. Videos of analogous laboratory techniques, previously made by the teacher, were also used, which offered a deeper understanding of the process and re-examination of unclear points.

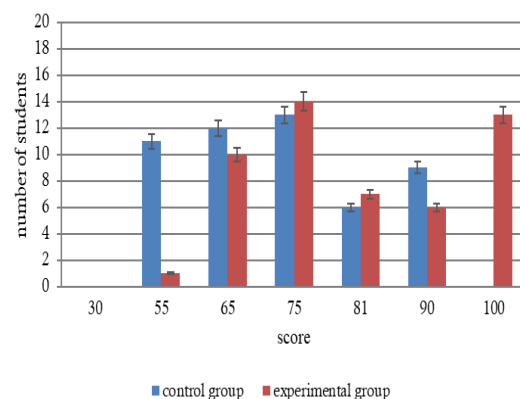


Figure 2. Distribution of the Results of the Assessment of Laboratory Work Performed by Students in the Studied Sample

The conventional study group had an average GPA of 67.45 ± 13.32 , while the multimedia study group had 77.51 ± 13.08 . Different assessment findings were statistically significant. The groups' median scores were 70 and 77. The experimental teaching group had more high-performing lab students. In the experimental group, 13 students achieved an A grade, indicating high laboratory work knowledge and skills. No students in the control group received an A. 18% of control students and 38% of study students completed

lab work, a 20% difference, which is noteworthy. The number of average-graded pupils was similar between groups. Compared to the experimental group, more control students obtained D grades. Both groups had almost the same C grades. Grade E was more common in the experimental group than the control. FX grades improved in the experimental group. No students in either group got Fs. In the control group, 42% of pupils performed below average in laboratories, while in the multimedia group, this figure was 38%.

At the next stage, the skills of creative and critical thinking were studied on the example of solving problematic tasks (Figure 3). Access to online platforms that create augmented reality helped students prepare for complex tasks and summarise the materials. Furthermore, they could practise such tasks during the modules, as each topic was accompanied by control tasks. The students had to provide their explanations for the biological processes that took place in the

proposed situations and predict their development. In the control group, the average score for this type of work was 65.51 ± 13.33 points, while in the experimental group, it was slightly greater – 70.43 ± 12.53 points. The median was 63 and 70 points, respectively. As these data show, the experimental group revealed a pronounced tendency to improve their performance in solving problematic tasks.

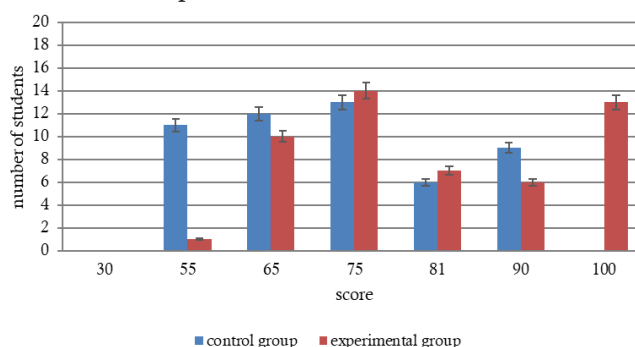


Figure 3. Distribution of the Results of the Assessment of Critical Problem-Solving by the Students of the Studied Sample

Some experimental group students achieved grade A, indicating outstanding knowledge and practical thinking skills in solving these. The experimental group showed a gain in knowledge, as none of the control group students received an A. Overall, 20% of students in the control group and 22% in the experimental group achieved high marks, but the distribution was different. In the experimental group, 11 students received a C, compared to 2 in the control group. This shows that experimental pupils fared better in the middle. E grades were similar in the control and experimental groups for low scores. Less experimental students obtained FX grades, which is an improvement over the control group. This statistically significant rise suggests that multimedia technologies help students who struggle to grasp biological processes learn the curriculum. Figure 3 illustrates data. No student in either group received an F grade, suggesting that all students demonstrated satisfactory performance in solving the assigned problems.

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Finally, a total grade for the semester was calculated, representing the average of all types of work. The analysis of the results shows that, as in each of the previous variants of work, the group that studied using modern methods was ahead of the control group in terms of academic performance. In the group using conventional methods, the average score was 67.76 ± 6.65 points, and in the group using multimedia methods, it was 73.34 ± 7.67 points. The median was 67 and 73 points, respectively.

The distribution also showed a positive trend, as presented in the diagram (Figure 4).

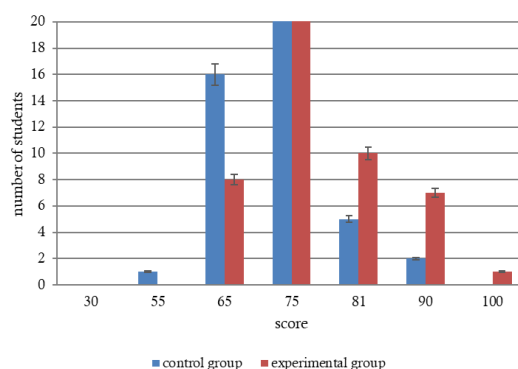


Figure 4. Distribution of Generalised Scores for Different Types of Work by Students of the Study Sample

In the multimedia group, one student got an A and seven got Bs. A useful indicator is that no control group students obtained the highest mark, and only 2 received grade B. Since conventional teaching approaches yielded 4% high-level grades and multimedia methods 16%, these results are substantial. Twice more experimental students obtained a C grade (20% vs. 10% in the control group). This suggests learning is improving. Interestingly, the control group had 34% D and E grades, while the creative approaches group had just 16%. All students in both groups obtained grades higher than F, indicating that they all knew the topic. Figure 4 demonstrates

that the experimental group outperformed the control group in semester total scores.

At the final stage of the study, the level of satisfaction with the learning process was investigated. The general analysis of the results shows that students who were taught using multimedia methods demonstrated a greater level of satisfaction with their studies compared to the group of conventional teaching methods. The average score in the experimental group was 6.75 ± 1.97 , which is greater than that in the control group – 5.45 ± 1.95 . There was a difference in the distribution of scores (Figure 5).

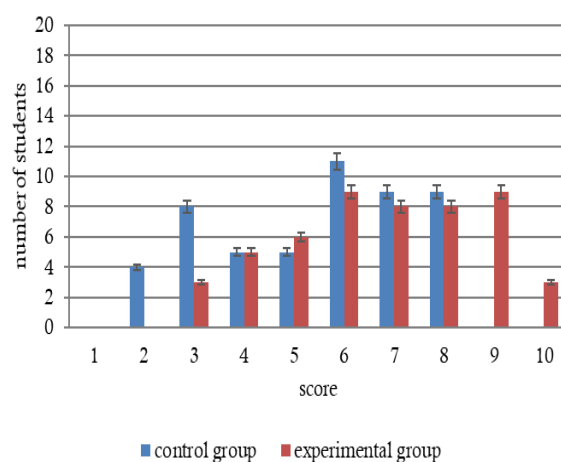


Figure 5. Distribution of Learning Satisfaction Results Among Students of the Study Sample

In the control group, a significant proportion of students (22) rated their satisfaction at 5 points or below, while in the experimental group, only 12 students rated their satisfaction below the average level. In terms of high scores, the multimedia group had a significant number of students who rated their satisfaction with the teaching percentage at 9-10 points, indicating high satisfaction. In contrast, the control group did not have any students with such high scores. Graphically,

the results of the survey are presented in Figure 5, which shows that the distribution of the experimental group's scores was shifted towards higher scores compared to the control group. Thus, the tendency to increase the level of satisfaction with learning was reflected in the assessment, with more students in the group using the latest methods reporting satisfaction with the learning process (Table 1).

Table 1. Statistical Comparison of Learning Outcomes Between the Control and Experimental Groups

Outcome	Control group, M $\pm$ SD	Experimental group, M $\pm$ SD	Test	df	p-value	Effect size
Theoretical knowledge	70.33 $\pm$ 13.57	72.07 $\pm$ 13.16	t = 0.66	100	0.512	Cohen's d = 0.13
Laboratory work	67.45 $\pm$ 13.32	77.51 $\pm$ 13.08	t = 3.85	100	0.00021	Cohen's d = 0.76
Problem-analytical tasks	65.51 $\pm$ 13.33	70.43 $\pm$ 12.53	t = 1.92	100	0.0576	Cohen's d = 0.38
Overall semester score	67.76 $\pm$ 6.65	73.34 $\pm$ 7.67	t = 3.93	100	0.00016	Cohen's d = 0.78
Learning satisfaction	5.45 $\pm$ 1.95	6.75 $\pm$ 1.97	t = 3.35	100	0.00114	Cohen's d = 0.66

Note: n = 51 in each group. M = mean; SD = standard deviation. Cohen's d was interpreted as the standardised mean difference between the experimental and control groups.

Other indirect markers of student satisfaction were recorded in addition to the quantitative questionnaire data, which show that multimedia approaches improve learning attitudes. Some experimental students installed the Khan Academy mobile app outside of class, indicating great intrinsic desire, autonomous learning, and a pleasant experience. Such behaviour indicates a genuine interest and the development of sustainable learning motivation, which, as the results show, enhances both academic achievement and emotional well-being. Digital tools assist learning and stimulate deeper cognitive and motivational changes.

Students who were taught using multimedia approaches were highly satisfied for several reasons. Modern learning tools allow students to actively interact with the information, making learning more engaging and exciting. Graphics, animations, and videos help explain complex biological processes, improving perception and learning motivation. Multimedia resources allow students to work at their own pace, which is especially important for those with various backgrounds and allows for customised learning. Youth readiness to perceive digital information was a major factor in their attitude toward current learning methods, as multimedia technologies are modern and relevant and provide a familiar information environment for pupils.

The relationship between the level of learning satisfaction and academic performance was analysed by conducting a correlation analysis of the test results. The presence of a statistically significant positive correlation between the level of learning satisfaction and the overall academic score was established. The value of

Pearson's correlation coefficient was 0.31 (the critical value at $p \leq 0.05$ is 0.28). Thus, there was a connection between these two indicators – perhaps a positive attitude towards the learning process and greater interest – which contributes to a more successful solution of educational tasks.

Active participation in learning, which improves learning, fuels the positive dynamics. Online platforms and models relate theoretical information to practical circumstances, making learning material more relevant and understandable. The employment of several formats (visual, auditory, interactive) to accommodate different learning styles boosts student engagement and interest, which improves education. Online intermediate knowledge quizzes give pupils immediate feedback, allowing them to alter their learning approach.

Thus, the introduction of innovative multimedia methods in studying biology showed positive outcomes on the cognitive and emotional aspects of students' functioning. This confirmed the significance of introducing modern technologies in the learning process and their potential to develop various skills, such as critical thinking, initiative, and creativity. Further research can help to better understand the mechanisms of these changes and find new ways to improve the learning process.

Positive educational trends emerged from a comparative evaluation of modern biology teaching approaches. Some pupils installed the Khan Academy smartphone app for classroom use. Most students welcomed this opportunity, and the experimental group expressed greater satisfaction with their learning. According to Chozas et al. (2023), Zarate et al. (2024), Loucif et al. (2019), and Delgado-Rodríguez et al. (2023), mobile apps simplify biology study by providing straightforward access to visual and textual materials. According to the study, students learnt complex cytology and genetics themes better with mobile support. Jeno et al. (2017) found that mobile apps could swiftly and accurately identify biological things, making them promising species identifiers. This aligns with students' positive experiences when using additional materials to enhance their understanding of biodiversity.

The study also found that films, animations, and interactive components promote student engagement and understanding of complicated biological ideas. Multimedia instruction improved student satisfaction and performance, according to the studies. Digitalisation transforms gadgets from distractions into learning instruments, according to Adeniyi et al. (2024). This study corroborated this, as experimental students actively used mobile apps and learning platforms to repeat lessons. Batyrkanovna (2023) found that mobile learning improved academic performance and motivation in Kazakhstani schoolchildren, and this study revealed the same. Makransky et al. (2019) showed that AR improves students' cognitive and emotional skills. The outcomes are similar because study group students were more motivated, focused, and active.

Many researchers point to increased motivation as one of the major factors in the successful learning of educational material. Jeno et al. (2020) noted that the use of mobile technologies positively affects students' learning motivation. In the present study, this was confirmed by the prominent level of satisfaction with learning in

the group using multimedia tools, which, according to the correlation analysis, was associated with an increase in the overall academic score.

Burley et al. (2021) emphasised the significance of digital modelling for abstract concepts, particularly molecular modelling. In this study, digital models were used to explain topics in genetics and cell biology, which significantly improved students' understanding of complex material. Chen et al. (2020) noted that the use of 2D and 3D modelling platforms for deoxyribonucleic acid (DNA), ribonucleic acid (RNA), and proteins promotes deeper learning, which is consistent with the approach used here. Ewais et al. (2024) pointed out that augmented reality can be an equivalent alternative to physical laboratories. In this case, the PhET and Labxchange platforms enabled students to effectively prepare for and successfully complete laboratory work, as evidenced by a significant advantage in grades compared to the control group. Recent evidence also indicates that student-informed virtual reality simulations can support the understanding of complex concepts and improve teaching and learning in the molecular sciences (Reen et al., 2025).

Results can be analysed using the Cognitive Theory of Multimedia Learning and the cognitive-load perspective. Biology students must process vocabulary, visual structures, dynamic mechanisms, and cause-and-effect linkages simultaneously. Verbal explanations of cell structure, enzyme activity, genetics, and microbiology may raise cognitive burden since students must mentally rebuild tiny or invisible processes. Multimedia materials, animations, and virtual simulations integrate verbal and visual information, reducing extraneous cognitive load and supporting germane cognitive load by allowing students to focus on essential biological relationships rather than imagining the process. The largest effect was seen in lab work because virtual laboratories and visual simulations externalised procedural procedures, permitted repeated rehearsal, and made biological mechanisms more visible before students conducted practical or problem-analytical activities. Thus, the intervention improved cognitive processing of complex biological material and motivation.

A lack of a statistically significant effect on theoretical knowledge and problem-analytical performance is itself informative rather than something to set aside. Theoretical assessment in this study relied on a single end-of-semester recall-based test, and such measures are comparatively insensitive to multimedia-supported learning, which appears to strengthen how students engage

with material during preparation rather than how much discrete factual content they can recall under test conditions; a one-off recall test may therefore under-detect conceptual gains that develop gradually over a semester. For problem-analytical tasks, the group difference approached but did not reach conventional significance ($p=0.058$, $d=0.38$), suggesting a real but modest effect that a larger sample might confirm; solving open-ended analytical problems requires transferring knowledge to unfamiliar situations, a skill that depends more on structured practice with feedback than on exposure to visual material alone, and the intervention offered comparatively less scaffolding of this kind than it did for laboratory rehearsal. Taken together, these patterns suggest that the digital tools used in this study were most effective for skills anchored in direct visualisation and procedural rehearsal (laboratory work), only partially effective for tasks requiring knowledge transfer (problem analysis), and least effective for isolated factual recall (theoretical knowledge) – a gradient consistent with the cognitive-load explanation outlined above.

The most pronounced results in this study were obtained in laboratory work, as the average score in the experimental group was 10 points greater than the average score in the control group, and the number of students who completed the task at a high level was 20% higher. Students in the experimental group had access to visualisation and could consolidate their practical knowledge using the PhET Interactive Simulations and Labxchange simulation platforms. Such data is confirmed by many studies, including Hermansyah et al. (2019), Brockman et al. (2020), and Jakubowski et al. (2024), in which laboratory simulations helped improve the learning of the material. In a large-scale study, Whitworth et al. (2018) demonstrated the improvement of test results using virtual laboratories. This is confirmed by the findings obtained, including a significant increase in the number of students who received A grades. Brockman et al. emphasised the significance of combining real and virtual experimentation, a perspective that can be confirmed by the positive results of the research team. Sweeney et al. (2022) described the positive experience of creating laboratory modules using videos and tests, which methodologically resonates with the approaches used.

Many researchers who conducted studies in countries with a low level of technical support for the educational process pointed to the potential for replacing practical work with simulations. Farhana et al. (2024), Brockman et al. (2020),

and Ewais et al. (2024) emphasised the economic feasibility of these platforms. The experience gained during the study confirmed this thesis: in conditions of limited resources, the use of online laboratories provided high-quality access to educational content, which helped increase the level of knowledge of students in the experimental group. A recent review likewise demonstrated that virtual laboratories can expand access to experiential science learning, although their effectiveness depends on appropriate instructional design, technological accessibility, and integration with practical activities (Reyes et al., 2024).

The use of a modern approach to teaching biology contributed to the development of critical thinking and interaction skills among students. Projects involving real-life research and experiments enable students to apply theoretical knowledge in practice, which can increase their motivation and interest. Harrison et al. (2023) emphasised the effectiveness of virtual laboratories in shaping satisfaction with the learning process, which is fully consistent with the data obtained from surveys. Adanır and Muhametjanova (2021) compared students from Kyrgyzstan and Turkey in terms of their perception of digital methods. They concluded that for students in Kyrgyzstan, attitudes play a crucial role – analogous to the experimental sample of the present study, where students' proactive use of digital platforms indicated a positive attitude towards such tools.

Chen (2019) studied the use of augmented reality in teaching mathematics and found a decrease in anxiety and an increase in motivation. An analogous effect was recorded in the present study: students who had access to interactive tools demonstrated stable engagement, increased confidence, and were more effective in solving problem-analytical tasks. More specifically, a recent review of augmented reality in biology education confirmed its potential to improve visualisation, interactivity, learner engagement, and the comprehension of complex biological structures and processes (Stanič & Špernjak, 2025).

The findings also have implications for the development of teachers' digital competence, particularly through the Technological Pedagogical Content Knowledge framework. In this study, the effectiveness of digital tools depended not only on the availability of platforms but also on the teacher's ability to connect biological content, pedagogical aims, and appropriate technologies. For vocational teacher training programmes in Kyrgyzstan, this means that digital competence should be operationalised through practical

modules in which future teachers learn to select biological topics that require visualisation, design multimedia explanations, adapt virtual laboratory simulations to limited laboratory resources, and assess students' understanding through rubrics and problem-based tasks. Such training may include microteaching, peer review of digital lesson plans, preparation of short multimedia sequences, and the creation of low-cost blended laboratory scenarios using platforms such as PhET, Labxchange, Khan Academy, and Coursera. This approach would allow vocational colleges to move from occasional use of digital tools to a systematic TPACK-based model of biology instruction.

Recent studies on mobile and digitally supported learning help explain why the intervention had a positive effect on students' engagement and learning outcomes. Mobile learning is not only a matter of access to digital content; it changes the organisation of learning by allowing students to return to materials, repeat explanations, and work with visual or interactive resources at their pace. This is consistent with studies showing that mobile learning can improve students' attitudes, engagement, and perceived usefulness of digital instruction in higher education (Alturki & Aldraiweesh, 2022; Anh & Uyen, 2023; Salhab & Daher, 2023). Broader reviews also indicate that mobile technologies support flexible and sustainable learning models, although their effectiveness depends on pedagogical design rather than on technology alone (Sobral, 2020; Criollo-C et al., 2021; Hwang et al., 2021).

From the perspective of cognitive load theory, the positive results can be explained by the ability of multimedia and mobile tools to reduce unnecessary cognitive effort and make complex material easier to process (Beatrice et al., 2024). Biology involves many abstract, microscopic, and dynamic processes, such as cell organisation, enzyme reactions, heredity, and microbiological mechanisms. When teachers explain such topics verbally, students must mentally reconstruct invisible processes, which may increase cognitive load. Digital visualisation, short videos, mobile applications, and interactive tasks can distribute information across visual and verbal channels and help students focus on essential relationships. This interpretation is supported by studies on cognitive load in mobile and e-learning environments, including screen size, task complexity, multidimensional cognitive load, and cognitive load management (Alasmari, 2020; Curum & Khedo, 2021; Choi & Lee, 2022; Chen et al., 2023).

Research shows that mobile learning is most effective when it connects to concrete subject content and active learning tasks, which aligns with the findings. For example, mobile applications have been shown to support performance in programming, renewable energy education, forestry education, and other applied fields, suggesting that digital tools are especially useful when students need to combine conceptual understanding with practical or problem-orientated activity (Halim & Eh Phon, 2020; Tereshchenko et al., 2020; Hoque et al., 2023). In the present study, this was reflected in the stronger outcomes for laboratory work and problem-analytical tasks, where students needed not only to reproduce biological knowledge but also to apply it in practical contexts.

The findings also confirm that digital learning should not be limited to the mere use of devices. Studies on mobile applications and mobile teaching models show that learning gains depend on interaction, feedback, task structure, and the meaningful integration of digital resources into the teaching process (Chu et al., 2019; Criollo-C et al., 2022; Zhang, 2022). Therefore, the results of this study suggest that multimedia technologies are most effective in vocational biology education when they are used as pedagogical tools for visualisation, rehearsal, laboratory preparation, and student-centred learning, rather than as supplementary materials only.

Thus, the effectiveness of the training depended on the quality of the development of these programmes. In his study of English language learning, Sadiq (2020) concluded that students' performance directly depends on the role of the teacher as a motivational leader and their teaching methods, which was fully supported by the findings obtained. Safitri et al. (2017) emphasised the role of teachers' digital competence, particularly the ability to use multimedia resources, which enabled the effective implementation of technology in their study. Aumann et al. (2024) pointed out that young teachers often focus on tools rather than content. Experience shows that the gradual introduction of technology within a sound methodological strategy can achieve a pedagogical balance.

The results indicate that multimedia and simulation-based biology instruction is effective when educators align digital tools with the structure of biological knowledge. Visualisation is especially valuable for biological materials because it helps students observe scale, sequence, interaction, and causality in processes that are otherwise difficult to perceive directly. For vo-

cational education in Kyrgyzstan, the practical implication is that teacher training should not focus only on technical familiarity with digital platforms but also on the ability to integrate these platforms into biology-specific explanations, laboratory preparation, and problem-analytical learning tasks.

CONCLUSIONS

The study established that digitally enhanced biology instruction was more effective than conventional teaching primarily in developing laboratory skills, improving overall academic performance, and increasing students' satisfaction with the learning process, whereas its effect on theoretical knowledge was limited and the improvement in problem-analytical performance represented a positive but statistically inconclusive tendency. These findings should be interpreted as context-specific to a single technical college in Kyrgyzstan and should not be generalised to other institutional, cultural, or resource settings without further verification. Multimedia presentations, online platforms, mobile applications, and virtual laboratory simulations supported the visualisation of complex biological processes, enabled repeated preparation for practical tasks, and facilitated more active engagement with learning materials. The positive relationship between learning satisfaction and academic performance further indicates that motivational and cognitive outcomes should be considered jointly when evaluating digitally supported instruction. Accordingly, blended teaching models that combine conventional classroom and laboratory activities with accessible digital resources may be recommended for vocational biology education in Kyrgyzstan and similar resource-constrained educational contexts. The scientific contribution of the research lies in providing context-specific quasi-experimental evidence on the use of low-cost digital technologies in Central Asian vocational science education and in demonstrating that their main educational value concerns practical skill formation and learning engagement rather than uniform improvement across all types of academic achievement. The findings also extend the application of multimedia learning principles to technical-college biology education and provide a basis for developing teacher-training modules focused on digital pedagogy, virtual laboratory preparation, and criterion-based assessment. Nevertheless, the conclusions should be interpreted with caution because the study involved one institution, lacked a formal pre-intervention test, and did not statistically control students'

previous digital experience, motivation, access to devices, or possible teacher effects; therefore, further multi-institutional and longitudinal research using pre-test and post-test designs is required to verify the stability and broader applicability of the identified effects. Future studies should replicate this design across multiple technical colleges in Central Asia, incorporate randomised or pre-test/post-test designs, and examine whether the stronger effects observed for practical skills compared with theoretical knowledge are consistent across institutions and student populations before these findings are used to inform regional curriculum policies.

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