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Analytical Evaluation of the Impact of Experiments on Student Motivation in Biology Teaching in the Context of Pedagogical Opportunities and Limitations

Biyoloji Öğretiminde Deneylerin Öğrenci Motivasyonuna Etkisinin Pedagojik Olanaklar ve Sınırlılıklar Bağlamında Analitik Değerlendirilmesi

Abstract

This study examines the impact of experiments on student motivation in biology teaching within the framework of pedagogical opportunities and limitations. The primary objective is to evaluate how experimental activities influence students' cognitive engagement, interest in learning, and the development of scientific thinking. Both traditional laboratory-based experiments and contemporary virtual experimental environments are analyzed through a comparative perspective. The findings indicate that experimental activities strengthen intrinsic motivation, encourage students to assume active research roles, and facilitate the practical application of theoretical knowledge. Experimental learning also contributes to the development of analytical thinking, problem-solving abilities, and collaborative skills. At the same time, several factors limiting the effective implementation of experiments were identified, including insufficient material and technical resources, time constraints, and safety- and ethics-related considerations. The analysis further demonstrates that the integrated use of real and virtual experiments creates a more effective learning environment than the isolated application of either approach. Such integration increases student engagement and supports the development of scientific inquiry skills. Overall, experiments in biology teaching represent a significant pedagogical instrument that contributes not only to academic achievement but also to students' personal and intellectual development.

Keywords: *biology teaching, experiment, student motivation, virtual laboratory, research skills, scientific thinking*

Öz

Bu çalışma, biyoloji öğretiminde deneylerin öğrenci motivasyonu üzerindeki etkisini pedagojik olanaklar ve sınırlılıklar çerçevesinde incelemektedir. Araştırmanın temel amacı, deneysel etkinliklerin öğrencilerin bilişsel katılımına, öğrenmeye yönelik ilgisine ve bilimsel düşünme becerilerinin gelişimine nasıl katkı sağladığını ortaya koymaktır. Çalışmada geleneksel laboratuvar deneyleri ile günümüzde yaygın olarak kullanılan sanal deney uygulamaları karşılaştırmalı bir bakış açısıyla değerlendirilmiştir.

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Elde edilen bulgular, deney temelli öğrenme etkinliklerinin öğrencilerin içsel motivasyonlarını güçlendirdiğini, onları araştırma sürecinin aktif bir parçası hâline getirdiğini ve kuramsal bilgilerin uygulamaya aktarılmasını kolaylaştırdığını göstermektedir. Deneylerin aynı zamanda analitik düşünme, problem çözme ve iş birliği becerilerinin gelişimine katkı sağladığı belirlenmiştir. Bununla birlikte, materyal ve teknik altyapı yetersizlikleri, zaman kısıtları ile güvenlik ve etik boyutlara ilişkin sorunlar deneylerin uygulanmasını sınırlandıran temel etkenler olarak değerlendirilmiştir. Araştırma sonuçları, gerçek ve sanal deneylerin bütüncül biçimde kullanılmasının öğrenme ortamlarının niteliğini artırdığını, öğrenci katılımını güçlendirdiğini ve bilimsel sorgulama becerilerinin gelişimini desteklediğini ortaya koymaktadır. Sonuç olarak deneyler, biyoloji öğretiminde yalnızca akademik başarıyı değil, öğrencilerin kişisel ve zihinsel gelişimlerini de destekleyen önemli bir pedagojik araç niteliği taşımaktadır.

Anahtar Kelimeler: *biyoloji öğretimi, deney, öğrenci motivasyonu, sanal laboratuvar, araştırma becerileri, bilimsel düşünme*

Introduction

Improving the quality of teaching and increasing students' active participation in the learning process are among the primary priorities of contemporary education systems. In this context, the application of the experimental method in biology teaching has gained particular significance. Experiments enable students not only to acquire theoretical knowledge but also to verify, apply, and interpret that knowledge through practical experience. As a result, the learning process moves beyond passive reception of information and becomes more active, inquiry-oriented, and student-centered.

Contemporary educational research indicates that experimental activities play an important role in the development and sustainability of student motivation. Particularly in biology and other natural sciences, direct engagement with living organisms, biological phenomena, and observable processes strengthens students' curiosity, interest in discovery, and scientific thinking skills. At the same time, the implementation of experiments is influenced by various practical considerations, including the availability of material and technical resources, time constraints, safety requirements, and ethical standards.

The main purpose of this study is to provide an analytical evaluation of the influence of experiments on student motivation in biology teaching by examining both their pedagogical potential and their practical limitations. To achieve this objective, the concept of experimentation, its educational functions, major motivational perspectives, and examples derived from teaching practice were examined comprehensively.

Literature Review

The role of experiments in biology teaching and their impact on student motivation have been widely studied in pedagogical literature. In classical methodological approaches, the experiment is presented as one of the main components of biology teaching, with particular emphasis placed on its cognitive, developmental, and educational functions. Studies conducted in this field indicate that experimentation serves not only as a means of confirming theoretical knowledge but also as an important mechanism for the development of scientific thinking among students (Verzilin & Korsunskaya, 1983; Ponomareva et al., 2007).

Representatives of the traditional Soviet and post-Soviet pedagogical school evaluate the biology experiment as a central element of instruction and emphasize the importance of its systematic and purposeful application. For example, Binas and colleagues associate the use of experiments in school biology with the development of students' observation and analytical skills and present experimentation as a major tool for mastering scientific knowledge (Binas et al., 1990). In addition, methodological studies highlight the importance of careful planning and appropriate instructional organization in the implementation of experimental activities.

In contemporary methodological approaches, the integration of experiments with project-based learning and innovative technologies has gained particular relevance. The project-based learning model creates opportunities for students to conduct independent investigations and links experimentation with the solution of real-world problems. In this regard, Polivanova and Matyash note that the application of experiments within project activities contributes to the development of students' creative and critical thinking skills (Polivanova, 2011; Matyash, 2014). At the same time, the integration of information technologies into biology teaching has facilitated the emergence of new forms of experimental activity, including virtual laboratories and simulation-based learning environments (Titov & Morozova, 2010; Galkina, 2013).

Studies addressing the use of digital technologies in biology education indicate that such approaches are particularly useful for presenting complex biological processes and strengthening students' visual understanding of scientific concepts. Multimedia tools support the visualization of abstract phenomena and contribute to a more engaging learning environment (Galkina, 2013).

International studies on student motivation also emphasize the significance of practical and experiment-based learning. Research in science education demonstrates that active participation in experimental activities can strengthen students' interest in learning, increase engagement, and support more positive attitudes toward biology. Furthermore, contemporary studies suggest that providing students with greater autonomy during learning activities contributes positively to motivation and classroom participation (Grobmann et al., 2023).

At the same time, methodological manuals, practicums, and curriculum-oriented resources define the organizational foundations for the systematic application of experiments in biology teaching. These materials address issues such as the planning of experimental activities, adherence to safety requirements, and the appropriate interpretation and evaluation of results (Kartashova & Kulitskaya, 2016; Luzianin & Blinova, 2013; Paldyaeva, 2015). Thus, the literature indicates that experiments occupy a central position in both traditional and contemporary approaches to biology teaching. Their positive contribution to student motivation has been widely recognized, while current developments increasingly emphasize the integration of experimental activities with innovative technologies and project-based learning environments.

Methodology

The study is based on a qualitative research approach and primarily employs theoretical analysis, comparative analysis, and pedagogical observation methods. International and local scientific literature, methodological resources, and teaching practices related to the topic were systematically examined.

During the analysis process, different models of experiment application in biology teaching were compared, and their influence on student motivation was interpreted within the framework of contemporary motivational perspectives. In particular, self-determination theory and the expectancy-value approach served as the main theoretical foundations of the analysis.

In addition, observations derived from school-based educational practice constituted an important component of the methodological framework. The influence of different types of experiments, including laboratory activities, field observations, and virtual experiments, on student behavior and classroom engagement was examined. Particular attention was given to the challenges encountered during the implementation of experimental activities and to their implications for the effectiveness of the learning process.

Findings

The conducted analytical analysis and pedagogical observations show that the application of experiments in biology teaching has a systematic and multi-level mechanism of influence on the formation of student motivation. The table below provides a comparative analysis of the results obtained by the author of the article with the existing literature.

Table 1. Author's results and comparative analysis of the literature on the impact of experiments on student motivation in biology teaching

Research direction	**The author's conclusion**	**Current approach in the literature**	**Comparative analysis**	**Reference**
Motivation	Experiments strengthen intrinsic	Motivation is related to autonomy,	The author confirms the theoretical	Deci & Ryan, 2000

	motivation and turn the student into an active researcher	competence and social connectedness	approach with practical observations	
Cognitive activity	Experiments strengthen analytical thinking and problem solving	Practical activities increase cognitive activity	There is a correspondence, the author specifies it in the context of biology	Eccles & Wigfield, 2002
Real experiments	More effective in developing practical skills	Laboratory experiments are the main learning tool	Complete correspondence, the author additionally emphasizes the school reality	Hofstein & Lunetta, 2004
Virtual experiments	Creates a visual understanding and safe learning environment, but poorly develops practical skills	Virtual laboratories are an effective alternative	The author takes a more critical approach and highlights the limitations	Odadžić et al., 2017
Project-based learning	Creative and critical thinking increases when experiments are combined with projects	Project-based learning develops research skills	Complete correspondence, the author specifies the role of the experiment more specifically	Matyash, 2014
Individual approach	The possibility of choice significantly increases motivation	Student autonomy is a key condition for motivation	Complete correspondence, the author applies it in an experimental environment	Grobmann et al., 2023

Summer experiments	Long-term observations strengthen independent research and professional orientation	Practical activities ensure continuous learning	The author adds a new context (summer vacation)	Ponomareva et al., 2007
Limitations	Material-technical, time and ethical problems are the main obstacles	The application of experiments depends on resources	Complete correspondence, the author systematically summarizes the problems	Kartashova & Kulitskaya, 2016

This comparison shows that the author's results are largely consistent with existing scientific approaches, but differ in that they are interpreted more deeply in the context of practical school environments and specific biology teaching. At the same time, the author brings an application-oriented scientific innovation to the topic by highlighting reflective approaches.

Discussion

Historical Development and Formation of the Experimental Method in Biology Teaching

The emergence of experimentation as a scientific research method is closely associated with the development of modern natural science. The earliest systematic approaches in this field are commonly linked to the works of Galileo Galilei and William Gilbert. Galileo's experimental investigations of mechanics and natural phenomena, together with Gilbert's explanation of magnetic processes in *De Magnete*, contributed significantly to the establishment of experimentation as a recognized scientific method (Gilbert, 1600; Galilei, 1632).

The philosophical foundation of experimentation was further developed by Francis Bacon. In *Novum Organum*, he emphasized the importance of observation and experience as the basis of scientific knowledge and articulated the principles of inductive reasoning (Bacon, 1620). This approach subsequently became one of the methodological foundations of the natural sciences, including biology.

The systematic incorporation of experimentation into biology teaching became more evident during the second half of the nineteenth century and the beginning of the twentieth century. During this period, increasing attention was devoted to observation, practical activity, and direct interaction with natural phenomena as essential components of science education. At the same time, T. H. Huxley emphasized the importance of laboratory and experimental approaches in scientific instruction and argued that science education should be grounded in experience (Huxley, 1880).

During the twentieth century, the scientific foundations of biology teaching methodology were further developed. Verzilin and Korsunskaya, in *Obshchaya metodika prepodavaniya biologii*, explained the interrelationship between observation, practice, and experimentation in biology teaching and justified the systematic integration of these methods into school education (Verzilin & Korsunskaya, 1983). Their work reinforced the understanding of experimentation as a structured and purposeful pedagogical method rather than an occasional instructional activity. Subsequently, Ponomareva and other methodologists contributed to the development of modern forms of experimental activity in biology teaching, particularly through the expansion of laboratory work and practice-oriented learning within educational programs (Ponomareva et al., 2007). The introduction of digital technologies and virtual laboratories has further expanded the possibilities of experimental learning in the twenty-first century.

The Concept and Functions of Experimentation in Biology Teaching

In biology education, experimentation is not viewed merely as a laboratory activity but as a complex didactic process through which students observe natural phenomena, manipulate variables, and interpret results on a scientific basis. Contemporary pedagogical approaches regard experimentation as an active cognitive activity that fundamentally differs from traditional explanatory and descriptive methods (Hofstein & Lunetta, 2004).

Practical educational experience demonstrates that determining the presence of starch in leaves through the iodine test often produces a stronger cognitive effect than a purely theoretical explanation of photosynthesis. In such situations, students do not simply receive information; they construct knowledge through direct experience. This process reflects one of the fundamental educational functions of experimentation and supports the constructive development of scientific understanding (Driver et al., 1994).

The functions of experimentation are multifaceted and directly influence the quality of biology teaching. First, experimentation performs a cognitive function by activating observation, comparison, analysis, and generalization skills. For example, when students compare plant growth under different light conditions, they independently identify causal relationships. At the same time, experimentation fulfills a developmental function by fostering responsibility, perseverance, patience, and research skills.

Experimentation also serves a verification function. During activities such as measuring transpiration, students empirically evaluate previously formulated assumptions and compare them with observed results. This process contributes to the development of scientific reasoning and evidence-based thinking.

In addition, experimentation performs an important motivational function by linking biological concepts to observable phenomena and practical experience. As a result, biology is perceived not as an abstract body of information but as a dynamic field of inquiry connected to real-life processes. Studies indicate that lessons incorporating laboratory activities often demonstrate higher levels of student participation, engagement, and attention than lessons based solely on theoretical instruction (Abrahams & Millar, 2008).

Table 2. Analytical-comparative table of the functions of the experiment in teaching biology

Function	**Essence**	**Impact on the learning process**
Cognitive function	Activates the student's observation, analysis, comparison and generalization skills	Strengthens logical thinking and understanding of cause-and-effect relationships
Constructive function	Ensures the construction of knowledge by the student's "discovery"	Provides a transition from passive to active learning
Developmental function	Forms research skills and personal qualities	Develops patience, responsibility and the ability to work independently
Verifying function	Ensures empirical testing of hypotheses	Forms the ability to think scientifically and draw evidence-based conclusions
Motivational function	Increases interest by linking learning to real life	Increases student activity and engagement in the lesson

As can be seen from the table, experimentation is not merely a means of knowledge transfer in biology teaching but also a multifunctional pedagogical tool that supports the comprehensive development of students' cognitive abilities and personal qualities. The comparison demonstrates that, compared with traditional instructional approaches, the experimental method produces more substantial outcomes in both cognitive development and student motivation.

The Concept of Student Motivation and Major Theoretical Approaches

Student motivation can be defined as a system of psychological mechanisms that stimulates learning activity through the interaction of internal and external factors. In contemporary educational theory, motivation is regarded not only as an outcome-oriented phenomenon but also as a process-oriented one. From this perspective, the application of experiments in biology lessons represents an important factor influencing the structure and sustainability of student motivation.

Among contemporary motivational theories, self-determination theory occupies a prominent position. According to this theory, effective learning depends on the fulfillment of three basic psychological needs: autonomy, competence, and relatedness (Deci & Ryan, 2000). Classroom observations indicate that when students are given opportunities to make choices during experimental activities, such as selecting variables or procedures, their engagement and interest in learning increase considerably.

Another influential perspective is expectancy-value theory. According to this approach, motivation increases when students perceive both a high probability of success and a high value in the task being performed (Eccles & Wigfield, 2002). For example, physiological experiments involving measurements of the human body, such as pulse rate monitoring, are often perceived as highly meaningful because they are directly connected to students' everyday experiences.

Educational practice indicates that forms of motivation based exclusively on external rewards tend to have limited long-term effects. By contrast, intrinsic motivation characterized by curiosity, a desire for discovery, and enthusiasm for problem-solving is generally more sustainable. In this respect, biology experiments function as a powerful pedagogical mechanism that promotes the transformation and strengthening of student motivation.

Pedagogical Opportunities of Experiments in Biology Teaching

The use of experiments in biology lessons enables students to participate in the learning process as active investigators rather than passive recipients of information. This approach supports the construction of knowledge by learners themselves and is consistent with the fundamental principles of constructivist learning theory. For example, when investigating the water requirements of plants, students not only learn the outcome but also understand the processes leading to that outcome.

Classroom observations suggest that experiments help students maintain attention and engagement for longer periods. Activities such as observing cell structures through microscopy often generate a sense of discovery that strengthens emotional involvement in learning. As a result, knowledge acquired through direct experience tends to be retained more effectively than information obtained through purely theoretical instruction (Hattie, 2009).

Another important pedagogical advantage of experimentation is the development of research competencies. Through practical activities, students become familiar with the stages of scientific inquiry, including hypothesis formulation, variable identification, data collection, analysis, and conclusion drawing. For instance, a student investigating the influence of temperature on enzyme activity is simultaneously applying the fundamental principles of scientific methodology.

Experimental activities also contribute to the development of social and communication skills. Laboratory work conducted in groups encourages cooperation, responsibility, and the exchange of ideas. Educational observations indicate that students who are less active during traditional lessons frequently demonstrate greater participation and involvement during collaborative experimental activities.

Pedagogical Limitations in the Application of Experiments

Despite their considerable educational value, experiments in biology teaching are accompanied by a number of objective and subjective limitations that may influence their effectiveness in practice.

Table 3. Pedagogical constraints affecting the use of experiments in biology Teaching

Limitation direction	**Explanation of the content**	**Impact on the learning process**
Material and technical support	Insufficient laboratory resources and equipment limit the possibilities of fully organizing experiments	Students' practical activity decreases, experiments become more demonstrative
Time constraints	Since the preparation and execution of experiments require a lot of time, teachers often prefer theoretical explanations	Experimental activity becomes episodic and systematicity weakens
Methodological difficulties	The complexity of some biological processes makes their practical application at the school level difficult	Subjects are simplified or the practical part is shortened
Safety and ethical factors	A number of experiments are limited because working with chemicals and living objects poses risks	The variety and application possibilities of experiments decrease

Limitations of virtual experiments	The digital environment does not fully replace real laboratory conditions	The formation of practical skills and technical habits weakens
Psychological and social factors	The level of activity of students in group work varies and some students remain passive	Evaluation of individual participation becomes more difficult

Pedagogical and Developmental Importance of Organizing Biological Experiments During the Summer Holidays

The limitations presented in the table demonstrate that the effectiveness of experiments in biology teaching depends not only on the nature of the method itself but also on the characteristics of the pedagogical environment in which it is implemented. While material, technical, and time-related constraints primarily affect the scale and continuity of experimental activities, methodological and safety-related issues influence their quality and educational value. As a result, experiments may become simplified or, in some cases, be excluded from educational practice altogether. Although virtual laboratories can compensate for certain deficiencies, they cannot fully replace hands-on practical experience, creating specific limitations in the experimental dimension of biology education. Psychological and social factors represent a more subtle yet equally important aspect of the learning process, sometimes creating discrepancies between actual student participation and the objectivity of assessment. Overall, if these limitations are not systematically addressed, the pedagogical potential of experimentation cannot be fully realized, and its motivational and developmental impact may be reduced.

The summer vacation period represents a particularly favorable stage for the development of students' independent research skills in biology. Since experimental activities conducted during this period take place outside the traditional classroom environment, they provide opportunities to observe natural phenomena under real conditions and to carry out long-term investigations. Methodological literature emphasizes that such activities foster investigative thinking and help students perceive biology not as an abstract academic subject but as a scientific discipline directly connected with everyday life (Ponomareva et al., 2007).

One of the most important characteristics of summer projects is their reliance on continuous observation. Processes such as seed germination, plant growth, and responses to environmental factors develop over time, allowing students to monitor changes systematically and analyze results comparatively. This approach strengthens their understanding of cause-and-effect relationships and enhances scientific reasoning skills (Verzilin & Korsunskaya, 1983).

Summer experiments also provide opportunities for direct interaction with natural environments. Field observations of living organisms, ecosystem changes, and human impacts on nature contribute significantly to the development of ecological awareness. Such activities encourage responsible attitudes toward environmental issues and strengthen students' understanding of ecological interdependence (Teremov et al., 2012).

Another important aspect of summer projects is their contribution to career orientation. Long-term experimental activities help students better understand their interests and abilities, which may influence future educational and professional choices. For example, agricultural experiments may stimulate interest in biological and agricultural sciences, whereas investigations related to human physiology may encourage interest in medicine and biomedical fields (Matyash, 2014). In this respect, summer experiments function not only as educational activities but also as instruments of professional self-discovery.

Methodological approaches indicate that the effectiveness of such projects depends largely on appropriate planning and the degree of independence granted to students. Within this framework, the teacher acts primarily as a guide and mentor rather than as a controller. Encouraging students to maintain research journals, visualize results, and present findings contributes to the development of analytical, organizational, and communication skills (Kartashova & Kulitskaya, 2016).

Digital Laboratories and the Transformation of Experimental Learning in Biology Teaching

The implementation of digital laboratories in biology teaching represents one of the most significant transformations in contemporary educational practice. These technologies complement traditional experimental instruction and make learning more precise, measurable, and visually accessible. Methodological studies indicate that the integration of digital tools into biology education improves the quality of observation and experimentation while simultaneously supporting the development of scientific thinking skills (Teremov et al., 2012).

One of the principal advantages of digital laboratories is their capacity to facilitate the quantitative investigation of biological processes. Whereas many biological phenomena were traditionally taught primarily through descriptive explanations, modern digital sensors enable these processes to be measured and analyzed numerically. For example, photosynthetic activity can be monitored in real time through light sensors and oxygen measurement devices. Such approaches help students connect biological processes with quantitative data and strengthen analytical thinking skills (Titov & Morozova, 2010).

Digital laboratories also play a crucial role in the visualization of complex biological phenomena occurring at both microscopic and macroscopic levels. Processes such as DNA replication, enzymatic reactions, and intracellular mechanisms, which are difficult to observe directly, can be represented through simulations and three-dimensional models. According to Galkina (2013), multimedia and simulation technologies facilitate the comprehension of abstract biological concepts and increase the interactivity of the learning process.

These technologies also enhance instructional effectiveness. The simultaneous activation of visual and auditory channels supports deeper understanding and longer retention of information. This characteristic is particularly valuable in biology, where many topics depend heavily on visual representation.

Educational practice demonstrates that digital microscopes and interactive displays increase student engagement in laboratory activities. Unlike traditional microscopes, which allow only individual observation, digital microscopes enable the entire class to observe the same image simultaneously. This expands opportunities for collaborative discussion and collective analysis. Kartashova and Kulitskaya (2016) note that such technologies promote active participation in scientific inquiry and strengthen the facilitator role of the teacher.

Another important advantage of digital laboratories lies in their simulation capabilities. Biological processes that are difficult, expensive, or time-consuming to reproduce under real conditions can be modeled through specialized software. Population dynamics, ecosystem interactions, and genetic inheritance patterns can be manipulated through virtual variables, allowing immediate observation of outcomes. Such activities strengthen students' understanding of variability, control, and experimental design.

However, the use of digital laboratories also presents several pedagogical limitations. One of the most significant concerns relates to the incomplete development of practical laboratory skills. Although students can effectively conduct experiments in virtual environments, skills such as microscope handling, specimen preparation, and direct manipulation of laboratory equipment may remain insufficiently developed. Consequently, many educational specialists advocate a balanced integration of digital and traditional laboratory experiences.

Digital laboratories also optimize aspects of instructional management. Automated assessment systems facilitate objective measurement of learning outcomes while allowing teachers additional time for individualized support. This is particularly beneficial in large classes where differentiated instruction can otherwise be difficult to implement.

Overall, digital laboratories transform biology education from a predominantly descriptive model into a dynamic, interactive, and data-oriented learning environment. These technologies encourage students not only to acquire information but also to analyze, model, and interpret scientific evidence. As a result, digital laboratories have become an important pedagogical tool for developing competencies associated with twenty-first-century learning.

Despite their advantages, methodological literature also emphasizes several pedagogical and technical limitations associated with digital laboratories. These limitations primarily concern the practical dimension of learning, skill development, and resource availability.

One of the most important challenges involves the incomplete development of hands-on laboratory skills. Although students can observe outcomes through digital platforms, opportunities to develop competencies such as microscope use, specimen preparation, and direct laboratory manipulation remain limited. Consequently, the experimental essence of biology may only be partially experienced within purely virtual environments.

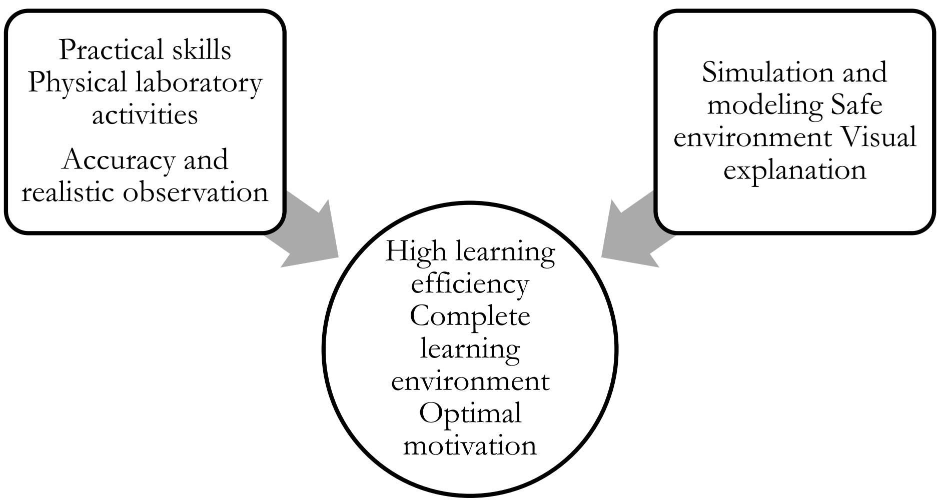
Another limitation concerns health and psychophysiological factors. Extended screen exposure may contribute to visual fatigue and reduced concentration. For this reason, digital activities should be carefully balanced with other forms of instruction, and their duration should be managed appropriately within the educational process (Titov & Morozova, 2010).

Material and technical support also remains a significant issue. The high cost of modern equipment, software, and interactive systems limits their widespread implementation in many educational institutions. Kartashova and Kulitskaya (2016) emphasize that effective integration of digital technologies requires a strong technical infrastructure, which may not be equally available across all educational contexts.

The successful management of digital laboratories also requires advanced information and communication technology competencies on the part of teachers. In addition to pedagogical responsibilities, teachers must often address technical issues, which may increase workload and affect instructional efficiency (Teremov et al., 2012).

Assessment in collaborative digital environments presents another challenge. Since students frequently work together on projects and investigations, accurately determining individual contributions can be difficult. This may affect the objectivity and reliability of assessment procedures. Technical problems, including software malfunctions, display errors, and connectivity issues, may also interrupt the continuity of learning activities and limit the effectiveness of planned experiments. Overall, although digital laboratories constitute an important innovation in biology education, their implementation should be accompanied by careful consideration of these limitations. A balanced integration of digital technologies with traditional laboratory instruction remains the most effective strategy for achieving meaningful educational outcomes. The diagram below provides a visual representation of the integration of real and virtual experiments.

Figure 1. Integration of Real and Virtual Experiments in Biology Teaching



In the scheme, the left side illustrates the advantages of real (physical) experiments, whereas the right side presents the advantages of virtual (simulation-based) experiments. The integration of these two approaches leads to the outcomes shown in the central section. The elements presented on the left, including practical skills, hands-on laboratory activities, and direct observation, represent the principal strengths of real experiments. Through direct interaction with laboratory equipment, students develop measurement, observation, and analytical skills. This process contributes to the formation of both practical competencies and scientific inquiry skills. At the same time, real laboratory environments may present certain challenges related to resource availability, safety requirements, and time constraints.

The right side of the scheme highlights the advantages of virtual experiments, including simulation and modeling, safe learning environments, and enhanced visualization. Virtual environments enable students to explore complex or potentially hazardous biological processes without risk, repeat experiments multiple times, and understand abstract concepts through visual representations. These characteristics are particularly valuable when teaching complex biological topics.

Directions and Principles for Selecting Project Topics in the School Biology Curriculum

The selection of project topics within the school biology curriculum is determined by students' age characteristics, curriculum content, and available research opportunities. Studies indicate that the most effective and widely implemented projects are those connected to real-life situations and supported by observation and experimentation (Thomas, 2000; Bell, 2010). Such projects help students perceive biology not only as theoretical knowledge but also as a scientific discipline closely related to everyday life.

Plant-related projects represent one of the most common areas of school biology. Students frequently investigate seed germination, plant responses to environmental factors such as light and temperature, and physiological processes including photosynthesis and transpiration. Because these projects can be conducted under relatively simple experimental conditions, they are suitable for both lower and upper secondary education. For example, comparing the growth of the same plant species under different light conditions enables students to observe biological patterns directly.

Projects in zoology are generally associated with animal behavior and ecological studies. Students may observe microscopic organisms, investigate the behavior of invertebrates, or conduct simple observational studies in natural settings. Such activities increase interest in living organisms while simultaneously developing observation and analytical skills (Krajcik & Blumenfeld, 2006).

Projects related to human biology also occupy an important place in school practice. Students may investigate the effects of physical activity on pulse rate and respiration, examine reflex responses, or analyze the relationship between healthy lifestyles and physiological functioning. These topics contribute to the development of health awareness and personal responsibility.

At higher educational levels, project topics become increasingly complex and include areas such as cell biology, genetics, ecology, and biotechnology. Research projects focused on genetic inheritance, biodiversity conservation, and environmental challenges contribute to the development of analytical thinking and encourage engagement with contemporary scientific issues (Larmer et al., 2015).

Application of an Individual Approach in Biological Research and Its Pedagogical Foundations

The individual approach in biological studies represents one of the central principles of contemporary educational theory and is based on recognizing differences in students' cognitive abilities, interests, and learning styles. This approach transforms biology teaching from a standardized process into a flexible system adapted to the developmental needs of individual learners. Consequently, students become active participants who take responsibility for their own learning rather than passive recipients of information (Tomlinson, 2014).

One of the major characteristics of this approach is differentiated instruction. Tasks of varying levels of complexity are provided within the same topic according to students' prior knowledge and learning capacities. This allows less experienced students to master fundamental concepts while simultaneously creating opportunities for advanced students to engage in more complex and creative investigations. As a result, biology education can support the development of each student according to individual potential (Hattie, 2009).

Another factor contributing to the effectiveness of individualized learning is the provision of choice. Allowing students to select research topics, working methods, and presentation formats strengthens intrinsic motivation and encourages greater responsibility for learning outcomes. This principle is particularly relevant in biology, where student interest often increases when investigations are connected to personal preferences and experiences (Bransford et al., 2000).

An individualized approach also requires consideration of different learning styles. Activities adapted to visual, auditory, and practical learners create conditions for more effective mastery of biological concepts. For example, simulations implemented in digital laboratories facilitate understanding of complex biological processes and strengthen the connection between theoretical knowledge and practical experience (Mayer, 2009).

The role of the teacher is also transformed within this framework. Rather than serving exclusively as a transmitter of information, the teacher functions as a mentor who guides students, supports their learning processes, and facilitates independent inquiry. Such an approach promotes autonomous thinking and brings students closer to authentic scientific investigation (Vygotsky, 1978).

Compilation and Mathematical Processing of the Results of Biology Experiments

The compilation and analysis of experimental results constitute an important stage in the development of students' scientific research skills. Methodological literature emphasizes that accurate documentation of laboratory and field observations is one of the key indicators of successful mastery of scientific methodology (Ponomareva et al., 2007). This process involves not only recording observations but also organizing, processing, and interpreting data scientifically.

At the initial stage, all obtained indicators are recorded accurately and systematically. Subsequently, the collected data are processed through mathematical and statistical procedures and transformed into scientific conclusions. As noted by Binas and colleagues, the reliability of results obtained in school biology experiments depends directly on the accuracy of measurement and data processing procedures (Binas et al., 1990).

A typical example of mathematical processing is the calculation of water loss in plants. Suppose the initial mass of a plant is 120 g and its final mass is 110 g. The mass loss is determined as follows:

Δm=m_0-m_1

Where: m_0 = 120 g, m_1 = 110 g

Calculation: Δm=m0−m1=120−110=10g

If this loss is divided by the leaf surface area (P = 25 cm²) and 24 hours, the transpiration intensity is expressed as follows:

$$I_t = \frac{\Delta m}{P \cdot t}$$

I_t = 10 / (25 × 24) = 10 / 600 = 0.0167 q/sm²·s

Such calculations demonstrate to students that biological processes can also be evaluated quantitatively and contribute to the development of scientific thinking skills.

Visualization plays an important role in the presentation of results. Through graphs, tables, and diagrams, data can be presented more clearly, and cause-and-effect relationships become easier to analyze (Koncevaya et al., 2016). At the same time, when interpreting the obtained results, students are expected to explain not only numerical outcomes but also the biological principles underlying them.

Thus, the process of compiling the results of biology experiments integrates observation, measurement, mathematical processing, visualization, and scientific interpretation. This approach enables students to develop research competencies and to perceive biology as both a practical and analytical scientific discipline.

Organizing Failed Experiments as a Reflective Learning Environment in Biology Teaching

In biology education, unsuccessful experiments should not be regarded as weaknesses in the learning process but rather as valuable pedagogical resources that contribute to the development of scientific thinking. Methodological literature emphasizes that errors encountered during experimental activities can strengthen critical thinking skills and help students understand the authentic nature of scientific inquiry (Ponomareva et al., 2007). This perspective supports the application of the principle of learning from mistakes and encourages a more realistic understanding of the research process.

The pedagogically effective use of unsuccessful experiments is primarily based on the analysis of errors through cause-and-effect relationships. For example, insufficient moisture during a seed germination experiment may prevent successful development. In such cases, the teacher and students can jointly analyze environmental factors and scientifically explain why the expected outcome was not achieved. According to Verzilin and Korsunskaya, situations of this kind create opportunities for deeper conceptual understanding in biology teaching (Verzilin & Korsunskaya, 1983).

The teacher's role at this stage is particularly important. Rather than providing ready-made answers, the teacher should encourage students to formulate hypotheses and test alternative explanations. In practical school experiments, especially those related to agricultural and plant cultivation activities, factors such as inappropriate fertilizer application or inadequate lighting conditions may influence outcomes and lead to unexpected results (Kartashova & Kulitskaya, 2016). Such situations help students recognize the iterative nature of scientific investigation.

At the same time, reflective analysis of unsuccessful outcomes contributes to the development of self-assessment skills. Students learn to evaluate not only the final result but also the entire research process. Research journals play an important role in this regard because they allow students to document changes systematically and identify factors influencing outcomes at each stage.

Consequently, when unsuccessful experiments are managed through appropriate pedagogical strategies, they become effective learning tools that stimulate cognitive activity and strengthen scientific reasoning. This process directs students not only toward obtaining results but also toward understanding the nature and logic of scientific inquiry itself.

Conclusion

Based on the findings of the study, several scientific contributions can be identified.

It was demonstrated that the impact of experiments on student motivation in biology teaching is shaped not only by cognitive activity but also by the interaction of autonomy, competence, and social connectedness.

The comparative analysis of real and virtual experiments revealed that their integrated use produces stronger pedagogical outcomes than the isolated application of either approach.

The study showed that combining experiments with project-based learning and individualized instructional practices contributes simultaneously to the development of analytical, critical, and creative thinking skills.

It was determined that long-term biological experiments conducted during summer periods play a significant role in fostering independent research skills and supporting students' career orientation.

The findings further indicate that the reflective analysis of unsuccessful experiments represents an effective pedagogical mechanism for strengthening scientific reasoning and self-assessment skills.

The study also demonstrated that digital laboratories have transformed experimental learning in biology education; however, their effective implementation requires a balanced integration with traditional laboratory practices to ensure the development of practical competencies.

A systematic classification of the principal constraints affecting the implementation of experiments in biology teaching, including material and technical limitations, time-related factors, methodological challenges, and ethical considerations, was developed and their influence on instructional quality was comprehensively evaluated.

Finally, it was established that the motivational impact of experiments is not limited to learning outcomes alone. Rather, experimental activities influence the learning process itself and contribute to the formation of sustained learning behaviors and long-term engagement with scientific inquiry.

Author Contributions

Aynur Mammadova contributed to the conceptualization of the study, research design, literature review, data collection and analysis, interpretation of the findings, drafting of the manuscript, and critical revision of the text. The author reviewed and approved the final version of the manuscript and agrees to be accountable for all aspects of the work.

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