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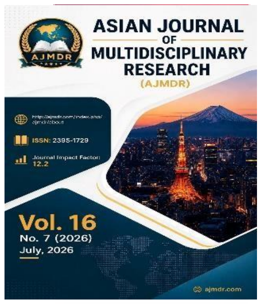

MODERN METHODOLOGICAL APPROACHES TO TEACHING THE MICROBIOLOGY MODULE IN A DIGITAL LEARNING ENVIRONMENT

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Abstract. This article examines modern methodological approaches to teaching the Microbiology module in a digital learning environment. It theoretically substantiates the integration of Digital Pedagogy, Connectivism, Blended Learning, Constructivism, Inquiry-Based Learning, Problem-Based Learning, and Experiential Learning with virtual and real laboratory activities. An integrative methodological model is proposed to enhance students' active learning, research skills, practical abilities, digital competence, problem-solving capacity, and reflective competence. The study provides methodological principles and recommendations for organizing competency-based Microbiology education through digital learning resources and virtual laboratories.

Keywords: Microbiology, digital learning environment, Digital Pedagogy, Connectivism, Blended Learning, Constructivism, Inquiry-Based Learning, Problem-Based Learning, virtual laboratory, competency-based education, digital competence, methodological approaches.

INTRODUCTION. In contemporary higher education, the teaching of biological sciences is increasingly shifting from the acquisition of ready-made knowledge toward the development of students' abilities to independently seek knowledge, analyze it scientifically, apply it in practical situations, and evaluate their own learning activities. This is particularly important in teaching Microbiology, a module that requires the integration of theoretical knowledge, experimental activities, and professional-practical training. Microbiological knowledge is not limited to understanding the structure, physiology, or classification of microorganisms; it also encompasses such complex activities as observation, evidence-based interpretation, analysis of experimental results, scientific decision-making in problem situations, and planning of laboratory activities.

In this context, the development of a digital learning environment is creating new requirements for the methodology of teaching the Microbiology module. The mere availability of digital tools does not automatically ensure educational effectiveness; their pedagogical value primarily depends on the methodological concept underlying their selection, the sequence in which they are incorporated into the learning process, and the extent to which they are connected with students' cognitive and practical activities. From this perspective, ensuring coherence between technological tools and pedagogical approaches in organizing Microbiology education within a digital environment has become an important methodological issue.

The specific nature of Microbiology education requires not the application of methodological approaches in isolation, but rather their functional integration [1].

Constructivism positions the student not as a passive recipient of ready-made knowledge, but as an active subject who constructs knowledge on the basis of prior experience and new learning tasks, while the competency-based approach directs acquired knowledge toward its application in professional activities. The activity-based approach reveals the mechanism through which knowledge is formed through active engagement. Inquiry-Based Learning strengthens students' abilities to formulate questions, propose hypotheses, collect evidence, and draw conclusions, whereas Problem-Based Learning enables the functional application of knowledge through real or simulated problems.

In addition, Blended Learning provides an organizational and methodological basis for integrating classroom, independent, and digital learning activities into a unified educational process. Digital Pedagogy defines the general methodological direction for using digital tools in accordance with pedagogical objectives. While Connectivism explains the formation of knowledge through digital networks, information resources, and social and professional connections, Experiential Learning ensures continuity between learning experiences, active engagement, reflection, and the development of new conclusions. Thus, each of these approaches can address a specific didactic task within the Microbiology module; however, their interconnection as a unified methodological system is more important than their isolated application.

From this perspective, in developing the methodological foundations for teaching the Microbiology module in a digital learning environment, ensuring a logical relationship between the *"digital tool → pedagogical approach → student activity → expected learning outcome"* is an important methodological condition. In this framework, the digital environment should be regarded not as the goal of education, but as an environment that facilitates the achievement of predetermined pedagogical outcomes. For example, the availability of a virtual laboratory is not, in itself, an educational outcome; its actual pedagogical effectiveness depends on its integration with the formulation of research questions, selection of experimental procedures, analysis of results, and reflective activities. Similarly, an electronic task or simulation can be considered methodologically justified only when it contributes not merely to students' activity, but to the development of scientific thinking, problem-solving abilities, and professional competencies.

Therefore, the methodological model of contemporary Microbiology education should be viewed not merely as a set of individual pedagogical technologies, but as an *integrated pedagogical system that enables students to acquire knowledge, apply and test it through practice, analyze their experiences, solve problems, work with digital information resources, and reflectively evaluate their own learning activities*. Such an approach can reduce the gap between theoretical and practical preparation, establish meaningful connections between digital and real laboratory activities, and organize learning outcomes on the basis of competency-oriented criteria.

MAIN PART. The development of the digital learning environment necessitates a reconsideration of the methodological foundations for organizing the teaching process in higher education. The central issue is not merely the introduction of digital technologies into the educational process, but rather their pedagogical integration with educational objectives, student activities, learning content, and expected outcomes. From this perspective, Digital Pedagogy, Connectivism, and Blended Learning represent interconnected methodological foundations for developing a methodology for teaching the Microbiology module in a digital learning environment.

Digital Pedagogy is an approach aimed at selecting and organizing the use of digital technologies in accordance with pedagogical objectives. Its fundamental characteristic is that technology is not regarded as an independent educational goal, but rather as a means of addressing specific didactic tasks. The DigCompEdu framework developed by the European Commission relates educators' digital competence to the selection, creation, and adaptation of digital resources, the organization of learning activities through digital technologies, and the support of students' participation in the learning process [2].

In the Microbiology module, the Digital Pedagogy approach involves adapting digital tools to the specific characteristics of the learning content. In this context, the digital environment should not merely support students' reception of ready-made information, but should facilitate activities such as observation, analysis, comparison, modeling, interpretation of experimental results, and independent conclusion-making. Thus, Digital Pedagogy provides the methodological basis for moving from *"using technology"* *to* *"designing pedagogical activities through technology"* in Microbiology education.

Connectivism explains the formation of knowledge in a digital environment not merely through individual units of information, but through the connections and networks established among them. In this approach, proposed by G. Siemens, one of the essential aspects of learning is the ability to identify sources where the required knowledge is available, establish connections with these sources, and construct meaningful relationships among different areas of knowledge [3; Pp. 3-10].

The interdisciplinary nature of the Microbiology module further increases the relevance of the Connectivism approach. Since microbiological knowledge is closely interconnected with biology, genetics, biochemistry, molecular biology, immunology, and other fields, it is important for students to establish connections among information obtained from different digital sources. Accordingly, students' activities in a digital learning environment should not be limited to finding information; they should also involve selecting appropriate sources, evaluating their reliability, integrating information, and formulating evidence-based scientific conclusions.

Blended Learning, in turn, involves integrating conventional face-to-face instruction with digital learning activities into a unified pedagogical system. Garrison and Vaughan associate this approach not simply with combining face-to-face and online learning experiences, but with their meaningful integration and the *redesign of the educational process* [4].

The methodological value of *Blended Learning* in the Microbiology module lies in its ability to connect theoretical, digital, and laboratory activities within an integrated learning process. While the digital environment supports students' independent preparation and acquisition of subject-specific knowledge, classroom and laboratory sessions are directed toward applying the acquired knowledge in practical activities, analyzing experimental results, and performing professional tasks. Consequently, the learning process is organized not as a collection of separate digital and traditional classes, but as a *continuous and interconnected learning activity.*

Effective teaching of the Microbiology module in a digital learning environment is determined not by students' reception of ready-made knowledge, but by their ability to *actively acquire knowledge, connect it with experimental and practical activities, and reflectively evaluate the outcomes of their own learning activities.* In this respect, Constructivism, the Activity-Based Approach, and Experiential Learning can be regarded as complementary methodological foundations. Their common feature is that the student is viewed not as a passive object of the educational process, but as a *subject who constructs knowledge and develops through active engagement.*

From a *Constructivist* perspective, knowledge is not transmitted in a ready-made form; rather, it is actively constructed through interaction among students' prior knowledge, personal experiences, and new learning tasks. Piaget's views on cognitive development and Vygotsky's sociocultural theory are regarded as important theoretical foundations of constructivist education [7, 8]. Therefore, in the Microbiology module, instead of simply explaining a new concept, it is methodologically more effective to activate students' existing knowledge, formulate a problematic question, organize observation, and guide students toward new conclusions based on evidence.

The digital learning environment provides extensive opportunities for constructivist learning activities. In this context, an electronic resource, digital model, or virtual experiment is not used as an object for delivering ready-made knowledge, but rather as a *didactic environment that stimulates students'* *independent thinking and reconstruction of knowledge*. For example, in a digital scenario related to the growth conditions of microorganisms, instead of receiving a predetermined conclusion, students can modify different factors, observe the resulting changes, and explain the causes of these changes. Such activities promote an understanding of cause-and-effect relationships rather than mechanical memorization of information.

The *Activity-Based Approach* emphasizes the formation of knowledge and competencies through active engagement. According to its fundamental principle, students should perform specific learning, research, or practical activities during the process of acquiring knowledge. Therefore, reducing the gap between *"knowing" and "doing"* is an important methodological task in teaching the Microbiology module. In a digital environment, this approach can be implemented through interactive tasks, modeling, virtual experiments, problem situations, and the analysis of digital data.

An important feature of the Activity-Based Approach in Microbiology education is the *purposeful, systematic, and outcome-oriented organization* of learning activities. While performing a specific task, students not only apply biological knowledge, but also search for information, make decisions, analyze experimental results, and substantiate their conclusions. In this way, theoretical knowledge becomes connected with practical activity, bringing the learning process closer to elements of professional practice.

A third important direction for deepening students' active cognitive engagement is *Experiential Learning*, or learning through experience. In Kolb's experiential learning model, knowledge is viewed as a cyclical process involving concrete experience, reflective observation of the experience, abstract conceptualization, and active experimentation [9]. This approach is particularly compatible with the theoretical and experimental nature of the Microbiology module.

In digital learning environments, experiential learning is not limited to physical laboratory work. A virtual laboratory, digital simulation, or interactive model can support students in conducting experiments, observing results, and developing conclusions. However, the pedagogical value of such tools is determined not by their mere availability, but by their integration into the *experience–*

observation–analysis–conceptual conclusion–reapplication cycle. Therefore, it is methodologically appropriate to design virtual activities not as isolated digital exercises, but as components of experiential learning that are connected with subsequent theoretical and practical activities.

The integration of these three approaches makes it possible to organize students' active cognitive engagement in the Microbiology module according to the following sequence: *activating prior knowledge → posing a problem or inquiry task → active engagement → experimentation or modeling → observation of results → reflection → construction of new knowledge → application of knowledge in a new situation.*

The content of the Microbiology module is directly associated with the structure and life processes of microorganisms, their interactions, relationships with the environment, and the identification of causes and consequences of various biological processes. Therefore, in teaching this module, it is important to organize activities that go beyond the acquisition of ready-made knowledge and involve *posing questions, seeking evidence, analyzing experimental results, and making evidence-based decisions in problem situations*. From a methodological perspective, such activities can be supported by *Inquiry-Based Learning (IBL)* and *Problem-Based Learning (PBL)* approaches.

Inquiry-Based Learning is based on students acquiring knowledge through the independent investigation of a particular question or phenomenon rather than receiving knowledge in a predetermined form. In the pedagogical literature, the inquiry approach is characterized by students' ability to formulate questions, seek evidence, and draw well-founded conclusions from that evidence [10; Pp. 99-107].

In the Microbiology module, the methodological logic of this approach can be expressed through an inquiry process that begins with the question *"Why?": question → hypothesis → inquiry/experiment → evidence collection → analysis → conclusion.*

For example, when investigating differences in the growth of microorganisms under specific conditions, students first formulate a question aimed at identifying the cause of the observed phenomenon. They then develop a tentative answer-a hypothesis-and examine available information and experimental results in a digital or virtual environment. Based on the collected evidence, they subsequently confirm or reject their hypothesis. In this process, the digital learning resource does not function as a ready-made source of knowledge, but rather as an *environment that supports inquiry-based activity.*

Problem-Based Learning (PBL), in contrast, organizes instruction around a meaningful *problem situation* whose solution cannot be determined immediately, rather than around a specific theoretical question. In PBL, the problem encourages students to activate their existing knowledge, identify knowledge gaps, search for relevant information, develop alternative solutions, and reach a justified decision [10; Pp. 235-266]. In Microbiology education, its general logic can be represented as follows: *problem situation → problem identification → analysis of causes → search for necessary information → development of solution options → decision → justification.*

Although IBL and PBL are closely related, their methodological focuses are not identical. The *starting point of IBL is a question and inquiry*, whereas the *starting point of PBL is a problem and the need to solve it.* In IBL, students seek an evidence-based answer to the question, *"Why is this phenomenon occurring?"*; in PBL, they address the question, *"What solution should be selected in this situation?"* Therefore, IBL primarily strengthens the *logic of scientific inquiry*, whereas PBL emphasizes the *logic of problem-solving and professional decision-making* (Table 1).

Table 1.

Comparative characteristics of Inquiry-Based Learning and Problem-Based Learning approaches in teaching the Microbiology module

Criterion	Inquiry-Based Learning (IBL)	Problem-Based Learning (PBL)
Starting point	Question	Problem situation
Key question	"Why?"	"What solution can be found?"
Main activity	Inquiry	Problem-solving
Process	Question → hypothesis → evidence → conclusion	Problem → analysis → alternatives → decision
Outcome	Evidence-based scientific conclusion	Justified solution and decision

In a digital learning environment, the possibilities of these two approaches are further expanded. Digital databases, interactive models, virtual laboratories, and electronic learning resources can support *evidence searching and analysis in IBL, and the modeling of problem situations and testing of possible solutions in PBL.* In this context, technology does not replace the methodological approach; rather, it expands its pedagogical potential.

The effectiveness of teaching the Microbiology module in a digital learning environment cannot be adequately assessed solely by the extent to which students have mastered theoretical knowledge. In contemporary higher education, an important indicator of educational achievement is the ability to *independently apply acquired knowledge in practical, research, and professional activities*. From this perspective, the methodological essence of the competency-based approach can be expressed as a shift from the question *"What does the student know?" to "In what situations and to what extent can the student apply their knowledge?"* Within the competency-based approach, the integration of knowledge, skills, experience, and personal activity determines the ultimate educational outcome [12].

Taking into account the content of the Microbiology module and the possibilities of the digital learning environment, competency-based outcomes can appropriately be considered as an interconnected set of *microbiological knowledge, laboratory-practical, research, digital, problem-solving, and reflective competencies.* Such an approach creates a mechanism for transforming knowledge into activity without separating the theoretical content of the module from practical engagement.

Microbiological knowledge competence refers to students' acquisition of knowledge about the morphological, physiological, ecological, and other biological characteristics of microorganisms, as well as their ability to apply this knowledge in new learning and professional situations. In this context, the amount of knowledge is less important than its *systematic nature, understanding of cause-and-effect relationships, and ability to transfer knowledge to practical tasks.*

Laboratory-practical competence encompasses students' understanding of the procedures for conducting microbiological experiments, their ability to properly organize laboratory activities, make observations, and interpret the results obtained. In a digital learning environment, virtual laboratories enable students to safely and repeatedly practice certain components of this competence. At the same time, virtual activities should not be regarded as a complete substitute for real laboratory experience, but rather as a *preparatory, reinforcing, and reflective component* of practical training.

Research competence refers to the ability to identify a microbiological phenomenon or problem, formulate a research question, search for relevant information, analyze evidence, and draw scientifically grounded conclusions. This competence is directly connected with the *Inquiry-Based Learning* approach discussed in the previous section. The digital environment provides additional opportunities to access scientific information sources, compare data, and process research findings.

Digital competence involves the purposeful selection and use of digital resources related to Microbiology, analysis of digital information, and presentation of results through digital tools. This competence is not limited to the technical ability to operate digital devices. The DigCompEdu framework likewise associates pedagogical activity in digital environments with the selection and purposeful use of digital resources, digital assessment, and the support of learning activities through digital technologies [2].

Problem-solving competence refers to students' ability to identify a problem in a microbiological process or professional situation, analyze its causes, develop alternative solutions, and make evidence-based decisions. This competence is directly integrated with *Problem-Based Learning*, enabling students to apply their theoretical knowledge in real or simulated situations. As a result, knowledge is no longer an end in itself, but becomes a *means of solving problems*.

Reflective competence, in turn, refers to students' ability to analyze their own activities and the results obtained, identify errors, recognize areas that have not been sufficiently mastered, and determine ways to improve their subsequent performance. In a digital learning environment, feedback, results of electronic tasks, virtual laboratory activities, and self-assessment tools can contribute to the development of this competence.

The interrelationship among these competencies establishes the following logic within the Microbiology module: *knowledge → practical activity → research → digital activity → problem-solving → reflection → competency-based outcome.*

These competencies should not be understood as separate outcomes developed independently of one another. For example, while studying a particular microbiological process in a virtual laboratory, a student first applies theoretical knowledge, works with a digital tool, analyzes experimental results, makes a decision when a problem situation arises, and finally evaluates their own performance.

Accordingly, the competency-based approach in digital Microbiology education can be regarded as a *methodological mechanism for transforming "knowledge acquisition" into "the transformation of knowledge into purposeful activity."* Its primary outcome is not simply students' ability to use digital resources, but the development of their capacity to use these resources to *understand and investigate microbiological problems, perform practical tasks, make evidence-based decisions, and improve their own activities*. This system of competencies can subsequently provide a methodological basis for developing diagnostic criteria to evaluate the effectiveness of the Microbiology teaching methodology during the experimental study.

In teaching the Microbiology module within a digital learning environment, the effective use of virtual laboratories requires viewing them not simply as electronic representations of laboratory procedures, but as *active learning environments organized on the basis of specific methodological approaches*. The didactic value of a virtual laboratory is determined not by its technical capabilities alone, but by the extent to which it engages students in observation, experimentation, decision-making, analysis of results, and reflection. Therefore, integrating Constructivism, the Activity-Based Approach, Experiential Learning, Inquiry-Based Learning, Problem-Based Learning, and the competency-based approach with virtual laboratory activities expands the methodological potential of Microbiology education.

From a *Constructivist* perspective, a virtual laboratory should be designed not for students to receive predetermined conclusions, but to enable them to *independently interpret experimental results and construct new knowledge on the basis of their existing understanding*. Students can modify parameters within a virtual environment, observe different outcomes, and compare the resulting data with their prior knowledge. In this way, the virtual laboratory is transformed from a tool for "demonstration" into an *environment for knowledge construction*. The Activity-Based Approach further enriches this process through specific learning actions, enabling students to follow laboratory procedures, record data, analyze results, and substantiate their conclusions.

The integration of virtual laboratory activities with *Experiential Learning* is particularly important. According to Kolb's experiential learning cycle, knowledge is developed through concrete experience, reflective observation, abstract conceptualization, and active experimentation [9]. From this perspective, a virtual laboratory can support the following cycle: *virtual experiment → observation of results → analysis and reflection → theoretical conclusion → repeated experimentation or application in a new situation.*

This sequence transforms virtual laboratory activity from a purely technical exercise into a structured learning experience in which students can connect practical observation with theoretical understanding and subsequently transfer the acquired knowledge to new learning or professional contexts.

This cycle transforms students' activities in the virtual laboratory from simple technical operations into *meaningful cognitive activities*.

When integrated with *Inquiry-Based Learning (IBL)*, the virtual laboratory functions as an *inquiry environment*. Before conducting an experiment, students formulate a specific question, propose an assumption or hypothesis, perform the relevant activities in the virtual environment, record the results, and draw conclusions based on the available evidence. Thus, the methodological function of the virtual laboratory within IBL is not merely to reproduce an experiment according to a predetermined algorithm, but to organize scientific inquiry through the sequence: *question → hypothesis → experiment → evidence → conclusion.*

When integrated with *Problem-Based Learning (PBL)*, the virtual laboratory provides opportunities to model problem situations and test alternative solutions. Students are presented with a specific microbiological situation and are required to identify the causes of the problem, search for the necessary information, compare alternative courses of action, and make an evidence-based decision. In this case, the virtual laboratory functions not only as an environment for conducting experiments, but also as a *space for analyzing problems and practically testing proposed solutions.*

The *competency-based approach* determines the ultimate outcome of these activities. In a virtual laboratory, students simultaneously apply microbiological knowledge, work with digital tools, analyze experimental results, solve problem situations, and evaluate their own performance. Therefore, a single virtual laboratory task can contribute to the integrated development of several competencies. This process can be represented as follows: *microbiological knowledge + digital activity + laboratory activity + inquiry + problem-solving + reflection → integrated competency-based outcome.*

However, interpreting the virtual laboratory as a complete substitute for real laboratory activities is not methodologically appropriate. Its principal advantage lies in the ability to *model experiments in a safe environment, repeat procedures, modify parameters, analyze errors, and prepare for real experimental work*. Therefore, within the framework of *Blended Learning*, it is more appropriate to organize virtual and real laboratories according to the principle of functional complementarity rather than treating them as alternatives.

For example, in the virtual environment, students can master the experimental procedure and analyze possible outcomes, while in the real laboratory they can connect this knowledge and these skills with *actual biological materials, laboratory equipment, and authentic experimental conditions*. Such integration allows virtual laboratory activities to serve as a preparatory and reinforcing component of practical training while preserving the irreplaceable role of real laboratory experience in developing professional practical competence.

The effectiveness of teaching the Microbiology module through digital learning resources and virtual laboratories is determined not by the number of digital tools employed, but primarily by their *purposeful, systematic, and pedagogically justified use.* Therefore, in organizing Microbiology education in a digital environment, methodological principles should not be regarded as a collection of separate rules, but as an integrated system that connects the learning objective, content, student activity, digital tool, and expected outcome. Within this system, the principles of *scientific validity, systematicity and consistency, activity and independence, practical orientation, interactivity, individualization, integration, and reflectivity* have particular methodological significance.

The *principle of scientific validity* requires the knowledge, digital content, virtual models, and laboratory tasks presented in the Microbiology module to correspond to contemporary scientific understanding and reliable evidence. The abundance of information sources available in a digital environment further increases the importance of this principle. Therefore, students should not only acquire information, but also develop the ability to evaluate its scientific validity.

The *principle of systematicity and consistency* ensures the development of microbiological knowledge from simple to complex, from theoretical concepts to practical activities, and from individual elements of knowledge toward an integrated system. Digital learning resources, virtual laboratories, and classroom activities should not be designed as disconnected activities, but as sequential stages of a unified learning process. Each digital task should activate previously acquired knowledge and create the necessary foundation for subsequent learning activities.

The *principle of activity and independence* directs students' activities in the digital environment from the passive reception of information toward independent inquiry, experimentation, analysis, and conclusion-making. In a virtual laboratory, merely observing a result is insufficient; allowing students to select parameters, formulate hypotheses, compare results, and interpret findings strengthens their role as active participants in the learning process. Consequently, the digital environment becomes a pedagogical space that supports independent learning.

The *principle of practical orientation* requires microbiological knowledge to be connected with laboratory, research, and professional activities. Students should be able to apply acquired concepts in specific situations, analyze laboratory results, and substantiate solutions to microbiological problems. From this perspective, virtual laboratory activities can serve as a means of transferring theoretical knowledge into practical activity.

The *principle of interactivity* ensures active interaction among students, teachers, digital learning resources, and other participants in the educational process. The methodological value of interactivity is not limited to technological opportunities for clicking or providing responses, but is determined by students' ability to make decisions, influence outcomes, and receive feedback. Therefore, interactive tasks should be designed to stimulate students' thinking and practical engagement.

The *principle of individualization* involves taking into account differences in students' levels of preparation, learning pace, and educational needs. A digital environment allows students to review learning materials, complete additional tasks, or select activities with different levels of complexity. In this context, individualization should not be interpreted as teaching every student according to a completely separate program, but as *creating opportunities to achieve a common educational goal through different learning trajectories.*

The *principle of integration* serves to establish connections among microbiological knowledge, digital technologies, laboratory activities, and other biological disciplines. In particular, the close relationship of Microbiology with genetics, biochemistry, molecular biology, immunology, and ecology provides broad opportunities for applying this principle. The digital environment, in turn, enables diverse sources of knowledge to be integrated around a common learning task.

The *principle of reflectivity* enables students to understand their own activities, achieved results, mistakes, and directions for further development. At the end of a virtual laboratory activity or digital task, it is insufficient to ask only *"What was the result?"*; reflective questions such as *"Why was this result obtained?", "At which stage was an error made?", and "How could the result be improved?"* can develop students' ability to regulate their own learning activities [13; Pp. 9-15].

The effectiveness of teaching the Microbiology module in a digital learning environment depends not on the application of a particular method or technology, but on the *integration of different methodological approaches within a unified didactic logic*. Although the Digital Pedagogy, Connectivism, Blended Learning, Constructivism, Activity-Based Learning, Experiential Learning, Inquiry-Based Learning, Problem-Based Learning, and competency-based approaches analyzed above have different theoretical foundations, they functionally complement one another in the context of teaching the Microbiology module in a digital environment. On this basis, they can be integrated into a unified *integrative methodological model.*

The initial level of this model is formed by *Digital Pedagogy*. Its function is not simply to introduce digital tools into the educational process, but to select them according to specific pedagogical objectives, learning content, and student activities. At the next level, *Connectivism* establishes connections among different sources of knowledge, information flows, and learning activities within the digital learning environment. *Blended Learning*, in turn, integrates these digital activities with classroom instruction and real laboratory sessions, thereby creating a unified learning process.

The next methodological layer of the model focuses on organizing students' active cognitive engagement. *Constructivism* ensures the active construction of new knowledge on the basis of students' prior experiences and new learning tasks. The *Activity-Based Approach* emphasizes the acquisition of knowledge through purposeful practical action, while *Experiential Learning* deepens learning through experience, observation, analysis, and reflection. Therefore, these approaches should not be considered separate stages within the model, but rather as *interrelated components of a unified mechanism of active cognition.*

At this level, the learning process moves beyond the simple transmission of microbiological information and becomes an organized sequence in which students construct knowledge through purposeful activity, test it through experience, interpret the obtained results, and connect new understanding with previously acquired knowledge. Such organization creates the methodological conditions for the subsequent transition from active cognition to inquiry and problem-solving activities.

This methodological foundation is transformed at the next stage into inquiry-based and problem-oriented activity through *Inquiry-Based Learning and Problem-Based Learning*. While Inquiry-Based Learning enables students to formulate questions, develop hypotheses, seek evidence, and draw conclusions, Problem-Based Learning directs this knowledge and evidence toward analyzing problem situations, developing alternative solutions, and making justified decisions. As a result, the student moves from being a *"recipient of knowledge" to a subject who seeks, tests, and applies knowledge in practical situations*.

The practical platform for this activity is the *integration of virtual and real laboratories*. A virtual laboratory enables students to model experiments, modify parameters, repeat procedures, identify errors, and acquire initial practical experience in a safe environment. A real laboratory, in turn, provides opportunities to apply the acquired knowledge and skills with actual biological materials, equipment, and laboratory conditions. Therefore, within the proposed model, the virtual laboratory is not regarded as a substitute for the real laboratory, but as a *digital component that prepares, complements, and reinforces* real laboratory activities.

Another important element of the model is *reflection*. Students should not simply record the results of an experiment or problem-solving activity, but should analyze their decisions, actions, errors, and achievements. At the reflective stage, questions such as *"What have I learned?", "Which evidence supports my conclusion?", "Where did I make an error?",* and *"How can I improve my subsequent activity?"* contribute to the development of metacognitive activity. Thus, reflection should not be considered the final stage of the model; rather, it functions as a *feedback mechanism that facilitates the transition to subsequent learning activities*.

The final outcome of the model is determined by *competency development*. In the digital learning environment, students develop not only microbiological knowledge, but also laboratory-practical, research, digital, problem-solving, and reflective competencies in an integrated manner. Therefore, the outcome of the methodological model is not the formation of an isolated body of knowledge or a particular skill, but the preparation of a *competent student capable of transforming knowledge into purposeful activity*.

Based on the theoretical foundations discussed above, we propose the following *authorial integrative methodological model* within the framework of this study (Figure 1).

CONCLUSION AND RECOMMENDATIONS. The theoretical and methodological analysis conducted in this study demonstrated that improving the effectiveness of teaching the Microbiology module in a digital learning environment cannot be achieved merely through the use of individual digital tools. Rather, it requires the *integration of digital technologies, contemporary pedagogical approaches, laboratory activities, and competency-based outcomes into a unified methodological system*. From this perspective, Digital Pedagogy, Connectivism, and Blended Learning provide the general methodological foundation of the digital learning environment; Constructivism, the Activity-Based Approach, and Experiential Learning determine the mechanisms of students' active cognition; while Inquiry-Based Learning and Problem-Based Learning provide mechanisms for organizing inquiry and problem-solving activities.

Based on the analysis, it was established that organizing learning activities in the Microbiology module according to the sequence *“question – inquiry – experiment – evidence – analysis – problem – solution – reflection”* is methodologically appropriate. In this process, the virtual laboratory should not be interpreted as a tool that replaces students’ real laboratory activities, but rather as a *digital didactic environment that enables experiment modeling, safe practice, repeated verification of results, and preparation for authentic practical work*. The integration of virtual and real laboratory activities was identified as an important methodological condition for establishing a connection between theoretical knowledge and practical activity.

Figure 1. An Integrative Methodological Model for Teaching the Microbiology Module in a Digital Learning Environment

The final outcome of the *integrative methodological model* proposed within the framework of the study is not merely an increase in the volume of knowledge, but the development of *integrated competencies* that enable students to apply microbiological knowledge in practice, conduct research, use digital resources purposefully, make evidence-based decisions in problem situations, and reflectively evaluate their own activities. This represents a methodological shift from the criterion of “What does the student know?” to “What can the student apply their knowledge to, and how can they apply it?”

Based on this, the following *recommendations* have been developed:

- direct the digital resources of the microbiology module not merely toward information delivery, but toward the organization of inquiry-based and problem-based learning activities;
- establish a strong connection between virtual laboratory tasks and real laboratory sessions;
- increase the proportion of digital tasks that enable students to make independent decisions and interpret the results obtained;
- when assessing learning outcomes, diagnose not only knowledge but also *laboratory-practical, research, digital, problem-solving, and reflective competencies*;
- at the next stage, integrate the developed methodological model with specific didactic support, an electronic textbook, virtual laboratory tasks, and an experimental methodology.

As a result, the proposed set of methodological approaches provides a theoretical and methodological foundation for transforming the microbiology module from *traditional education that merely uses digital tools into an active, research-oriented, practice-based, and competency-oriented digital learning model*.

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