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The effectiveness of immersive simulations in studying nutrient chemical transformations in higher education institutions

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The relevance of this study is driven by rising expectations for the quality of specialist training in the natural sciences and biomedical disciplines amid the digital transformation of higher education, as well as by the complexity of disciplinary content that requires the integration of molecular, metabolic, physiological, and technological mechanisms. The multilevel nature of nutrient chemical transformations imposes a substantial cognitive load and necessitates the use of innovative pedagogical tools capable of supporting a coherent, system-level understanding of biochemical processes. The aim of the article is to provide a theoretical rationale for implementing immersive simulations in the teaching of nutrient chemical transformations in higher education institutions and to determine their educational potential for improving the quality of learners' professional preparation. To achieve this aim, the study employs analytical synthesis of the scholarly literature, systematization of approaches to educational process digitalization, structural and logical analysis of the cognitive complexity inherent in biochemical disciplines, and comparative analysis of the functional capacities of immersive technologies in professional education. The findings indicate a high integrative and cognitive level of complexity in nutrient chemical transformations and confirm the effectiveness of immersive simulations as a tool for interactive modeling of biochemical processes. Their potential to foster systems thinking and to develop learners' analytical and predictive competencies is substantiated. The study also identifies key scientific and practical challenges associated with implementing immersive technologies, including the lack of standardized integration models, limited empirical verification of long-term educational effects, and technical and organizational constraints. The conclusions emphasize the appropriateness of systematic integration of immersive simulations into educational programs in the natural sciences and biomedical disciplines. Future research directions include developing valid instruments for evaluating the effectiveness of immersive learning, empirically testing its long-term impact on learners' professional preparation, and establishing an evidence-based model for the digital transformation of biochemical education.

Keywords: digital educational technologies, virtual reality, biochemical education, metabolic processes, cognitive load, professional competencies, interactive modeling, STEM education.

Ефективність імерсивних симуляцій у вивченні хімічних перетворень нутрієнтів у закладах вищої освіти

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Актуальність дослідження зумовлена зростанням вимог до якості підготовки фахівців у галузі природничих наук та медико-біологічних дисциплін в умовах цифрової трансформації вищої освіти, а також складністю дисциплінарного змісту, що потребує інтеграції молекулярних, метаболічних, фізіологічних та технологічних механізмів. Багаторівневий характер хімічних перетворень поживних речовин створює значне когнітивне навантаження та зумовлює необхідність використання інноваційних педагогічних інструментів, здатних забезпечити системне розуміння біохімічних процесів. Метою статті є теоретичне обґрунтування доцільності впровадження імерсивних симуляцій у навчання хімічних перетворень поживних речовин у закладах вищої освіти та визначення їх освітнього потенціалу для підвищення якості професійної підготовки здобувачів. Для досягнення мети застосовано аналітичне узагальнення наукової літератури, систематизацію підходів до цифровізації освітнього процесу, структурно-логічний аналіз когнітивної складності біохімічних дисциплін та порівняльний аналіз функціональних можливостей імерсивних технологій у професійній освіті. Результати дослідження засвідчили високий інтегративний і когнітивний рівень складності хімічних перетворень поживних речовин та підтвердили ефективність імерсивних симуляцій як інструменту інтерактивного моделювання біохімічних процесів. Обґрунтовано їх потенціал у формуванні системного мислення, аналітичних та прогностичних компетентностей здобувачів. Виявлено основні науково-практичні виклики впровадження імерсивних технологій, зокрема відсутність стандартизованих моделей інтеграції, обмежена емпірична верифікація довгострокових освітніх ефектів, а також технічні й організаційні обмеження. У висновках підкреслено доцільність систематичної інтеграції імерсивних симуляцій в освітні програми з природничих наук та медико-біологічних дисциплін. Перспективи подальших дослідженьохоплюють розроблення валідних інструментів оцінки ефективності імерсивного навчання, емпіричну перевірку його довгострокового впливу на професійну підготовку здобувачів та створення науково обґрунтованої моделі цифрової трансформації біохімічної освіти.

Ключові слова: цифрові освітні технології, віртуальна реальність, біохімічна освіта, метаболічні процеси, когнітивне навантаження, професійні компетентності, інтерактивне моделювання, STEM-навчання.

Introduction

The relevance of this problem is determined by the digital transformation of higher education and the need to increase the effectiveness of training specialists in the natural sciences and biomedical fields under conditions of growing cognitive complexity of educational content. The study of nutrient chemical transformations requires the integration of molecular, metabolic, and physiological knowledge, which complicates the development of a coherent, system-level understanding of biochemical processes when traditional teaching methods are used. The application of immersive simulations is viewed as a promising direction for

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modernizing the educational process; however, the absence of comprehensive models for their pedagogical integration and for evaluating educational effectiveness creates a clear scientific need for focused research in this area.

Analysis of recent research. A review of current research indicates a gradual transformation of methodological approaches, shifting from traditional laboratory experiments to digital modeling of complex biochemical processes. For example, V. Kumar et al. demonstrate the potential of virtual reality for reproducing multi-stage chemical reactions and biochemical pathways in a safe, interactive environment. This creates conditions for a deeper understanding of nutrient metabolic transformations [1]. A. Negahban views the transition from physical experiments to digital immersive simulations as a natural stage in the development of engineering and natural sciences education, emphasizing the increased controllability of parameters and reproducibility of results [2]. The effectiveness of creating VR and AR resources for teaching chemical engineering is shown by M. Díaz et al., who highlight the ability to visualize reaction environments and technological processes in three dimensions [3].

In addition to the technological justification, empirical verification of the pedagogical effectiveness of immersive tools is of significant importance. T. Tene et al. demonstrate that the use of immersive environments in higher education enhances cognitive engagement and the depth of understanding of complex scientific concepts [4]. A. Sánchez-López et al. establish a statistically significant improvement in academic performance in the analytical biotechnology course when VR technologies are used [5]. B. Braga et al. investigate the effectiveness of immersive learning in the citric acid cycle, a key step in nutrient metabolism, observing an increase in long-term memory retention and conceptual understanding [6]. I. Kalimuthu et al. analyze the integration of AR in nutrition education, which facilitates a holistic understanding of digestive processes and biochemical transformations [7].

An important aspect of contemporary research is the combination of immersive technologies with interdisciplinary and project-based approaches. M. Bigonah et al. consider AR/VR solutions as a tool for gamifying education, which increases student motivation and activity in natural science subjects [8]. A. Rakhmanova substantiates the methodology of project-based learning in the STEM context, allowing for the integration of chemical process modeling with real food products and analysis of their composition [9]. O. Anichkina and co-authors emphasize the role of experimental activities with organic compounds as a factor in enhancing motivation to study chemistry [10]. U.-S. Savchenko investigates bioactive forms of vitamin C with hyaluronate, illustrating the practical significance of a deep understanding of the chemical properties of nutrients in medical-pharmaceutical practice [11].

The final block of research reflects the institutional and socially applicable aspects of implementing innovative technologies in the preparation of specialists. S. Fedienko and colleagues analyze the impact of innovative technologies on the development of Ukraine's pharmaceutical market, emphasizing the need for the modernization of educational tools [12].

O. Pasulia examines the influence of stylistic transformations in appearance on self-esteem and body perception, which indirectly highlights the significance of biochemical knowledge about nutrients and their effects on physiological and aesthetic characteristics [13].

Despite the growing interest in immersive technologies in STEM education, unresolved issues remain, such as the consideration of cognitive complexity in studying the chemical transformations of nutrients, the lack of a comprehensive model for integrating immersive simulations into educational programs, and the limited approaches to evaluating their impact on the development of professional competencies. Methodological mechanisms for aligning digital scenarios with learning outcomes and interdisciplinary content in education are underdeveloped.

The proposed study aims to systematize these aspects, substantiate the educational potential of immersive simulations, and develop structured approaches to their integration into

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natural sciences and medical-biological education, which will deepen theoretical foundations and improve the practical effectiveness of teaching.

The purpose of this article is to scientifically justify the feasibility of using immersive simulations in the study of nutrient chemical transformations at higher education institutions (HEIs) and to determine their potential for enhancing the quality of professional training for students.

To achieve this goal, the following tasks have been formulated:

1) to characterize the cognitive complexity of studying the chemical transformations of nutrients and determine the didactic potential of immersive simulations as a tool for modeling biochemical processes;

2) to assess the impact of immersive technologies on the formation of a systemic understanding of metabolic mechanisms and the development of professionally significant competencies in students;

3) to identify the scientific and practical challenges of implementing immersive simulations and justify approaches for their optimal integration into educational programs in natural sciences and medical-biological fields.

Scientific Novelty. The scientific novelty of this study lies in the theoretical substantiation of the educational potential of immersive simulations for learning nutrient chemical transformations as a tool for developing learners' systems thinking, analytical reasoning, and predictive thinking. The study уточнено the structure of the cognitive complexity of biochemical educational content, identifies the functional capabilities of immersive environments for modeling biochemical processes, and proposes approaches to their modular integration into educational programs in the natural sciences and biomedical disciplines.

Practical Significance. The practical significance of the obtained results consists in the possibility of applying the proposed approaches to implementing immersive simulations in higher education courses in biochemistry, nutrition science, food technology, and biomedical disciplines. The proposed provisions may be used when designing digital laboratories, developing interactive learning scenarios, and enhancing learners' professional competencies through the modeling of real biochemical processes.

Methodology

Research Methods. The study applied methods of analysis and synthesis of scholarly sources to systematize approaches to the use of immersive technologies in natural science and biomedical education, a systems and structural analysis to determine the cognitive complexity of learning nutrient chemical transformations, a comparative approach to contrast traditional and digital learning models, pedagogical modeling to substantiate the integration of immersive simulations into the structure of the educational process, and theoretical interpretation to generalize the obtained findings.

Data Sources. The information base of the study comprised current scholarly publications on digital didactics, biochemical and STEM education, findings on the use of VR and AR technologies in professional training, materials from digital learning platforms and virtual laboratories, and synthesized experience in implementing immersive educational environments in higher education institutions.

Analytical Tools. The material was processed using methods of theoretical synthesis, content analysis of scholarly sources, logical and structural analysis of instructional content, conceptual design of immersive learning scenarios, and comparative analysis of the didactic capabilities of digital educational environments.

Study Limitations. The study focuses on the theoretical and methodological substantiation of integrating immersive simulations into the teaching of nutrient chemical transformations, which defines its conceptual orientation and its focus on establishing a

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scientific basis for subsequent empirical research on the effectiveness of immersive learning across diverse educational contexts.

Results

The study of chemical transformations of nutrients within the higher education system is characterized by a high level of content density and cognitive complexity, which results from the integration of fundamental chemical, biochemical, physiological, and technological aspects. Mastering the mechanisms of hydrolysis, redox reactions, enzymatic catalysis, regulation of metabolic pathways, and their energy supply requires the integration of knowledge from organic chemistry, molecular biology, digestive physiology, and food technologies. A student must simultaneously work with the structural formulas of compounds, the spatial organization of macromolecules, the kinetics of reactions, and the functional consequences of transformations at the cellular and organismal levels. This multi-level complexity leads to an increased cognitive load, as the learning process involves not only memorizing individual reactions but also developing a systemic understanding of the interrelationships between the nutrient structure, environmental conditions, and the final biological effect.

In the current educational environment, an additional complicating factor is the need to interpret processes within the context of applied tasks – ranging from the development of functional food products to the clinical evaluation of metabolic disorders (Table 1).

Table 1

Structural Components of Cognitive Complexity in Studying Chemical Transformations of Nutrients in Higher Education

Component of Complexity	Content Description	Manifestation in the Learning Process
Molecular Level	Analysis of nutrient structure, types of chemical bonds, reaction mechanisms	Necessity to work with structural formulas and spatial models
Enzymatic Regulation	Study of enzyme specificity, catalysis mechanisms, cofactor influence	Interpretation of changes in reaction rates under various conditions
Metabolic Integration	Coordination of individual reactions within metabolic pathways	Formation of cause-and-effect relationships between catabolism and anabolism
Physiological Context	Dependence of transformations on the organism's state and hormonal regulation	Analysis of clinical and functional consequences of metabolic changes
Technological Dimension	Impact of processing, storage, and composition of food on chemical transformations	Application of knowledge in food and medical-biological practices

Source: Compiled by the author based on [1, p. 146; 6, p. 503; 7, p. 917; 10, p. 5; 11, p. 53]

The systematization of the structural components of cognitive complexity allows for the consideration of the process of mastering nutrient chemical transformations as an integrative model combining theoretical knowledge with applied professional actions. The combination of molecular, enzymatic, metabolic, physiological, and technological dimensions forms the foundation for transitioning from a fragmented understanding of individual reactions to a holistic comprehension of biochemical dynamics in the real functioning of the organism and food systems [1, p. 146]. This multi-level structure necessitates the processing of educational material through tasks of an analytical and predictive nature, in which students are required not only to reproduce the reaction mechanism but also to assess its consequences under varying environmental parameters.

In a professionally oriented context, this is manifested, in particular, in modeling changes in carbohydrate metabolism under different glycemic loads, predicting the effects of thermal

e-ISSN: 2786-586X

processing on protein denaturation and the loss of biological value of amino acids, analyzing lipid oxidation during food storage, and evaluating the antioxidant potential of dietary components. In medical-biological training, this knowledge is applied to interpret metabolic pathway disruptions, particularly in cases of insulin resistance or enzymatic deficiencies, which require simultaneous consideration of molecular mechanisms and systemic regulation. In the field of food technology, the integration of these components ensures a well-founded selection of processing, stabilization, and enrichment methods for products, taking into account the preservation of nutrient functional properties [10, p. 5].

Accordingly, the cognitive complexity of studying nutrient chemical transformations has an applied dimension and directly influences the ability of future specialists to conduct professionally sound analyses, predict the consequences of biochemical changes, and make decisions in conditions of multi-factorial interaction between chemical, physiological, and technological factors.

Immersive simulations in higher education are interactive digital environments that provide an immersive experience for the user in a simulated space, allowing active interaction with objects and processes. Their essence lies in combining three-dimensional visualization, dynamic reproduction of system parameter changes, and feedback mechanisms, which enable the transformation of abstract biochemical models into visually reproducible scenarios. In the context of modeling biochemical processes, immersive technologies create conditions for spatial representation of molecular structures, simulation of enzymatic reactions, variation in substrate concentrations, temperature, pH levels, and other factors that affect the course of chemical transformations. As a result, the educational material becomes dynamic, and complex mechanisms are made accessible for experimental reproduction in a virtual environment, eliminating the risks associated with equipment use or the need for expensive reagents (Table 2).

Table 2

Functional Capabilities of Immersive Simulations in Modeling Biochemical Processes

Functional Module	Capability Description	Educational Outcome
Three-Dimensional Visualization	Spatial representation of molecules, enzymes, and “substrate-enzyme” complexes	Development of understanding of spatial organization and interaction specificity
Dynamic Modeling	Reproduction of reaction progress over time with the ability to adjust environmental parameters	Understanding the dependence of reaction rate and direction on conditions
Interactive Interaction	Control of concentrations, temperature, pH, and presence of inhibitors	Mastery of biochemical process regulation principles
Scenario Reproduction	Modeling physiological and pathological states	Integration of knowledge about biochemistry and functional consequences of changes
Feedback System	Automatic analysis of user actions and evaluation of results	Error correction and increased awareness of learning

Source: Compiled by the author based on [1, p. 149; 3; 5; 6, p. 505; 8, p. 35]

The integration of the outlined functional modules into the structure of the educational process transforms the nature of biochemical knowledge acquisition from a reproductive to a research-analytic approach. Three-dimensional visualization of molecular objects, combined with dynamic modeling, allows for tracking changes in the spatial configuration of proteins, analyzing the interaction of substrates with the enzyme’s active site, and predicting the consequences of altering environmental parameters. The use of VR laboratories in higher education, particularly the Labster platform, demonstrates the ability to replicate complex

e-ISSN: 2786-586X

biochemical experiments, including enzyme kinetics modeling and metabolic pathway analysis, in a safe digital environment [14]. Such solutions enable interactive execution of laboratory scenarios with variations in reagent concentrations and temperature conditions, without the need for physical reagents.

Scenario reproduction of physiological states and molecular structure modeling is also realized in three-dimensional visualization environments, such as the Nanome platform, which is used for working with protein structures and biomolecular complexes in VR format [15]. These tools allow students to interact with spatial models of macromolecules, analyze conformational changes, and assess the impact of modifications on functional activity. In the educational process, this provides the opportunity to simulate inhibitor binding to an enzyme or study the impact of mutations on protein stability, which is directly relevant to biomedical and pharmaceutical training.

Thus, the use of immersive simulations in the context of modern educational digitalization combines theoretical concepts with the virtual reproduction of experimental scenarios. This approach expands access to complex biochemical models and contributes to the development of professional analytical competence through interactive engagement with the model of the studied process.

The educational potential of immersive simulations in studying nutrient chemical transformations is defined by their ability to form a comprehensive understanding of metabolic processes as interconnected dynamic systems, rather than a collection of isolated reactions. In a digital environment, students are able to simultaneously observe multiple levels of process organization, from changes in the concentrations of intermediate metabolites to the redistribution of energy flows between catabolic and anabolic pathways. This format encourages the transition from linear learning to a networked model of thinking, where the focus shifts to the integration of knowledge, prediction of consequences, and the making of informed decisions. An important characteristic of this educational potential is also the development of professionally significant competencies, including analytical, predictive, research, and communication skills, which have practical applications in the fields of food technology, clinical practice, and biomedical research (Table 3).

Table 3

Educational Potential of Immersive Simulations in Developing Professional Competencies

Competency Dimension	Content of Development	Professional Projection
Systemic Thinking	Integration of individual reactions into a holistic model of metabolism	Analysis of the relationships between nutrients and energy balance
Analytical Competence	Interpretation of process parameter changes and their consequences	Evaluation of food product quality and metabolic indicators
Predictive Ability	Modeling potential reaction scenarios	Predicting the outcomes of technological processing or metabolic changes
Research Skills	Selection of optimal conditions and hypothesis testing in a virtual environment	Designing technological or biomedical solutions
Communication Competence	Justification of results and explanation of mechanisms	Professional interaction in interdisciplinary teams

Source: Compiled by the author based on [4, p. 91; 7, p. 919; 9, p. 29; 10, p. 7; 12, p. 109; 13, p. 2096]

The integration of defined competency dimensions into the digital educational environment facilitates the transition from fragmentary acquisition of individual mechanisms

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to the modeling of complex biochemical scenarios involving multifactorial interactions. Systemic thinking is developed through the analysis of metabolic flux redistribution in response to changes in macronutrient ratios in the diet or under conditions of energy deficit. In this context, students track the interrelationship between glycolysis, the citric acid cycle, and beta-oxidation of fatty acids. This integration enables the interpretation of the effects of altering a single parameter on the functioning of the entire metabolic system. Analytical competence is cultivated through working with digital indicators, such as the concentrations of intermediate metabolites, reaction rates, and substrate conversion coefficients, all modeled in real-time. For instance, while analyzing technological processing conditions, students can assess the impact of temperature and heating duration on the preservation of amino acid composition or the degree of lipid oxidation, comparing the results with nutritional value indicators. In the biomedical context, modeling enzyme activity disturbances allows the investigation of changes in glucose or ketone body concentrations, leading to well-founded conclusions regarding the mechanisms of metabolic shifts [7, p. 919]. Predictive and research components are realized through the variability of scenarios, enabling the testing of alternative reaction conditions without the risk of material loss. Modeling the effects of antioxidant supplements on fat stability during storage or evaluating the consequences of pH changes on digestive enzyme activity creates the conditions for designing technological solutions based on biochemical principles [13, p. 2096]. Communicative competence is developed through collaborative analysis of digital models and the argumentation of results, in line with the current requirements of interdisciplinary collaboration in the fields of food technology, clinical dietetics, and biomedical research. In general, immersive simulations not only deepen knowledge of the mechanisms of chemical transformations of nutrients but also create conditions for developing professional readiness to make decisions in complex, multi-level systems, where a combination of analytical precision, predictive thinking, and practical orientation is required.

The integration of immersive technologies into higher education is accompanied by methodological, organizational, technical, psychological-pedagogical, and regulatory challenges. A primary issue is the absence of standardized didactic models for embedding VR/AR environments into educational programs. In practice, immersive tools are often used fragmentarily, without alignment with learning outcomes, competency descriptors, and assessment criteria, which reduces their systemic educational impact [6, p. 505]. Insufficient pedagogical methodologies for designing immersive scenarios further limit their transformation from visualization tools into полноценні educational-research instruments.

Another problem concerns the limited evidence base regarding long-term learning effects and transfer of acquired competencies to professional activity. Existing studies are frequently short-term and methodologically heterogeneous, complicating generalization. Traditional assessment approaches inadequately capture systemic and analytical thinking developed in immersive environments. Technical barriers include high equipment costs, infrastructure requirements, uneven institutional resources, and cybersecurity risks associated with cloud services. Psychological-pedagogical risks involve cognitive overload, distraction by technological effects, and individual sensitivity to virtual environments. Organizational challenges relate to instructor training and the development of digital pedagogical competence, since without systematic support innovations remain formal rather than deeply integrated into disciplinary logic [8, p. 35]. Regulatory frameworks also insufficiently account for immersive learning formats.

Optimization requires coordinated didactic and organizational solutions focused on clearly defined learning outcomes. A modular integration approach, where immersive scenarios function as structured components of specific topics with predefined competencies and assessment indicators, ensures coherence between technology and course content. Combining immersive simulations with case-based and problem-based learning transforms

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them into tools for developing systemic and predictive professional thinking. Adaptive learning pathways aligned with learner preparedness, instructor digital competence development, institutional regulations, and phased implementation—pilot testing, monitoring, refinement, and scaling-provide conditions for sustainable integration of immersive simulations into natural science and medical-biological education.

Discussion

The obtained results confirmed that the use of immersive simulations in learning nutrient chemical transformations supports a shift from fragmented acquisition of isolated reactions to a system-level understanding of biochemical processes as multilevel dynamic systems. The interpretation of the findings indicates that the core educational effect arises from combining visualization, parametric modeling, and interactive engagement, which reduces cognitive overload and promotes the development of analytical and predictive thinking. In this context, the immersive environment functions as a digital research laboratory that brings learning activities closer to the professional analysis of biochemical processes.

These conclusions are consistent with prior studies reporting increased depth of understanding of complex scientific concepts and higher student cognitive engagement in immersive environments [4, p. 91]. The observed improvement in knowledge integration aligns with evidence on the effectiveness of VR-based modeling of metabolic processes and enhanced long-term retention [6, p. 503–505]. The results also confirm the feasibility of representing multistage chemical reactions with controllable parameters for instructional experimentation [1, p. 146; 3], which corresponds to findings on the integration of AR and VR in nutrition science and STEM education, where a more holistic view of physiological and biochemical processes has been demonstrated [7, p. 917–919]. The alignment with inquiry-based and project-oriented learning approaches further supports increases in learners' academic activity and motivation [8, p. 35; 9, p. 29]. At the same time, the present study extends existing approaches by emphasizing not the technological effect itself, but the cognitive structure of instructional content and the need for systematic integration of immersive simulations.

The scientific novelty of this study lies in the theoretical substantiation of the educational potential of immersive simulations for learning nutrient chemical transformations as a tool for developing learners' systems thinking, analytical reasoning, and predictive thinking. The structure of the cognitive complexity of biochemical instructional content is refined through the integration of molecular, enzymatic, metabolic, physiological, and technological levels, and the functional capabilities of immersive environments for modeling biochemical processes are defined. A modular approach to integrating these tools into educational programs in the natural sciences and biomedical disciplines is substantiated, which is consistent with the stated provisions of the introduction.

The practical significance of the results lies in the possibility of applying the proposed approaches when modernizing higher education courses in biochemistry, nutrition science, food technology, and biomedical disciplines. The proposed integration of immersive simulations as structural components of instructional modules supports the development of professional competencies, the capacity to analyze biochemical processes, and the ability to predict their outcomes. The results may be used in designing digital laboratories, developing interactive learning scenarios, and implementing models for the digital transformation of natural science and biomedical education.

Conclusions

The study found that the study of nutrient chemical transformations in higher education institutions is characterized by high cognitive complexity, resulting from the multi-level organization of biochemical processes and the need to integrate molecular, metabolic, physiological, and technological knowledge. Traditional approaches do not fully support the

e-ISSN: 2786-586X

development of systemic biochemical thinking, highlighting the need for innovative digital tools.

It is argued that immersive simulations have significant educational potential in developing a comprehensive understanding of nutrient chemical transformation mechanisms, enhancing analytical, predictive, and research competencies, and promoting interdisciplinary integration of knowledge. Their use facilitates the transition from reproductive learning to the modeling of complex biochemical scenarios.

At the same time, the study identified key challenges in the implementation of immersive technologies, including insufficient standardization of didactic integration models, limited empirical verification of long-term educational effects, difficulty in assessing competency development, technical and infrastructure limitations, and the need to enhance the digital pedagogical competence of instructors.

Future research prospects are linked to the development of valid tools for assessing the effectiveness of immersive learning, empirical analysis of its long-term impact on professional training, and the formulation of a scientifically grounded model for integrating immersive technologies into natural science and medical-biological education.

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