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Models for the Integration of Artificial Intelligence Technologies into Adaptive Chemistry Learning Systems

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Abstract. *The article examines approaches to the implementation of intelligent algorithms in digital educational environments oriented toward the personalization of the educational process. The* ***aim*** *of the article is to carry out a comprehensive theoretical and methodological analysis and systematization of contemporary models for the integration of artificial intelligence technologies into adaptive learning systems in chemistry, and also to assess their influence on the personalization of educational trajectories, on the cognitive effectiveness of learning, and on the optimization of the didactic process. The study employs the* ***methods*** *of systems analysis and the comparative analysis of scholarly sources, the content analysis of contemporary educational platforms, the method of the pedagogical modeling of adaptive learning environments, and the generalization of empirical experience in the introduction of intelligent learning systems into the teaching of chemistry. Elements of conceptual design and of structural-functional analysis are additionally employed. As a* ***result*** *of the study, the principal models for the integration of artificial intelligence into adaptive learning systems are identified,* *in particular machine-learning-based models for the personalization of educational trajectories, intelligent recommendation systems, the automated assessment of knowledge, and adaptive feedback. It is established that the use of such models contributes to enhancing the motivation of learners, to improving the quality of the assimilation of complex chemical concepts, and to the optimization of the educational process. The* ***conclusions*** *note that the integration of artificial intelligence technologies into adaptive systems of chemistry instruction constitutes a promising direction in the development of education. It ensures the individualization of instruction, enhances the effectiveness of the educational process, and provides new opportunities for the development of digital educational environments. It is expedient to direct further research toward refining the algorithms of adaptation and toward assessing their effectiveness under real instructional conditions.*

Keywords: *personalized learning, digital education, intelligent educational platforms, learning analytics, recommendation algorithms, adaptation of learning content, cognitive technologies, digital competencies.*

Моделі інтеграції технологій штучного інтелекту в адаптивні системи навчання хімії

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Анотація. *У статті досліджено підходи до впровадження інтелектуальних алгоритмів у цифрові освітні середовища, орієнтовані на персоналізацію освітнього процесу.* ***Мета статті*** *– здійснити комплексний* *теоретико-методологічний аналіз і систематизацію сучасних моделей інтеграції технологій штучного інтелекту в адаптивні навчальні системи з хімії, а також оцінити їхній вплив на персоналізацію освітніх траєкторій, когнітивну ефективність навчання та оптимізацію дидактичного процесу. У дослідженні застосовано* ***методи*** *системного та порівняльного аналізу наукових джерел, контент-аналіз сучасних освітніх платформ, метод педагогічного моделювання адаптивних навчальних середовищ, а також узагальнення емпіричного досвіду впровадження інтелектуальних навчальних систем у процес викладання хімії. Додатково використано елементи концептуального проєктування та структурно-функціонального аналізу.* ***У результаті*** *дослідження визначено основні моделі інтеграції штучного інтелекту в адаптивні системи навчання, зокрема моделі на основі машинного навчання для персоналізації освітніх траєкторій, інтелектуальні системи рекомендацій, автоматизоване оцінювання знань та адаптивний зворотний зв'язок. Встановлено, що використання таких моделей сприяє підвищенню мотивації здобувачів освіти, покращенню якості засвоєння складних хімічних понять та оптимізації освітнього процесу.* ***У висновках*** *зазначено, що інтеграція технологій штучного інтелекту в адаптивні системи навчання хімії є перспективним напрямом розвитку освіти. Вона забезпечує індивідуалізацію навчання, підвищує ефективність освітнього процесу та надає нові можливості для розвитку цифрових освітніх середовищ. Подальші дослідження доцільно спрямувати на вдосконалення алгоритмів адаптації та оцінювання їхньої ефективності в реальних умовах навчання.*

Ключові слова: *персоналізоване навчання, цифрова освіта, інтелектуальні освітні платформи, освітня аналітика, алгоритми рекомендацій, адаптація навчального контенту, когнітивні технології, цифрові компетентності.*

Introduction. In the context of the digital transformation of education and the development of artificial intelligence (hereinafter, AI) technologies, the need arises to reconsider the didactic approaches to the teaching of chemistry. Traditional reproductive methods are insufficiently effective for the individualization of instruction, which lowers motivation and complicates the assimilation of the material.

In this connection, particular relevance attaches to adaptive learning systems oriented toward the personalization of educational trajectories with due account taken of the individual characteristics and the level of preparation of learners. Their effectiveness is substantially enhanced through the integration of machine learning methods, of data analysis, and of learning analytics, which provides for a more precise accommodation of educational needs and of the dynamics of academic achievement.

At the same time, notwithstanding the available technological capabilities, the problem of designing and validating models for the integration of AI into chemistry instruction remains insufficiently studied. In particular, deeper substantiation is required for algorithmic solutions, for the mechanisms of processing learning data, and for ensuring the pedagogical expediency, the inclusiveness, and the usability of the corresponding systems.

In this context, particular weight attaches to the necessity of adapting the above approaches to the conditions in which Ukrainian educational institutions operate, with due regard for the available resources, the level of digital preparedness of teaching staff, and the current regulatory requirements. The elaboration of scholarly grounded models for the integration of AI is thus an important precondition for enhancing the quality of education and for the realization of individualized instruction.

Literature review. The contemporary stage of the development of education is characterized by the active introduction of AI technologies into the educational process, in particular in the field of the natural sciences. A considerable number of scholarly studies are devoted to the creation and refinement of adaptive learning systems that ensure the personalization of the educational process with due regard for the individual characteristics of learners. In particular, O. Zadorina, M. Yashanov, and S. Rendiuk demonstrate the effectiveness of the use of adaptive systems of personalized learning grounded in AI technologies as a significant instrument for raising the level of academic achievement of learners within a digitalized educational environment [1].

In her scholarly article, O. Sahan emphasizes that the fragmentary use of AI technologies for the personalization of learning hinders the comprehensive deployment of educational platforms and diminishes the effectiveness of the adaptation of the educational process [2].

Miziuk V., A. Khyzhniak, and V. Khrenova carry out an analysis of adaptive educational platforms designed for distance learning, with an emphasis on their capacity to ensure the individualization of the educational process. At the same time, the said studies do not sufficiently address the question of the strategic readiness of higher education institutions (hereinafter, HEIs) for the introduction of such innovative technological solutions into educational practice [3].

Within the scholarly discourse, L. Kutsak underscores that the digital transformation of the educational sphere is not confined to the automation of instructional processes but, above all, presupposes their adaptation and personalization in accordance with individual educational needs. At the same time, the insufficient elaboration of applied models and of effective methods for the introduction of adaptive educational systems gives rise to a substantial scholarly gap in the field in question [4].

In her scholarly studies, O. Kravchenko emphasizes that the introduction of virtual and augmented reality (hereinafter, VR/AR) technologies contributes to the individualization of the educational process, to the optimization of decision-making

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procedures, and to the enhancement of the competitiveness of educational programs. The said technologies are thereby regarded as an effective instrument for the formation and development of the digital educational environment [5].

Podzharskyi M. addresses the strategic significance and the applied aspects of the introduction of AI technologies into the system of training future chemical engineers at HEIs. The scholar substantiates conceptual approaches to the integration of intelligent systems into educational programs and analyzes their capabilities for the modeling of chemical processes, the individualization of the educational process, and the formation of the professional competencies of learners. Particular attention is devoted to the identification of the principal challenges and prospects for the effective use of the said technologies within the educational environment [6].

Tsekhmistrenko S., V. Bitiutskyi, and I. Lastovska emphasize the significant role of AI in the development of chemical and biotechnological research and its educational potential. The authors consider the application of machine learning methods to the optimization of synthesis processes, to the modeling of chemical reactions, to the prediction of the properties of substances, and to the analysis of genetic information, all of which contribute to the development of personalized medicine and to the creation of environmentally safe biomaterials [7].

Papach O., V. Melniichuk, and V. Antonova focus on identifying the potential of the application of generative AI for the creation of educational content and on the development of practical recommendations for its effective introduction into the educational process [8].

Iliichuk L. emphasizes the necessity of harmoniously combining classical methods of instruction with the latest technological solutions, underscoring at the same time the importance of carefully evaluating the quality of generated content [9].

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The scholars T. Sichko, O. Zelinska, and D. Afanasieva emphasize that the use of AI in higher education enhances the effectiveness of the creation of instructional materials by rendering them more adaptive to the needs of learners and conducive to personalized learning [10].

Thus, the analysis of recent research attests that AI technologies are being integrated ever more actively into educational environments, in particular into adaptive learning systems, ensuring the personalization of educational trajectories, the enhancement of the effectiveness of the assimilation of instructional material, and the automation of feedback. In the context of chemistry instruction, such technologies make it possible to model complex chemical processes, to adapt tasks in accordance with the learner's level of preparation, and to support the formation of subject-specific competencies through interactive digital tools.

Identification of the previously unresolved aspects of the general problem. Notwithstanding the rapid development of AI and its integration into digital educational environments, the theoretical-methodological and applied aspects of its use in the adaptive teaching of chemistry remain insufficiently formalized and empirically grounded.

A pressing problem is the creation of unified architectures for intelligent learning systems capable of ensuring the multifactor adaptation of content with due regard for the specificity of chemistry as a STEM discipline and for the individual educational needs of learners. The available solutions are for the most part fragmentary in character and do not constitute a coherent adaptive educational infrastructure.

Models for the adaptive modeling of learning trajectories grounded in learning analytics and data mining remain insufficiently developed. Contemporary approaches to personalization frequently employ simplified algorithms that do not reflect the complex nonlinear nature of the educational process and that fail to provide a complete multidimensional profiling of the learner.

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A separate problem is the insufficient interpretability of AI-derived decisions in the educational context, which reduces the pedagogical effectiveness of the systems, especially in the modeling of chemical processes and in the solving of stoichiometric problems.

The questions of the integration of AI with traditional didactic approaches likewise require further investigation, in particular with regard to the role of the instructor as a facilitator and interpreter of analytical data, as well as the safeguarding of pedagogical agency and ethical responsibility.

Thus, the further development and experimental verification of integrative models of AI in chemistry instruction are necessary, ensuring the personalization, the interpretability, and the pedagogical effectiveness of the educational process under conditions of digital transformation.

Formulation of the article's objectives (statement of the problem). The aim of the article is to carry out a comprehensive theoretical and methodological analysis and systematization of contemporary models for the integration of AI technologies into adaptive learning systems in chemistry, and also to assess their impact on the personalization of educational trajectories, on the cognitive effectiveness of learning, and on the optimization of the didactic process. To achieve the stated aim, a system of interrelated objectives has been formulated, in particular:

1) to investigate the theoretical foundations of the application of AI technologies in education, in particular in the natural sciences;

2) to identify the principal approaches to the integration of AI algorithms into adaptive learning environments;

3) to develop a conceptual model for the integration of AI technologies into adaptive systems of chemistry instruction.

Research results. Contemporary education is actively introducing digital technologies, in particular machine intelligence, which provides opportunities for the personalization of learning, for enhancing its effectiveness, and for the formation

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of individual educational trajectories, especially in the natural sciences, such as chemistry. In this connection, AI-based adaptive learning systems acquire particular significance, since they take into account the individual characteristics of learners, their level of preparation, and their pace of assimilation of the material, automatically modify the instructional content, offer personalized tasks, and provide prompt feedback. It is for this reason that, within the said context, particular relevance attaches to the investigation of models for the integration of AI into educational environments with the aim of enhancing the quality of chemistry instruction, as well as to the identification of their advantages, limitations, and prospects for implementation under conditions of the digital transformation of education [11, p. 198].

A logical continuation of the problematics outlined consists in turning to the theoretical and methodological foundations of the integration of digital intelligence technologies into the educational process. It is worth noting that their investigation constitutes one of the important directions of contemporary pedagogy and digital didactics, since it is precisely these foundations that form the conceptual grounding for the transformation of traditional models of instruction under the conditions of the digitalization of education. In this respect, the problem acquires particular significance in natural-science education, in particular in the teaching of chemistry, which is characterized by the necessity of operating with abstract concepts, with complex structural and functional models, and with extensive interdisciplinary connections, all of which accordingly imposes heightened requirements upon the organization of an effective and individualized educational process.

Within the contemporary scholarly paradigm, AI in education is regarded as a complex of intelligent information and computing technologies that provide for the semantic analysis of learning data, the prediction of learning outcomes, the adaptive management of content, and feedback in real time. Its functioning rests upon the methods of machine and deep learning, of natural language processing, and

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of intelligent data analysis, which in their combination constitute adaptive learning environments [12, p. 151]. Thus, the said technological foundations define not only the instrumental but also the methodological vector of the modernization of the educational process, oriented toward enhancing its flexibility, its responsiveness to individual needs, and its effectiveness.

In this connection, it is expedient to specify the didactic capabilities of AI in natural-science education, and in chemistry education in particular. AI technologies thus perform a series of interrelated functions: the modeling of chemical processes at the micro- and macro-levels, the visualization of molecular structure, the simulation of reaction dynamics, the automated generation and verification of learning tasks, and the diagnostic-evaluative analysis of the formation of competencies. As a consequence, their application contributes to the enhancement of learning effectiveness through the realization of the principles of personalization, differentiation, and adaptivity that take into account the individual cognitive characteristics of learners and thereby ensure a deeper and more structured assimilation of complex chemical material [13, p. 409].

At the same time, the theoretical and methodological substantiation of the integration of AI into adaptive educational systems rests upon the propositions of cognitive pedagogy, of constructivist learning theory, of the concept of the individualization of the educational process, and of the competency-based paradigm of education. Within the framework of these approaches, adaptive systems of chemistry instruction are regarded as intelligent learning environments that carry out the continuous monitoring of the learning behavior of learners, analyze their educational trajectory, and, on the basis of algorithms of intelligent adaptation, perform the dynamic selection of instructional content, of didactic materials, and of leveled tasks in accordance with the individual level of preparedness.

Thus, the systematic investigation of the theoretical foundations of the application of AI in education creates a scholarly and methodological basis for the

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design and implementation of innovative models of adaptive chemistry instruction. This, in turn, contributes to enhancing the quality of the educational process, to the formation of a high level of subject-specific and key competencies, to the development of analytical and critical thinking, and to ensuring a deeper and more conscious assimilation of complex scientific concepts and chemical regularities.

The further development of this problematics is connected with the integration of algorithmic AI approaches into adaptive educational environments, which constitutes an important direction in the transformation of contemporary education, and of chemistry education in particular. It is grounded in the principles of personalized learning and is directed toward the reduction of cognitive load, the enhancement of the effectiveness of the assimilation of knowledge, and the formation of individual educational trajectories in accordance with the cognitive characteristics of learners [14].

In this context, the principal methodological toolkit consists of machine learning algorithms, which implement learning analytics and educational data mining. The application of these algorithms provides for the multidimensional diagnosis of the level of subject-specific competence, the identification of cognitive gaps, and the dynamic generation of relevant instructional content. In the context of chemistry, this acquires particular significance owing to the high level of abstraction of the instructional material and to the necessity of operating with symbolic representations and with inter-level relationships (the micro-, macro-, and symbolic levels).

A logical continuation is the introduction of intelligent tutoring systems (ITS), grounded in cognitive modeling and in the theory of adaptive instruction. Such systems implement mechanisms of context-sensitive support, providing for the generation of explanations, hints, and formative assessment in real time. They are capable of adapting the pace and the complexity of the presentation of the material

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to the individual rate of assimilation, which fosters a deeper conceptualization of chemical processes and regularities [15, p. 72].

In addition, a distinct direction is constituted by natural language processing algorithms, which provide for the functioning of dialogue interfaces and intelligent agents. In chemistry instruction, their application makes it possible to carry out the semantic analysis of the responses of learners, to interpret open-ended answers in an automated manner, and to support inquiry-oriented educational approaches.

An important supplement to the said technologies is recommendation systems, which operate on the basis of the methods of collaborative filtering and content-oriented selection. They provide for the construction of personalized learning paths with due regard for the academic history, the cognitive style, and the motivational characteristics of the participants in the educational process. In chemistry education, this may be realized through the intelligent selection of virtual laboratories, of simulations of molecular processes, and of interactive tasks of heightened complexity [16, p. 86].

In addition, of considerable importance is the use of adaptive testing grounded in item response theory and in Bayesian models of assessment. Such an approach provides for the dynamic adaptation of the complexity of tasks to the level of preparation of the learner, thereby enhancing the validity and the reliability of the measurement of academic achievement.

Thus, the integration of machine learning methods, of intelligent tutoring systems, of natural language processing, of recommendation algorithms, and of adaptive assessment creates a foundation for the development of intellectualized environments for chemistry instruction. This ensures the transition from traditional didactic approaches to educational models oriented toward data analysis and toward the needs of learners. At the same time, the contemporary stage of the evolution of educational systems is characterized by an intensive digital transformation occasioned by the large-scale introduction of information and communication

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technologies, among which a dominant position is occupied by intelligent systems grounded in AI methods. Within the paradigm of chemistry education, this determines the emergence of innovative didactic instruments that provide for the cognitively oriented personalization of learning, for the optimization of the processes of the conceptual assimilation of complex chemical categories, and for the intensification of the formation of research and experimental-analytical competencies of learners [17, p. 132].

In view of the foregoing, the conceptual and methodological model for the integration of AI technologies into adaptive learning systems in chemistry should rest upon the synergetic combination of pedagogical theories, of information-technological solutions, and of subject-specific (disciplinary) knowledge. The principal system-forming principle is the design of a dynamic, cognitively sensitive educational environment capable of context-dependent adaptation in accordance with the individual educational trajectories, the learning styles, the level of preparation, and the metacognitive characteristics of the subjects of instruction (Table 1).

Table 1

Core Components of the Adaptive Educational Model

Component	**Purpose**	**Key Functions**
Diagnostic Module	Identification of individual learner characteristics	Analysis of knowledge level, learning styles, and cognitive characteristics; construction of personalized learning pathways
Adaptive Content Module	Personalization of instructional materials	Selection and modification of content; interactive models, virtual laboratories, and simulations
Analytics Module	Analysis of learning data	Prediction of learning outcomes; identification of learning difficulties
Feedback and Recommendation System	Support and correction of the learning process	Personalized prompts, explanations, and recommendations
Interaction Interface	Facilitation of user communication	User-friendly interface; chatbots and conversational agents

Source: compiled by the author based on [18; 19, p. 105]

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A distinctive feature of the proposed model is that it does not exist abstractly but is filled directly with the content of chemistry education itself. This means that all of its components engage with concrete instructional material that requires not only explanation but also visual representation and conceptual reflection. This involves, first and foremost, the use of means for visualization at the microscopic level: the structure of atoms and molecules, the types of chemical bonds, the spatial arrangement of particles, and the mechanisms by which reactions proceed. Such instruments help to render comprehensible the processes that cannot be observed directly and to connect them with what learners observe at the macro-level.

An important role is also played by computer modeling, which makes it possible to “replay” chemical processes under varying conditions. For instance, by altering the temperature, the concentration, or the presence of a catalyst, the learner can observe how the rate of a reaction or its course changes. Such a possibility of experimenting without constraints of time or resources renders learning more flexible and more comprehensible.

In addition, of significance is engagement with experimental data, both real and simulated. This entails the processing of results, the performance of calculations, the construction of dependencies, and the formulation of conclusions. In combination with AI tools, this makes it possible to verify problem solutions rapidly, to identify typical errors, and to suggest the direction in which to proceed further.

Of additional importance is the diagnostic component, which provides for the initial determination of the level of knowledge, the learning styles, and the cognitive characteristics of learners. This makes it possible to adapt the complexity of the instructional material and to construct individual educational trajectories already at the stage of planning the instructional activity.

No less significant is the system of feedback and recommendations, which during the learning process provides learners with explanations, hints, and individual recommendations as to subsequent actions. In combination with intelligent

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algorithms, this ensures a more precise correction of the educational trajectory in accordance with current results and identified difficulties.

Separate emphasis should be placed on the interaction interface, which is implemented through convenient digital environments, in particular dialogue systems and intelligent agents. These provide for prompt communication between the learner and the system, rendering the learning process more accessible and more dynamic.

In sum, such an approach makes it possible to move from the formal assimilation of the material toward its deeper understanding, in which the learner does not merely reproduce knowledge but perceives the logic of chemical processes and is able to explain and apply them in practice.

Conclusions. Thus, the findings of the study have demonstrated that the theoretical foundations for the application of AI technologies in education, in particular in the natural sciences, form a coherent scholarly grounding for the transformation of traditional approaches to the teaching of chemistry. It has been established that the use of AI ensures not only the technological renewal of the educational process but also its reorientation toward the individual needs of learners, fostering a deeper understanding of complex chemical phenomena, the reduction of cognitive load, and the creation of conditions for more conscious and supportive learning.

At the same time, it has been determined that the integration of AI algorithms into adaptive learning environments rests upon the combination of machine learning methods, intelligent tutoring systems, natural language processing technologies, recommendation algorithms, and adaptive assessment. Their coordinated use ensures the personalization of educational trajectories, the timely diagnosis of learning difficulties, and the formation of individualized support, which contributes not only to enhancing the effectiveness of the assimilation of instructional material but also to developing learners' confidence in their own learning capabilities.

On the basis of the generalization of contemporary approaches, a conceptual model has been developed for the integration of AI technologies into adaptive systems of chemistry instruction, which reflects the interaction of the diagnostic, adaptive, analytical, and communicative components. A distinctive feature of the model is its orientation toward the combination of technological capabilities with pedagogical expediency and with the subject-specific particularities of chemistry, which ensures not only the assimilation of knowledge but also the development of research skills, critical thinking, and a scientific style of cognition.

In summary, it has been established that the integration of AI technologies into adaptive systems of chemistry instruction creates the conditions for the formation of an individualized, flexible, and supportive educational environment oriented toward the development of the personal potential of each learner. This ensures an enhancement of the quality of educational outcomes, contributes to the formation of stable cognitive motivation, and establishes the preconditions for a more humanistically oriented model of instruction under conditions of the digital transformation of education.

The prospects for further research are seen in the practical testing of the proposed models, in the evaluation of their long-term impact on learning outcomes, and in the expansion of the functional capabilities of intelligent educational systems.

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