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A set of online tools for teaching chemistry considering a systematic approach to the educational process

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Abstract

This article discusses the development and application of a set of online tools for teaching chemistry via a systems approach. The possibilities of integrating tools such as virtual laboratories, interactive simulators, and knowledge control platforms into the educational process are analyzed. These tools not only enhance the learning experience but also foster a deeper understanding of complex chemical concepts. The key advantages of the systems approach are highlighted, including personalization of learning, development of critical thinking, and improvement of practical skills. The use of digital tools allows students to experiment virtually, bridging the gap between theory and practice. The challenges associated with the implementation of online education, such as the need for teacher training and access to quality resources, are also considered. These challenges can be addressed through professional development programs and ensuring equitable access to technology. A model for assessing the effectiveness of using digital tools based on the level of teacher qualifications, digital equipment, and the size of groups is presented. In conclusion, there is a need to adapt curricula that incorporate modern technologies to improve the quality of chemistry teaching, ensuring that both educators and students benefit from these advancements.

Keywords: Chemistry, Critical thinking, Digital technologies, Educational effectiveness, Interactive simulators, Online learning, personalization of learning, Systems approach, Virtual laboratories.

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1. Introduction

In the era of the mixed material-digital reality of Richard [1], the game culture of Johan Huizinga, and the integration of digital and online learning methods into the processes of cognition, learning, and training have become traditional and promising trends in the evolution of education. After the COVID-19 pandemic and the subsequent reassessment of values, online virtual and digital learning has been utilized in almost all university areas [2], including medicine [3], chemistry [4], and other fields [5].

Today, the main source of information, especially for young people, has become the virtual space. In this sense, the development of online and distance learning in digital or analog formats (in the context of visualization) is an authentic solution for the positive dynamics of youth involvement in the processes of learning, training, and knowledge acquisition.

First, online learning in the content archiving mode is maximally adaptive to the needs and capabilities of students. A missed online lecture or lesson can be reproduced and learned by a student at any other time. Such educational variability allows for the optimal and effective distribution of the most valuable resource—time.

Online learning and hybrid learning are based on the implementation of the V Class (virtual classroom), V Labs (virtual laboratory), IntSup (Internet support), and Teach Online (online learning) paradigms [6]. These technologies are the primary ones used for the development of online, distance, and virtual learning and training systems. The use of virtual technologies must be accompanied by the implementation of educational, pedagogical, and scientific ethics [7].

The most active application of online learning is in the study of foreign languages at schools and universities. [7]. In this area, the most diverse and extensive set of online tools are used [8]. Personalized learning is rapidly supplemented or even replaced by virtual learning. This has a greater effect on student involvement in the educational process and the formation of critical thinking [9].

As in other areas of education, the COVID-19 pandemic has rapidly accelerated and stimulated the transition to online, distance, and chemistry education [10].

However, the transition to online learning due to COVID-19 was mostly emergent and rather hasty. Most teachers and professors were clearly not prepared for such a trend, and this necessity has created a number of challenges for the successful and effective implementation of online teaching methods and tools in recent years. First, the gradual loss of direct interaction has been a significant concern.

Teachers and lecturers in higher education institutions usually use digital online tools to visualize educational or scientific content. To a lesser extent, they adapt this visualization to activate students' attention and involvement. However, the online learning process certainly requires increased interaction between the teacher and the student to compensate for the lack of real communication.

Digital education has certain limitations due to institutional conditions, psychological archetypes, and the behavioral structures of the teaching staff. Usually, several parameters and attributes determine how effectively and diversely teachers and educators use online learning systems:

digital competence (digital divide),
collegial support,
digital self-efficacy
technostress

For online education in chemistry, modern technologies for teaching the subject are actively developing due to the widespread availability of online educational resources, which allows for their integration into the overall learning process. Online tools based on a systemic approach play an important role in creating a unified educational environment where theory and practice reinforce one another.

There are several types of online tools that can be integrated into a chemistry learning system.

1.1. Virtual laboratories

Virtual labs allow you to perform experiments online using a computer model of laboratory equipment and reagents. Platforms such as Labster and PhET interactive simulations provide the ability to conduct chemical reactions in a virtual environment.

Example of use: Students can "mix" reagents by setting different conditions (temperature, pressure, and concentration of substances) to observe the results of the reaction. This not only saves time and resources but also makes the process safe.

Theoretical rationale: According to the study by Smetana and Bell [11], virtual laboratories facilitate better acquisition of practical skills, as they allow for the observation of reactions that are impossible to carry out in a school setting. This significantly expands the possibilities for studying chemistry, making it accessible to a larger number of students.

1.2. Interactive Simulators and Visualizers of Molecular Structures

Simulators such as ChemCollective and Molecular Workbench help students visualize molecular structures and chemical dynamics. Interactive simulations allow students to explore complex concepts such as reaction mechanisms or chemical kinetics through animations.

Example Use: Students can explore the molecular structure of water, study bond angles, and determine how water molecules interact with each other at the molecular level.

Theoretical background: Research by De Jong and Van Joolingen [12] shows that visualizing molecular structures through simulators helps students better understand abstract concepts such as stereochemistry and quantum chemistry. The model approach also helps develop analytical thinking, as students can change experimental parameters and see the results of these changes.

1.3. Platforms for Testing and Knowledge Control

Using online testing with instant feedback helps quickly assess knowledge and adapt the learning process depending on the student's progress. Platforms such as Quizlet and Socrative allow teachers to create tests and quizzes, helping students check their knowledge and receive comments on mistakes.

Example use case: Quizlet allows teachers to create flashcards with chemical equations and theory questions. Students answer the questions and obtain instant grades, which helps reinforce knowledge before an exam or quiz.

Theoretical background: Alharbi, et al. [13] reported that immediate feedback from testing helps students learn better because they can immediately understand and correct their mistakes. This approach reduces stress before exams because students have constant access to materials for self-checking.

2. Materials and Methods

The research described in this study was based on a systematic approach and focused on the development, implementation, and evaluation of a suite of online tools for teaching chemistry. The methodology consisted of several key stages aimed at a comprehensive analysis of the effectiveness of the implemented technologies.

2.1. Theoretical Analysis

The initial phase involved an in-depth examination of existing approaches and tools in digital education, including the following:

Review of the literature on the integration of virtual laboratories, simulators, and online platforms into the educational process.

Traditional and digital teaching methods in chemistry should be compared to identify the strengths and limitations of each.

Evaluating the theoretical foundation of the systematic approach, its applicability in educational settings, and its integration of components such as theory, practice, visualization, and knowledge assessment.

2.2. Conceptual and Methodological Development of Online Tools

The next stage was the conceptual development of a suite of online tools, including the following:

Virtual Laboratories: Enabling practical experiments in a safe environment.

Interactive Simulators: Allowing the modeling of molecular processes, reactions, and the study of chemical kinetics.

Knowledge Assessment Platforms: Featuring adaptive content tailored to the students' levels of preparedness.

Formalization of Research through Mathematical Modeling.

A primary mathematical model for the online processing of the comprehensive model was developed.

The study employed a robust system of evidence grounded in the following methodological, conceptual, and theoretical approaches:

2.3. Evidence base

2.3.1. Systematic Approach in Education

The use of a systematic approach that integrates various educational tools into a unified system was considered. This approach organizes the interconnection of theoretical material, practical activities, visualizations, and knowledge assessment.

2.3.2. Prior Research

Previous studies, such as those examining the use of virtual laboratories and interactive simulators in chemistry, were analyzed. These studies validate their ability to deepen understanding and expand learning opportunities.

2.3.3. Empirical Evidence

Empirical research demonstrates the successful application of virtual laboratories and simulators to enhance material retention. For example, Smetana and Bell [11] confirmed that virtual laboratories improve the acquisition of practical skills by enabling students to observe reactions that are not feasible in physical laboratories.

2.3.4. Personalized Learning Trajectories

Data indicating that personalized learning paths using online tools improve student engagement and performance were considered, supporting the effectiveness of this approach.

2.3.5. Mathematical Modeling

A formal mathematical model was created to evaluate the impact of factors such as instructor qualifications, digital infrastructure, and group size on the efficiency of the educational process.

The evidence, derived from theoretical analysis, empirical data, mathematical modeling, and examples of successful practices, provides a robust and multifaceted foundation for determining the positive impact of a systematic approach and online tools on the effectiveness of chemistry education. This model not only enhances the learning process but also sets the stage for broader application in modern educational systems.

3. Literature Review

Today, the realm of digital interaction and communication is evolving into a space for digital and innovative education, reflecting a trend in modern education and training systems as a whole [14].

The development of virtual space and digital progress has significantly expanded the scope and authority of online education within the overall system of education and training for qualified personnel. One of the main advantages of online education is the ability to visualize complex chemical concepts, including the visualization of molecular structures, chemical reactions, and processes [15]. Within the framework of online learning platforms, the effectiveness of learning and teaching has significantly increased due to the use of interactive simulations and virtual laboratories. In addition to visualization, chemical reactions and processes can be imitated or modeled in real-time and at any convenient time, aside from purely educational time [16].

The most popular online services for learning are Edmodo [17], LearningApps.org[18], and Google Classroom [19].

Online tools are inclusive and significantly expand access to educational resources, particularly for students with disabilities and those who cannot attend lectures and laboratories in person. Thus, online education completely removes the problem of the localization of students. For example, a study group may include students who are in different geographical locations.

Online learning requires a systematic approach in which the educational process is viewed as a single, integrated system for the transfer and adaptation of knowledge via digital tools.

A systems approach to education is a method that views learning as a unified system in which teachers, students, and educational tools interact. In this approach, each element of the educational process (e.g., lectures, practical assignments, tests, and resources) does not exist in isolation but is interconnected with other components.

The following main characteristics of the systems approach in relation to educational processing can be identified:

- Integrity: All educational components are closely linked to one another, which helps improve the understanding of the material.
- Sequence: the material is structured so that knowledge develops logically from simple to complex.
- Adaptability: The system considers the needs of different students, providing them the opportunity to master the material at their own pace.
- Feedback: The use of digital technologies allows you to instantly receive feedback on the level of mastery of the material and adjust the learning process.

The use of a systematic approach in teaching chemistry allows for the creation of a unified environment where students gain theoretical knowledge and can simultaneously apply it in practice, while teachers can monitor the process and adapt the material quickly. Systematicity, in turn, requires a careful approach to planning, integrating, and using online educational resources [20].

The integration of online tools into chemistry teaching should also consider the individual learning needs of students. Research shows that a personalized approach to learning through digital technologies promotes better learning, as students can work at their own pace and choose the forms of interaction with the material that best suit them [21]. A key aspect is the creation of digital resources that support a variety of learning styles and allow students to approach the material flexibly [22]. A systems approach allows one to structure the learning process so that digital tools do not exist in isolation but are part of a holistic educational process. The advantages of a systems approach include the following:

Integrity and logicality of learning – a systems approach allows teachers to structure material in such a way that students can complete the course in a sequential and integrated manner [23]. This promotes better knowledge acquisition, as students perceive the material in the context of previous and subsequent topics.

Support for individual learning paths—Due to a systematic approach to integrating online tools, teachers can create different learning paths for students, taking into account their level of preparation and learning preferences. This helps each student learn the material more effectively.

Developing critical thinking skills – Using online simulations and testing allows students to not only memorize the material but also apply it in practice, which helps develop critical thinking and analytical skills.

The vast majority of teachers prefer traditional methods of teaching chemistry [24]. However, online chemistry courses are increasingly becoming widespread in higher education institutions, schools, and colleges. Online education in chemistry is also actively utilized in Kazakhstani educational institutions [25].

Despite the many benefits, the process of introducing online tools into the chemistry teaching process also faces several challenges. The main problem is ensuring the availability of resources and their quality. There is also a need to train teachers in new methods of working with digital tools and creating specialized content for platforms so that students can receive a complete and comprehensive education. In the future, the question of adapting educational programs for maximum integration of online tools, taking into account the requirements of a systems approach and the individual educational needs of students, remains open. The use of a set of online tools in teaching chemistry, considering the systemic approach, can significantly improve the efficiency and quality of the educational process. The integration of such tools allows for the creation of a flexible, inclusive, and multilevel educational environment where each student can gain knowledge that meets their needs and interests. However, successful implementation requires a comprehensive approach, from the development of curricula to teacher training.

4. Results

We propose the concept of an online complex of tools for teaching chemistry based on a systems approach.

The creation of a set of online tools for teaching chemistry through a systemic approach opens new opportunities for effectively mastering the material. Online resources allow for the personalization of the learning process, taking into account the learning characteristics of each student and improving practical skills. The integration of such tools requires careful preparation and development, but this makes teaching chemistry more exciting, accessible, and effective.

A systematic approach to using online tools in teaching chemistry enables the creation of a holistic and effective system. The advantages of this approach include the following:

Increased student motivation: Interactive platforms allow students to actively participate in the learning process, which enhances their interest in learning chemistry.

Flexibility in learning: With online tools, students can study at their own pace, review difficult topics, and work at their own speed.

Support for critical thinking: Simulators and virtual labs enable students to make independent decisions in experiments, promoting the development of analytical and critical thinking.

Example: Creating a combined chemistry course using a systems approach.

When creating a course, a teacher can use online simulations to explain the theoretical material, virtual labs to reinforce knowledge, and testing platforms to assess it. For example, after studying the topic of acid-base reactions, students can simulate the ChemCollective platform, which models a neutralization reaction. The Labster virtual lab allows them to conduct a series of experiments to reinforce their knowledge, and then, students can take a test on Quizlet, which checks how well they have learned the topic.

Despite the advantages of the systemic approach, its implementation is also associated with several difficulties. First, teachers need to undergo additional training to work with new tools. In addition, there is a need to develop specialized teaching materials so that the content is adapted to the requirements of the school or university program.

In the future, the issue of adapting educational programs remains important so that the integration of online tools does not become an additional burden for students but is organically woven into the educational system.

We formulate the general principles of the effectiveness of online education in chemistry based on a systems approach in the context of the modular structure of a set of online tools.

4.1. Modular Structure

It is preferable for the complex, as an online platform, to have a modular structure (with API integration). The modular structure allows for the transformation of functionality, minimizing or maximizing some of the most effective functions, or disabling unwanted or currently unnecessary functions.

The basic structure of the modular online system includes five main components:

- Theoretical module.
- A practical module that
- Visualization module – visual dynamic and static 2D and 3D models of chemical formulas and chemical reactions, diagrams, graphs of chemical kinetics, gamification, etc.
- A control module that includes assignments, assessments, and ranking tests for knowledge assessment, automated performance analyzers, chemical constructors, and basic and special questionnaires.
- An adaptive module that includes components for tailoring chemical educational content to specific tasks, levels, and individual interests of pupils and students.

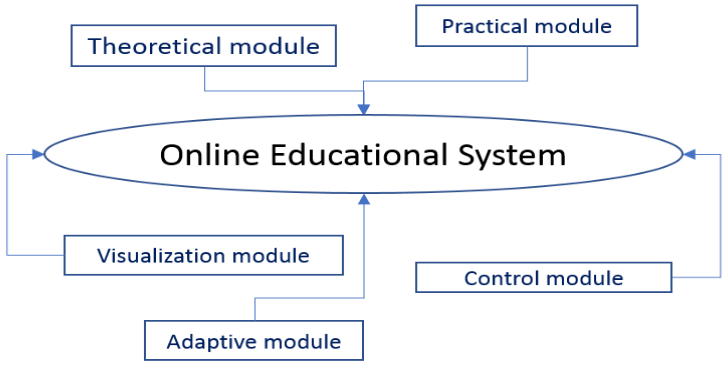

Figure 1.
Modular structure of the online educational system.

The theoretical module includes a fundamental set of knowledge in chemistry (interactive educational materials, articles, books, manuals, etc.). The objective of the theoretical module is purely educational: mastering basic and specialized knowledge in the field of chemistry through educational or popular science content.

The theoretical module includes the following attributes:

- *Interactive educational materials*
- *Electronic textbooks*
- *Virtual lecture.*
- *Electronic manuals*
- *Articles*
- *Presentations*
- *Video courses*

The practical module includes the following attributes:

- *Seminar content*
- *Practical exercises*
- *Simulators of chemical experiments*
- *Experimental simulators and schemes for chemical reactions*
- *Chemistry problems*
- *Chemistry simulators*
- *Practical schemes for chemical reactions*

The visualization module includes the following attributes:

- *Visual, dynamic, and static 2D and 3D models of chemical formulas and chemical reactions*
- *Schemes*
- *Graphs of chemical kinetics and reactions*
- *Modular gamification systems, etc.*

The control module includes the following attributes:

- *Control tasks,*
- *Assessment and ranking tests for knowledge evaluation*
- *Automated performance analyzers*
- *Chemical test constructors*
- *Basic and special questionnaires on the subject of chemistry*

The adaptive module includes the following attributes:

- *Modules for adapting chemical educational content to specific tasks, levels, and individual interests of pupils and students*
- *Interfaces for additional modules*
- *Modular grabbers and parsers for updating and adapting new information in educational chemistry*

As an example of a closed cycle of functioning of a modular system, we can cite the following chain of educational events on the topic “Acid-base reactions.” Figure 2:

1. The theoretical module offers a lecture with text and video materials.
2. The practical module provides an interactive exercise for determining the pH of solutions through a virtual laboratory.
3. The visualization module demonstrates a three-dimensional animation of the process of acid dissociation in water.
4. The control module runs a test to check how well the student understands the material.
5. The adaptive module analyzes progress and offers an additional task if the test is completed with errors.

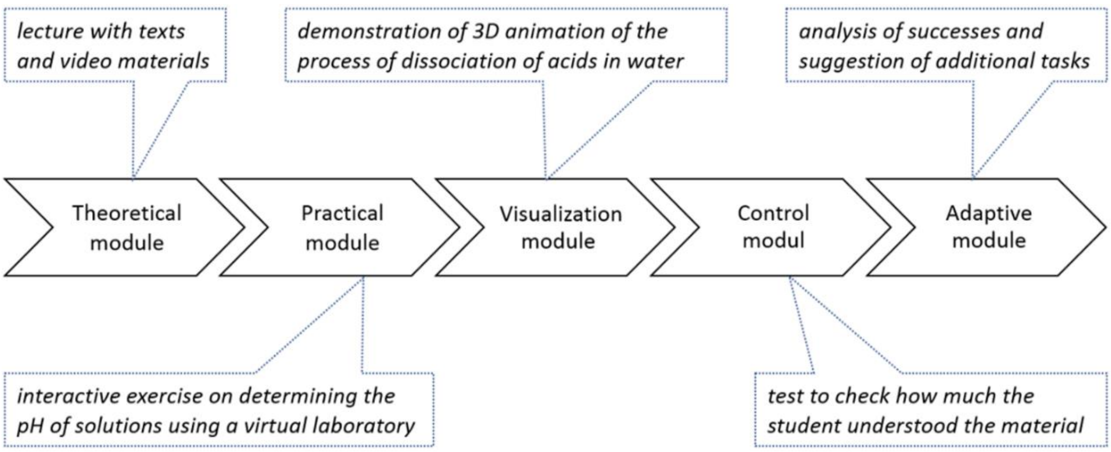

Figure 2.
An example of the interaction of modules on the topic “Acid-base reactions.”

Let us note the advantages of the described complex:

1. Systematicity and integration: All the components of the course work as a single system, where each module supports the others.
2. Personalization: Students receive recommendations and tailored assignments, which increase motivation and allow them to study the material at their own pace.
3. Efficiency: Hands-on activities and the visualization of complex processes help one understand and memorize the material in detail.

Thus, the developed set of online tools in chemistry, based on a systems approach, will support students at every stage of learning, offering not only a variety of formats but also ensuring a connection between theory, practice, and knowledge control.

4.2. Architecture of the Online Educational Complex

It is rational to create the architectural platform of the complex based on the Learning Management System (LMS). This approach is fully consistent with the concept, ideology, and principles of the Serious e-Learning Manifesto [26]. These include effective e-learning, advanced training, adaptation, interactivity, iteration, post-program support, authentic context, proactivity, simulation, imitation, gamification, measurability, etc.

This could be a certified model, such as Moodle and Canvas. Alternatively, a new cloud LMS platform specializing in chemical education, training, and learning is needed. This integrated online interactive software and hardware complex could be created as a universal platform for pupils and students in general and special chemistry and mixed sciences.

The architectural platform can be built on the principles of LMSs—a learning management system as an architectural core, LCMS—a learning content management system, TMS—a talent management system, DL—digital education, EL—electronic learning, DO—distance learning, and DLS—distance learning and adaptation systems (Figure 3.).

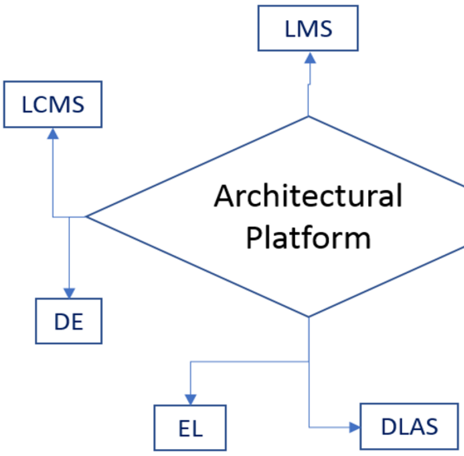

Figure 3.
Principles of the architectural platform.

The complete functionality of the architectural platform comprises a set of interconnected features and services that are interpreted as follows:

Content Service:
Subservices:
Content input/output
Publishing content
Content conversion
Nonlinear content
Content visualization

Service "Methodology"

- Group courses
- Individual courses
- Webinars
- Video courses
- Asynchronous learning

Custom training
Combination training
Adaptive methodology
Gamification

Service "Infrastructure":
Subservices:
Monitoring of training
Template management
Extensibility
Adaptability
Testing
Certification
Authorizing
Cybersecurity

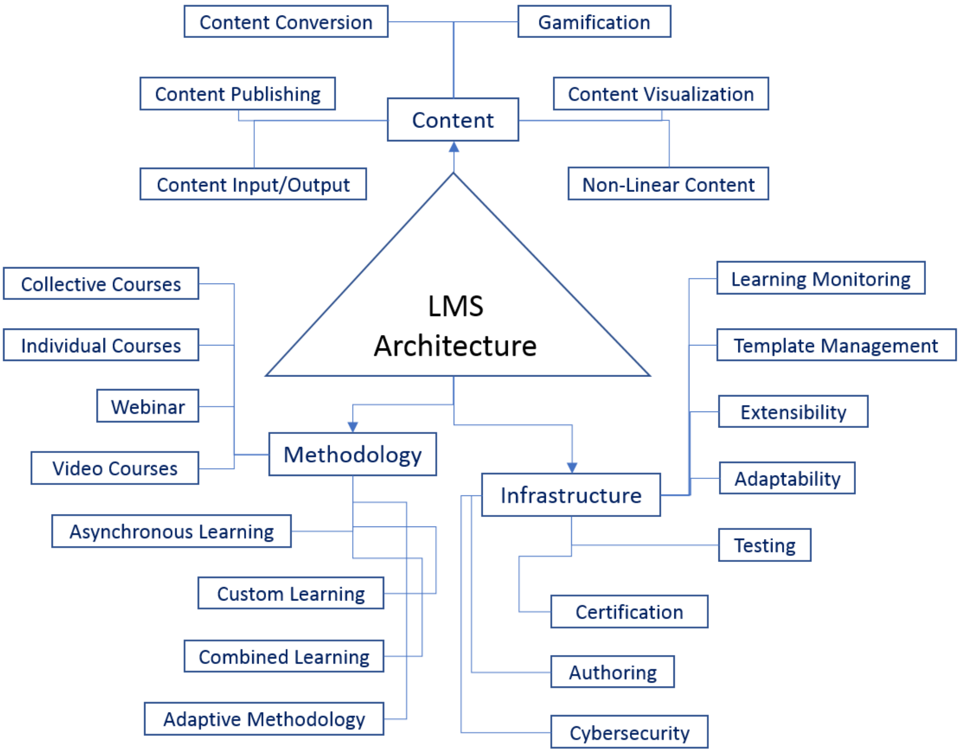

Figure 4.
Functional architecture of the complex.

4.3. Basic Mathematical Formalism of the Online Complex of a System in Chemistry

Let us consider the basic mathematical formalism that describes educational processing in the first approximation. This formalism is a simple superposition of the effectiveness of each module that we have considered: theoretical, practical, visual, control, and adaptive.

Let us introduce the concept of the coefficient of efficiency of training for complex E. In this case, E can be represented as the sum of individual components, which include point estimates and corresponding weight coefficients (1):

$$E = w1 \cdot T + w2 \cdot P + w3 \cdot V + w4 \cdot C + w5 \cdot A \qquad (1)$$

where:

- T - a score reflecting the assimilation of theoretical material (theoretical module);
- P - a score that reflects the completion of practical tasks (practical module);
- V - level of visual understanding of chemical processes (visualization module);
- C - the result of knowledge control (control module);
- A - level of adaptive compliance with the educational material (adaptive module);
- w1, w2, w3, w4, and w5 are weighting factors for each module, which can be adapted to the specific objectives of the course.

This expression is hypothetical. Within the framework of our hypothesis, we proceed from the fact that the modular structure of the online complex assumes independent results regarding the effectiveness of each module. That is, each module is autonomous in its parameters of influence on the effectiveness and efficiency of online educational processing.

Weighting factors depend on many conditions and vary widely. They may vary depending on the course level (basic or advanced) and the characteristics of the educational institution. In general, weighting factors depend mainly on the following three parameters of educational processing: the level of the teacher, the digital equipment, and the number of students, which we define as follows:

Teacher level (L) is an indicator of the teacher's qualifications and teaching skills, which include experience, academic qualifications, the ability to work with digital tools, and student interest.

Digital equipment (D) refers to the level of availability and quality of digital tools, such as virtual laboratories, 3D models, and the reliability of the online platform.

The number of students (S) is a factor that takes into account the size of a group of students, which can affect the teacher's ability to pay attention to each student.

In this case, we can represent the coefficient of training efficiency of the complex E in the following functional superposition (2):

$$E = w1 \cdot f(L) + w2 \cdot g(D) + w3 \cdot h(S) \qquad (2)$$

where w1, w2, and w3 are weighting coefficients that determine the significance of each factor,
f(L) is a function representing the teacher's level,
g(D) is a function reflecting the influence of digital equipment,
h(S) is a function that takes into account the influence of the number of students.

The coefficients can be selected empirically or on the basis of data from the analysis of a systematic online chemistry course,

Let us define authentic and adequate mathematical expressions for functions on the basis of simple considerations and assumptions.

The teacher-level function f(L)f(L)f(L) is represented in logarithmic form:

$$\mathrm{f(L)} = \alpha \cdot \ln(\mathrm{L} + 1) \qquad (3)$$

Here, α is the coefficient that takes into account the contribution of the teacher's level, and L is the teacher's qualification level (from 0--10, for example, where 10 is the highest level).

The digital equipment function g(D) is represented as (4)

$$\mathrm{g(D)} = \beta \cdot \sqrt{\mathrm{D}} \qquad (4)$$

Here, β is a coefficient reflecting the contribution of digital equipment, and D is an indicator of digital equipment, which can vary from 0 (no digital tools) to 10 (full equipment).

We represent the function of the number of students h(S) in the form:

$$\mathrm{h(S)} = \gamma \cdot \frac{1}{S+1} \qquad (5)$$

where γ is the coefficient reflecting the influence of the number of students, and S is the number of students in a group. The greater the number of students, the smaller the coefficient, which reflects the difficulty of providing quality education in large groups.

The teacher-level function f(L)=α · ln (L+1) was selected, taking into account several key factors related to the influence of teacher qualifications on the effectiveness of training, as well as the specifics of mathematical modeling.

The logarithmic function (L+1) has properties that effectively describe the influence of the teacher's level on the effectiveness of training. In particular, as the teacher's level (L) increases, the increase in the effectiveness of training slows. For example, the transition of a teacher from a beginner to an average level significantly increases effectiveness, but the difference between a high and very high level does not have such a strong effect on the final effectiveness.

The function has a +1 added inside the logarithm: (L+1). This is done to take into account the value L=0 (for example, in the absence of qualifications or if the teacher has just started working), which allows the model to correctly start from zero. Thus, even for a basic teacher level, the function yields f(L)=0, which is logical since the lack of qualifications minimizes the teacher's contribution to efficiency.

The coefficient α is a calibration parameter that can be selected for different courses and curricula. It regulates the contribution of the teacher's level to the overall efficiency coefficient E depending on the specific requirements and characteristics of the course. For example, for courses with an emphasis on the independent study of materials, the value of α may be smaller than that for courses where the teacher plays a leading role.

Other relationships, such as linear or quadratic relationships, do not capture the diminishing returns of teacher quality or the logarithmic relationship. In a linear function, the teacher's contribution continues to increase in direct proportion to L, which does not account for the real limitations of a highly qualified teacher's contribution, especially when students are also affected by access to digital resources or group learning conditions. A quadratic relationship would also be too steep, which does not correspond to the gradual decline in effectiveness at high teacher levels.

Thus, the logarithmic function α · ln (L+1) provides an adequate combination of increasing and smoothly decreasing influence of the teacher's level on the overall effectiveness of training. The choice of the logarithmic function f(L)=α · ln (L+1) allows optimal accounting of the teacher's contribution to the effectiveness of training, taking into account the effect of diminishing returns, an adequate start from scratch, and the possibility of flexible adjustment for different conditions.

The digital equipment function g(D)=β · √ D was chosen to adequately reflect the influence of the level of digital tools and resources on the effectiveness of learning. A linear function (g(D)) assumes that each new level of instrumentation has an equal effect on efficiency, which is not the case. We can assume that the basic instrumentation (the first levels of D has a significant effect, but with further increases, the saturation of the effects decreases. A logarithmic function (g(D)=β · ln (D+1) could also be used, but it smooths out the effects more sharply. With a square root dependence of D, we can specify a less aggressive decline, which better reflects the gradual decrease in the contribution of digital instruments as they are added further.

The root function D reflects the gradual saturation effect of increasing the amount of digital equipment. As with the teacher level, adding new digital resources makes a large difference when moving from a low level of equipment (e.g., 0 to 3) to a medium level. However, further increases (e.g., 7 to 10) make a relatively smaller contribution to learning effectiveness since the basic needs are already satisfied. Having a basic set, such as an online platform, video lectures, and a virtual chemistry lab, significantly improves learning compared with having no resources at all. However, adding a few more specialized tools, such as 3D visualizations of chemical reactions or analytical modules for solving chemistry problems, has a less pronounced effect on students who already have access to high-quality resources.

Using √D allows us to define a function that does not approach zero for small values of D, since even with a basic level of digital equipment (e.g., with minimal tools for work), learning effectiveness will be greater than with no digital support at all. Moreover, the function takes into account that as D increases, the value of g(D) increases slowly, supporting the idea of a gradual decrease in the effect.

The digital equipment function g(D) allows for a balanced consideration of the effect of diminishing returns of digital resources, where each subsequent level of digital tools has an increasingly smaller impact.

- Flexibility of customization for different educational conditions, owing to the β parameter, which allows the specifics of the course and its digital needs to be considered.

- Adequate reflection of basic equipment—the initial increase in efficiency is more pronounced, and further growth is slower, which corresponds to the real impact of digital technologies on the educational process.

This model helps establish a reasonable and flexible dependence of the effectiveness of training on the level of digital equipment.

The β coefficient serves to scale and adjust the function depending on the specific course conditions and the level of digital integration required for teaching chemistry. A high β level may be useful for courses that require intensive use of digital resources (e.g., complex experimental or theoretical courses) to reflect their increased importance. A low β level is suitable for courses where digital equipment plays a secondary role, for example, if the learning process is focused mainly on students working independently with physical materials or laboratories.

The function taking into account the number of students was chosen as h(S)=γ · 1/(S+1). The function 1/(S+1) reflects the inverse dependence of efficiency on the number of students. In particular, in educational processes, especially in disciplines such as chemistry, the larger the group of students is, the more difficult it is for the teacher to provide individual attention to each student. This can reduce efficiency since the workload of the teacher increases, and the ability to monitor the progress of each student decreases. Additionally, with an increase in the number of students, it is difficult to organize practical classes and provide effective feedback. Therefore, the effect of increasing the group size has an exponential nature, which is reflected in the function 1/(S+1).

Adding +1 to the denominator serves to prevent division by zero at S=0 and to account for very small groups. When S=0 (the idealized case of individual learning), the function value is maximized, meaning that the learning efficiency is at its highest level. Adding +1 makes the function smoother for small values of S, preventing a sharp jump in efficiency when moving from individual learning to a small group.

The coefficient γ adds flexibility and allows the model to be adjusted for courses that vary in class size. Large values of γ are appropriate for courses where a high degree of interaction with the instructor is important (e.g., hands-on labs that require frequent instruction and feedback). Smaller values of γ are appropriate for lecture-based courses or courses with more independent work, where the number of students is not as critical to learning the material.

Inverse proportionality best captures the overload effect: as the number of students increases, efficiency decreases faster when moving from small to medium groups. With a linear relationship, the decrease in efficiency would be too rapid or even lead to negative values, which is inappropriate in this context. The logarithmic function does not clearly show a sharp drop in efficiency with a small increase in the number of students. It decreases too slowly with increasing SSS, which does not correspond to the real effect of large groups on the decrease in learning efficiency.

In fact, in the hypothetical form presented, the student number function h(S) provides a model with the following properties:

- Taking into account the overload when the number of students increases, the inverse relationship reflects the real problem of loss of efficiency in large groups.
- Smooth transitions for small groups due to the addition of +1+1+1, which ensures correct calculations for small and medium groups and prevents division by zero.
- Adaptability through the γ coefficient allows for the consideration of the course characteristics and their dependence on group size.

This feature reflects the practical impact of student numbers on learning effectiveness, supporting a systematic approach to assessing the learning process.

Thus, based on the types of functions, the efficiency coefficient E can be represented in the following formal form:

$$E = w1 \cdot \alpha \cdot \ln(L+1) + w2 \cdot \beta \cdot \sqrt{D} + w3 \cdot \gamma \cdot \frac{1}{S+1} \quad (6)$$

This approach to calculating E can be used as a basis for adapting the online educational process in chemistry based on a systems approach and its optimization.

From the expression E, several characteristic features of educational processing within the complex can be identified: a high level of the teacher and high-quality digital equipment can compensate for large groups; a small number of students is especially important when there is insufficient digital equipment and a low level of the teacher. Additionally, the flexibility of the weighting coefficients allows the formula to be adapted for different educational institutions and courses.

5. Discussion

Digitalization, virtualization, and online learning have become essential components of teachers' tools and educational processes. Moreover, the number of instrumental teaching methods is growing rapidly, which presents a challenge for learning. Teachers often face the dilemma of choosing between various online learning tools, considering the characteristics of cognitive communication between the teacher and the student during online learning [27].

However, a systematic approach is needed to achieve an optimal balance between the visualization of teaching content and active student involvement in online learning processes.

We observe a systematic approach in the simultaneous use of a wide variety of tools, methods, and techniques for online learning.

In the context of selecting online learning tools, teachers and educators must go through several stages to choose or combine appropriate methods and techniques:

- Classification of the most appropriate and acceptable online learning tools in the context of their professional, technical, and methodological capabilities and conditions.
- To identify the most effective formats for using interactive online tools to enhance the teaching and learning of chemistry among university students.

When developing a systematic approach to online education, it is necessary to consider, first, the personal, social, psychological and emotional characteristics of teachers and lecturers [28].

The success of integrating digital technologies into educational processes in the field of chemistry depends on the characteristics of the teaching staff.

The development of online tools for teaching chemistry represents an important step toward transforming the educational process. Teaching chemistry has always been challenging due to the need to combine theoretical knowledge and practical experience, as well as the difficulties associated with understanding abstract concepts. Modern online tools, such as virtual laboratories, simulators, and online testing platforms, have become essential elements that allow for a harmonious combination of theory and practice, which is the basis of a systems approach. However, despite significant advances in the integration of these technologies, it is important to discuss some aspects of their application, including the challenges and prospects faced by teachers and students.

5.1. Benefits of a Systematic Approach to Using Online Tools

A systems approach allows for a more holistic and organized learning structure, where each element interacts with the others. For example, virtual labs and simulations enable students to actively participate in the learning process, model chemical reactions, and experiment with different conditions. These tools make the learning process interactive and visual, which positively affects student performance and motivation.

In addition, the systems approach supports the individualization of learning, as online platforms allow students to work at their own pace, review complex topics, and receive feedback. Personalized learning paths help students master the material more deeply and promote the development of analytical thinking, as each student has the opportunity to choose the most effective methods of interaction with the material.

5.2. Current Issues and Challenges

Despite their obvious advantages, the implementation of online tools faces several challenges and limitations. First, there is a need to train teachers to work with digital technologies and create specialized teaching materials, which requires time and money. Moreover, to fully utilize virtual laboratories and simulators, it is necessary to have access to stable internet and equipment, which can be a problem for remote regions and students with disabilities.

Another challenge is the quality and relevance of online resources. Many existing platforms contain outdated information, and their interfaces are not always user-friendly. Teachers must adapt materials to the curriculum and independently monitor the quality of the content, which increases the workload. Therefore, the successful implementation of an integrated approach requires the support of educational institutions to ensure the quality and availability of online resources.

5.3. Impact on Education Quality and Educational Outcomes

Research shows that students who use online tools systematically demonstrate higher levels of understanding and practical skills than those who use traditional teaching methods. Online tools allow students to see molecular interactions, model reactions, and receive immediate feedback, which enhances learning. Virtual laboratories and interactive simulations, as shown by research by Smetana and Bell [11], allow students to immerse themselves in real-world situations and develop decision-making and problem-solving skills that are difficult to replicate in a traditional learning environment. This article examines the benefits and challenges of using computer simulations in science teaching, including their effectiveness in supporting students' understanding of complex concepts and skill development.

Importantly, however, the use of online tools requires a balanced approach. Theory and practice should complement each other, as excessive enthusiasm for simulations without reference to theoretical foundations can lead to the mechanical assimilation of the material when students perform actions without a deep understanding. To prevent this, regular knowledge testing and control by the teacher, who can guide students to a deeper understanding of the processes, are necessary. A systems approach solves this problem by integrating online tools into the overall educational program and combining them with traditional teaching methods.

5.4. Prospects and Directions of Development

Given the current trends and needs of the educational system, the prospects for further development of online tools for teaching chemistry look promising. The development of artificial intelligence and augmented reality can make learning even more personalized and flexible. AI-based systems can adapt to the level of each student, suggesting more appropriate tasks, explanations, and tests, which will also allow teachers to pay more attention to the individual needs of students.

A promising direction is the integration of virtual and augmented reality (VR and AR) technologies, which will allow for an even deeper immersion in the study of chemistry. VR simulations help students visualize molecular structures in 3D, interact with molecules, and observe reactions, which makes the learning process more visual and memorable. Thus, owing to the development of technologies in the future, we can expect the creation of even more complex and comprehensive educational platforms that can take into account all the nuances of the learning process.

Using a set of online tools for teaching chemistry via a systems approach opens new horizons for the educational process. The advantages of this approach, including interactivity, flexibility, and personalization, make learning more effective, accessible, and interesting for students. Online tools provide the opportunity to visualize abstract concepts, conduct safe experiments in a virtual environment, and receive instant feedback, which contributes to a deeper assimilation of knowledge and the development of analytical thinking.

Moreover, using these tools effectively requires a thoughtful approach: integrating them into the learning structure, taking into account the level of students' preparation, and providing teachers with the resources and support to work successfully with them. A systems approach helps achieve this harmony by organizing learning as a holistic system, where each element contributes to the achievement of educational goals.

The future prospects lie in the adoption of modern technologies such as artificial intelligence and virtual reality, which promise to make learning even more adaptive and engaging. Despite these challenges, the future of using online tools in chemistry education will undoubtedly improve the quality of education and ensure inclusiveness and accessibility for all students.

The developed model for assessing the effectiveness of teaching chemistry using a system of indicators related to the teacher's level, digital equipment, and the number of students is a flexible and adaptive tool for optimizing the educational process. The main components of the model are functions.

$$f(L) = \alpha \cdot ln(L + 1)$$

$$h(S) = \gamma \cdot \frac{1}{S + 1}$$

– were chosen to adequately describe the influence of each of these factors. The logarithmic function for the teacher level, the root function for digital equipment, and the inverse relationship for the size of the group allow us to consider both the strong influence when moving from low to medium values and the saturation effect, in which a subsequent increase in indicators does not provide a linear increase in efficiency.

The introduction of this model into the educational process can contribute to a more accurate assessment and control of the level of digital support, the number of groups, and the level of teaching competencies. This can become the basis for managing the quality of the educational process and making management decisions aimed at improving the effectiveness of training. In the future, this model can be supplemented with other factors, such as the level of student preparation, the degree of student involvement, and the specific requirements of the chemistry course, which will make it more accurate and applicable to a wide range of educational conditions.

Thus, the proposed model provides flexibility and a systematic approach, allowing us to improve the educational process and adapt it to the needs of both students and teachers.

On the basis of the above, we believe that the most effective forms and methods of online chemistry teaching based on a systems approach are as follows:

The general paradigm of the complex online tools for teaching chemistry, taking into account the systems approach in the educational process, can be interpreted in the following graphic format:

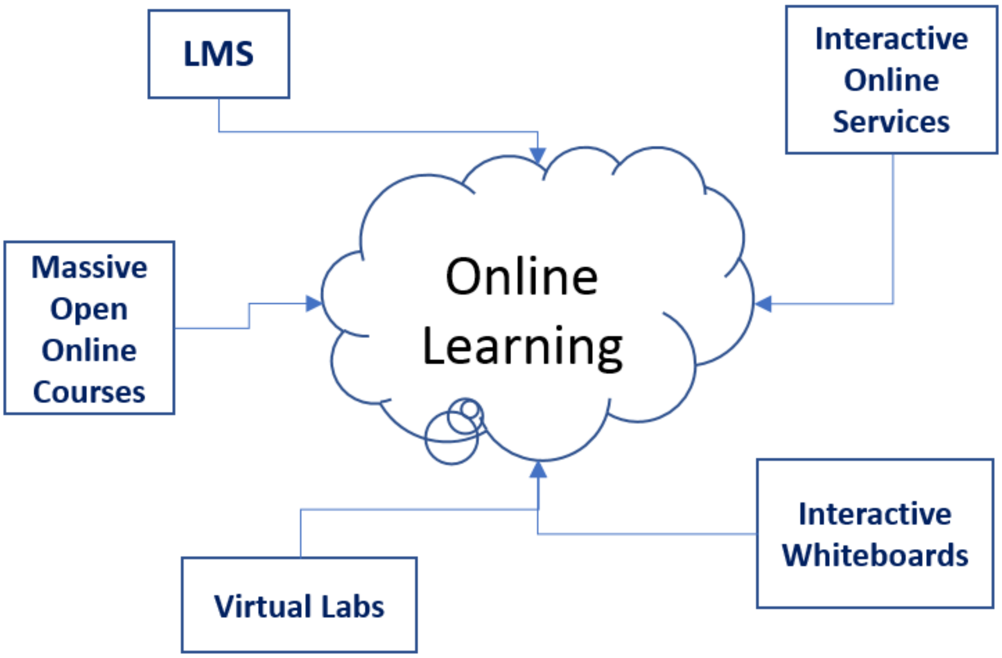

Figure 5.
The paradigm of complex online tools for teaching chemistry taking into account the systems approach in the educational process

Massive open online courses (MOOCs), interactive online services, and interactive whiteboards are among the most effective tools for education and self-education.
However, the best and most effective online tools are learning management systems (LMS) and virtual laboratories. The online chemistry education complex we reviewed is based on the principles of action and the concept of the LMS.

Laboratory practice in chemistry teaching remains the most important link in improving the quality and effectiveness of educational potential [29] and processing.

In real-time experimental practice with visual effects, it is quite difficult to delegate to the virtual online space in the context of authenticity and adequacy. Therefore, the most challenging problem in online, distance, and chemistry training is virtual laboratories.

However, the issue of using virtual laboratories can be completely resolved by utilizing the most modern technical and software tools. In particular, in the context of augmented and virtual reality glasses and 3D simulation packages such as Unity 3D and other software simulators. An integrated approach to this problem is often addressed through the use of virtual laboratory animations from the Iowa State Education Group [30, 31]. However, this is a question of the required level of financial support and professional staffing in computer modeling and animation.

The motivation of students and pupils in the context of their involvement in the online educational process is key to the effectiveness and efficiency of online learning. This motivation makes both real and virtual education effective in terms of academic performance. In this case, motivation is interpreted through involvement, interest, satisfaction, immersion, and a sense of belonging to the online educational process.

It is generally accepted that the motivation of students and learners is most influenced by blended course design, instructor support, the learning environment, and student characteristics [32-34].

However, we believe that the software and technical environment of online course implementation influences motivation significantly. In particular, the software and technical environment of implementation affects the immersion of the student and learner in the educational process. This involves the use of modern means of visualization and information transfer in the form of deep virtual immersion through augmented and virtual reality glasses or 3D effects.

In particular, augmented reality technologies can be effective in traditional education when additional or explanatory information is superimposed on real experiments. We believe that such hybrid learning is most effective in the process of teaching chemistry.

In this sense, one can pay attention to a modern paradigm known as the *"Four-Dimensional Education System." The essence of this concept is clearly expressed in the words of* Schleicher [35]*: "Four-Dimensional Education provides a clear and actionable, first-of-its-kind organization of the framework of competencies needed for this century. Its main innovation is not to present yet another universal list of what people should learn but to clearly define the spaces in which teachers, curriculum planners, policymakers, and learners can determine what students should learn—in their context and for their future"[36]*.

The proposed model for assessing the effectiveness of teaching chemistry using a system of indicators of the teacher's level, digital equipment, and number of students is a flexible and adaptive tool for optimizing the educational process. The main components of the model, functions f(L), g(D), and h(S), were chosen to adequately describe the influence of each of these factors. The logarithmic function for the teacher's level, the root function for digital equipment, and the inverse relationship for group size allow us to consider both the strong influence when moving from low to medium values and the saturation effect, in which a subsequent increase in indicators does not provide a linear increase in efficiency.

The implementation of this model in the online educational process of teaching chemistry can contribute to more accurate assessment and control of the level of digital support, the number of groups, and the level of teaching competencies. This can become the basis for managing the quality of the educational process and making management decisions aimed at improving the effectiveness of training. In the future, this model can be supplemented with other factors, such as the level of student preparation, the degree of student involvement, and the specific requirements of the chemistry course, which will make it more accurate and applicable to a wide range of educational conditions.

The creation of a complex mathematical model for assessing the effectiveness of teaching chemistry, taking into account various factors, is a multifaceted process. The model proposed in this case includes key parameters: the level of the teacher (L), digital equipment (D), and the number of students (S). Each of these factors has a significant effect on the effectiveness of the educational process, but their influence is nonlinear and depends on a number of conditions.

1. Teacher level. The impact of teacher qualifications on learning outcomes was modeled using a logarithmic function, which allowed for the effect of diminishing returns. This corresponds to the realities of the educational process: increasing a teacher's qualifications from a low to an average level significantly improves learning, but at higher levels of qualification, the effect becomes less pronounced. This approach allows for the most accurate reflection of the impact of teacher qualifications, especially in a course that requires intensive teaching.
2. Digital enablement. The digital enablement model also considers the saturation effect, whereby initial access to basic digital resources (e.g., virtual labs and online platforms) significantly enhances the learning process, but further increases in enablement have a less pronounced effect. Utilizing a function rooted in DDD prevents a sharp decrease in effect and ensures a smooth increase in efficiency as digital resources expand.
3. Number of students. The effect of group size on training efficiency is modeled by an inverse function. This is because, with an increase in the number of students, the complexity of control and individual work with each student increases, especially in chemistry classes, which require significant attention from each student. The inverse function allows for teacher overload in large groups and reduces the effect of increasing the number of students. Such a model helps make decisions on optimizing group sizes and managing teacher workload, which is especially important for courses that require laboratory work and the demonstration of experiments.

Thus, this model allows for the consideration of different aspects of the effectiveness of the educational process in chemistry through a systemic approach, treating them as interacting variables. The weighting coefficients w1, w2, and w3 also add flexibility, enabling the model to be adapted to the specifics of the course, shifting the emphasis and adjusting the assessment of effectiveness to various conditions (for example, a high degree of independent work or an intensive study load).

The proposed model provides flexibility and a systematic approach, facilitating the improvement of the educational process in chemical sciences and adapting it to the needs of both students and teachers in the field of chemical sciences.

6. Conclusion

The findings of this study emphasize the relevance of addressing both global educational trends and specific challenges in teaching chemistry, making the results crucial for improving educational quality and enhancing the competitiveness of graduates. This research aims not only to improve learning outcomes but also to foster a flexible and inclusive educational environment where students can effectively master the material and where instructors can deliver high-quality education.

This approach is particularly pertinent given the increasing integration of online learning tools and the systematic adoption of online methodologies. The significance of this research direction can be summarized as follows:

- Digital transformation and online learning: The rapid shift to digital and online education necessitates tools that not only preserve but also enhance the quality of the educational process, especially in subjects such as chemistry, where theory and practice are closely intertwined.
- Pandemic-induced Shift: The transition to distance learning during the pandemic underscored the need for tools that compensate for the lack of physical interaction. This created a demand for virtual labs, simulators, and knowledge control platforms, enabling comprehensive online chemistry education.
- Resource constraints: Chemistry often requires significant resources for laboratory sessions, which may be limited by financial or technical constraints. Virtual tools provide safe, accessible, and cost-effective alternatives to physical labs.
- Personalized learning: Modern students demand personalized approaches. Online tools offer opportunities to learn at an individual pace, tailoring content and difficulty levels to students' specific needs.
- Accessibility and skill development: Online education expands access to quality resources for students in remote areas or those with limited mobility while also fostering critical and analytical thinking skills essential for chemistry professionals.
- Digital competencies: The demand for skills in digital tools, simulators, and modeling in chemistry and related fields makes their inclusion in education essential.
- Curriculum modernization: Many curricula struggle to keep up with rapidly changing technologies and educational demands. The integration of systematic approaches and digital tools bridges this gap.

On the basis of these observations, the primary goals of this research are as follows:

- Develop a model for assessing educational processes based on instructor qualifications, digital infrastructure, and student numbers.

- Practical skills can be enhanced through virtual laboratories that simulate chemical experiments to master complex topics.
- Ensuring inclusive access to education for students with disabilities and those from remote areas.
- Interactive simulators and experiments are employed to stimulate analytical and research skills.
- All educational tools are integrated into a unified system for comprehensive and consistent learning.
- Adaptive educational trajectories enable students to learn at their own pace while considering their individual needs.

To achieve these objectives, this study introduces a comprehensive model of online tools for teaching chemistry within a systematic framework. This model significantly enhances the quality, accessibility, and efficiency of chemistry education through the integration of advanced online technologies.

The comprehensive model is based on the integration and adaptation of fundamental principles of online education, such as inclusivity, modularity, adaptability, the integration of digital tools, skill-oriented learning, and systemic formalization. The development of this model involved several sequential steps:

1. Problem analysis: Identifying existing issues in chemistry education and integrating selective data into the model's framework.
2. Systematic Approach to Design: Developing a concept that integrates theoretical, practical, and visualization modules with tools for knowledge control and adaptive learning processes.
3. Mathematical Model Development: Designing an authentic, linear mathematical model to evaluate the effectiveness of education, incorporating instructor qualifications, digital infrastructure, and student numbers.
4. Architecture development: Creating the structure of the educational complex.
5. Modular Structure Design: Developing a modular framework that comprises theoretical, practical, visualization, control, and adaptive modules.
6. Nonlinear interaction model: Constructing a hypothetical model of parameter interaction while accounting for its nonlinear nature.
7. Adaptive System Design: Developing an adaptive system to individualize students' educational trajectories based on their knowledge levels and preferences.

Key Findings of the Study:

- A comprehensive model for integrating and adapting online tools for teaching chemistry through a systematic approach was developed.
- The most significant factors influencing the effectiveness of education were the instructor's qualification level, the degree of digital infrastructure, and the size of the study group.
- A boundary condition of the comprehensive model was highlighted: smaller groups are more conducive to an individualized approach.
- A mathematical model was developed to interpret the increase in learning effectiveness through optimization and proper adaptation of these parameters.
- The availability of high-quality online resources and stable internet access is a key factor for the successful implementation of these technologies.

The results of this study demonstrate that a systematic approach utilizing online tools significantly enhances the quality of chemistry education, increasing the flexibility and accessibility of learning. However, for maximum effectiveness, critical factors such as instructor preparation, access to digital resources, and optimization of group sizes must be addressed.

The study also identifies methodological and technical limitations in achieving the maximum effectiveness of the comprehensive model in online education. These include the following resistance factors:

- The need for instructor training in the use of digital tools.
- There is limited access to high-quality resources in some educational institutions.
- High financial costs for developing specialized educational platforms.
- The successful implementation of systematic approaches and online tools requires the necessary infrastructure, including stable internet connectivity, access to digital platforms, and technical support. Without these conditions, even the most advanced technologies may prove ineffective.
- The cultural and social characteristics of students must be considered. For example, limited internet access or restrictions on certain digital platforms in some regions may impact the successful adoption of online tools.

The findings of this research will play a pivotal role in modernizing the educational system, making it more flexible, accessible, and adaptable to the challenges of the modern world. These results provide a foundation for transforming not only chemistry education but also broader teaching approaches, with a focus on inclusivity, personalization, and technological advancement.

On the basis of the results and discussion, the following conclusions can be drawn from this work:

- The integration of various online tools, such as virtual laboratories, simulators, and testing platforms within a systematic approach creates a cohesive educational environment that enhances theoretical understanding, practical skills, and critical thinking in students.
- The ability to customize the learning process to meet the needs and pace of each student makes education more accessible, effective, and motivating.
- Virtual laboratories and simulator technologies overcome the limitations of traditional teaching methods. They provide safe and cost-effective conditions for conducting chemical experiments that may be impossible or challenging in physical laboratories.

- The effective implementation of online tools requires training instructors to use new technologies and equipping schools and universities with high-quality digital resources.
- Optimizing group sizes can foster more productive interactions between instructors and students, which is especially critical for laboratory and practical work.
- Integrating augmented reality and artificial intelligence into the educational process can significantly enhance visualization and personalization while also fostering analytical skills and independent work in students.

The key takeaway from this study is that employing a systematic approach and modern online tools makes chemistry education more effective, accessible, and adaptable to contemporary requirements. However, successful implementation requires comprehensive efforts, including instructor preparation, infrastructure improvements, and curriculum adaptation. This approach paves the way for transforming the educational process, making it more interactive, flexible, and outcome-oriented.

If the developed comprehensive model becomes an official or unofficial standard in online education, particularly in the context of practical implementation and integration into educational processes, it could lead to the following prospective outcomes and consequences:

- Inclusivity: The application of the comprehensive model will foster a more inclusive society where individuals with disabilities and students from remote regions have equal access to educational resources and opportunities for development alongside others.
- Accessibility and engagement: Integrating a comprehensive model, interpreted through a systematic approach and online tools, will make chemistry education more accessible, interactive, and motivating for students. This will help learners gain a deeper understanding of complex chemical concepts while developing essential practical and analytical skills.
- Enhanced educational outcomes: In the long term, such comprehensive models can increase the overall educational preparedness of students, equipping them with knowledge and skills that are in demand in the labor market, especially in scientific and technological fields.
- Personalized learning: The ability to adapt the educational process using a comprehensive model to individual student needs increases student engagement and motivation. Students can work at their own pace, leading to better material retention and reduced stress.
- Scalability to Other Disciplines: In the future, comprehensive models of personalized learning can be applied to other disciplines, broadening access to high-quality education for students with varying levels of preparedness and diverse needs.

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