Design and validation of a virtual reality-based training program for student learning on tractor-plough setup

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Abstract

This study focuses on developing and testing a virtual reality (VR) software system created in the Unity 3D environment, specifically designed to train students of agricultural specialities in the complex process of setting up a plough with a tractor. The project aimed to create an immersive and interactive simulator that enables students to practice essential skills related to the adjustment of agricultural machinery, simulating real field conditions. As part of the research, an in-depth analysis of the structural features of the tractor and plough was carried out, which made it possible to develop highly detailed 3D models and realistically simulate their interaction. An interactive control system was implemented, allowing the user to perform all necessary plough adjustment operations, such as changing the tillage depth and configuring the tractor's hitch system in longitudinal and transverse directions, using standard VR controllers. A key element of the program is the inclusion of various training scenarios. A comprehensive feedback and assessment system was developed to track the accuracy and sequence of student actions, task completion time, number of mistakes made, and the quality of the final result. This enables students to assess their progress and identify areas that require improvement objectively. The developed VR program was piloted at Poltava State Agrarian University with the participation of students majoring in H7 "Agroengineering". A comparative analysis between the experimental group (trained using the VR simulator) and the control group (trained using traditional methods) revealed a significant increase in learning efficiency. Students who used the VR simulator demonstrated higher levels of theoretical knowledge, reduced the time required to acquire practical skills, and significantly decreased the number of errors during actual adjustment procedures. In addition to improving training quality, using VR technologies contributes to substantial savings in material resources and enhances the safety of the educational process. The study results confirm the high potential of virtual reality as an innovative tool for developing practical skills in agricultural production and support its integration into the curricula of higher agricultural education institutions.

Keywords

virtual reality, Unity, training, agricultural education, simulator

1. Introduction

The modern agro-industrial sector requires specialists to possess theoretical knowledge and well-developed practical skills, particularly in the operation and adjustment of agricultural machinery. Setting up a plough with a tractor for operation is one of the key stages of spring fieldwork, directly affecting the quality of soil cultivation, fuel and resource use efficiency, and overall labour productivity [1]. Improper adjustment can lead to poor ploughing quality, increased wear of components, excessive fuel consumption, and, consequently, significant economic losses [2].

Traditional training methods, which include lectures and hands-on sessions with real machinery, have certain limitations [3]. Firstly, access to agricultural equipment is often restricted due to its high cost, large dimensions, and the need for specific conditions to conduct practical training. Secondly,

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training on real machinery involves safety risks for students (e.g., injuries, equipment damage) and significant time and resource expenditures for preparing the equipment and ensuring safety compliance. Moreover, real-life training conditions do not always allow for the simulation of a wide range of possible scenarios and errors that may occur during actual fieldwork [4].

In light of these challenges, there is a pressing need to develop innovative training approaches that enable students to effectively acquire and refine practical skills in a safe, controlled, and accessible environment. One of the most promising directions in this context is using virtual reality (VR) technologies. VR simulators can create realistic, immersive environments in which students can repeatedly practice the procedures for plough adjustment, experiment with different parameters, and correct mistakes without any negative consequences [5]. This fosters a deeper understanding of mechanical processes, enhances spatial awareness, and contributes to developing durable, practical skills.

2. Analysis of recent research and publications

In recent years, there has been a rapid increase in interest in the use of virtual and augmented reality technologies in the educational process [6, 7, 8]. This trend is driven by the recognition of VR's potential to enhance student engagement, visualise complex processes, and create conditions for effective practical skill development. A thorough analysis of the existing scientific literature makes it possible to comprehensively assess the current state of research in this field, identify key trends, and reveal gaps that require further investigation.

Several studies have been devoted to the application of VR in technical education. For instance, in [9], the use of VR is explored for training engineers in industrial equipment maintenance, demonstrating a significant reduction in training time and an improvement in learning outcomes through immersive fault simulation and the practice of troubleshooting procedures. Study [10] focuses on developing virtual laboratories for mechanical engineering students, enabling them to safely and efficiently assemble complex mechanisms and disassemble, thereby minimising the risk of damaging expensive equipment or potential injuries. The authors of [11] highlight the advantages of using VR simulators for training agricultural machinery operators, emphasising the reduction of risks associated with operating large machines and the conservation of resources (e.g., fuel, machinery wear), representing a significant economic benefit.

In the context of agricultural education, VR technologies have also been actively adopted. Article [12] reviews existing VR solutions for training in agricultural specialities, including simulators for tractors and harvesters. However, most available solutions primarily focus on machinery operation and basic fieldwork. At the same time, detailed adjustment of mounted implements—such as ploughs—receives insufficient attention or is presented in a simplified manner. Publication [13] describes a pilot project for the development of a VR module demonstrating the operation of irrigation systems, highlighting the potential of VR to visualise complex agrotechnological processes and helping students gain a better understanding of their underlying principles.

Special attention should be given to studies on developing VR applications using the Unity platform. Unity is one of the leading platforms for creating interactive 3D applications due to its flexibility and powerful graphics and physics simulation tools. Study [14] demonstrates the capabilities of Unity in developing realistic simulators for training in construction-related fields, where precise modelling of physical interactions and spatial perception plays a crucial role. In [15], the use of Unity for simulating complex engineering systems is explored, confirming its effectiveness in creating detailed and functional VR simulators.

The psychological aspects of learning through VR are equally important. Study [16] shows that the immersiveness of virtual environments significantly increases student engagement, improves information retention, and fosters the development of spatial thinking by allowing users to explore objects from multiple perspectives interactively. Virtual reality also provides a safe environment for experimentation, where mistakes have no real-world consequences, thereby reducing students' fear of failure and encouraging active learning [17, 18]. This is especially important when mastering complex practical skills, where the “cost of error” in real-life settings can be very high. Moreover, VR simulations can promote the development of critical thinking and problem-solving skills, as students are exposed to realistic scenarios and must independently find optimal solutions [19]. However, it is important to consider potential psychological factors, such as motion sickness, which may affect user comfort, or the risk of excessive immersion, which may require time-use monitoring [20].

Regarding pedagogical methods for using simulators, researchers identify several key approaches. Discovery learning, where students independently explore the virtual environment and uncover cause-and-effect relationships, has proven particularly effective in VR settings [21]. Scaffolding, which involves the gradual increase in task complexity and the provision of guidance during initial stages, is also well-implemented in virtual environments [22, 23]. Scenario-based learning allows for the simulation of real-world industrial situations, preparing students to handle various challenges [24]. Another critical aspect is feedback. An effective VR-based training program should provide immediate, clear, and constructive feedback on the learner’s actions, helping them correct mistakes and improve their skills [25].

Thus, despite significant progress in the application of VR in education and the availability of simulators for operating agricultural machinery, insufficient attention has been given to specific, detailed tasks such as the precise adjustment of complex agricultural implements. Existing tractor simulators often oversimplify the aspects of configuring mounted equipment or exclude them entirely. This creates a gap in specialist training, as the correct adjustment is critical for efficiently executing fieldwork.

Therefore, there is an urgent need to develop a specialised VR solution focused specifically on calibrating the plow with the tractor. This solution would enable students to master all necessary stages and nuances of this process while considering the psychological and pedagogical advantages of the virtual environment and minimising the aforementioned limitations.

3. Formulation of the research objective

The primary aim of this study is to develop and test a virtual reality software package on the Unity platform for effective training of students specialising in H7 “Agroengineering” in the adjustment of a plough with a tractor for operation, as well as to evaluate its effectiveness compared to traditional teaching methods.

To achieve this aim, the following objectives were formulated:

- to analyse the features and key stages of the plow adjustment process with the tractor, and to identify the main parameters requiring virtual simulation;
- to develop highly detailed 3D models of the tractor and plow, enabling accurate simulation of their interaction and adjustment mechanisms;
- to implement interactive user mechanisms for manipulation of virtual objects during the adjustment operations;
- to design instructional scenarios and algorithms that sequentially guide the student through the adjustment process, providing feedback and assessing the correctness of actions;
- to develop an assessment system for knowledge and skills acquired in the VR environment;
- to conduct testing of the developed software among the target group of students specialising in H7 “Agroengineering” and to compare the effectiveness of VR-based training with traditional methods;
- to analyse the test results and formulate recommendations for further improvement of the VR program and its integration into the educational process.

4. Results

4.1. Architecture of the software package

The developed virtual reality software package features a modular architecture, ensuring flexibility and potential for further expansion. The main components of the system include the following modules:

- visualisation module;
- interaction module;
- training scenarios module;
- physics simulation module;
- assessment module.

The Visualisation Module is responsible for rendering the 3D scene, including the models of the tractor, plough, terrain, and surrounding environment. It uses animation and physical models to depict the interactions between objects realistically.

The Interaction Module provides the interface for user interaction with the virtual environment via virtual reality controllers. It includes mechanisms for grabbing objects, manipulating them, and activating interactive elements.

The Training Scenarios Module contains sequences of steps required for configuring the plough. Each scenario involves a set of tasks that the student must complete. The module offers hints and feedback throughout the process.

Physics Simulation Module imitates the physical properties of objects (mass, friction, inertia) and allows visualisation of changes in the plough's position during adjustments.

Assessment Module tracks the student's progress by recording completed actions, errors, and task completion times. Based on this data, it generates a report on the learning outcomes.

The stereoscopic image creation is handled by the open-source package Google VR SDK for Unity [26]. This package is designed for developing virtual reality applications for hardware devices such as Google Cardboard (figure 1). In VR applications, the screen is split into two parts and exhibits a fisheye effect. Combined with distortions from Google Cardboard's plastic lenses, this creates the illusion of image depth and maximises immersion in the virtual reality.

This package contains prefabs that control VR mode settings, one of which is adapting the screen to the Cardboard lenses. Additionally, the prefabs receive data from the smartphone's gyroscope to track head tilts and rotations. Thus, when the user turns their head, the camera in the video player also rotates accordingly.

4.2. Development of 3D models and virtual environment

Detailed 3D models of the MTZ-80 traction class tractor and the two-furrow plough type PN-2-30 were used to ensure a high degree of realism. Such models can be created using CAD software or Blender, considering real agricultural machinery's precise dimensions and structural features. Developing a digital twin of any agricultural machine, especially a tractor with many parts, is a highly complex technical and technological task [27]. Therefore, for our educational project, we utilised freely available 3D electronic models of the John Deere 6195M tractor [28] and a two-furrow plough [29]. Special attention was paid to the units directly involved in the adjustment process during the development of the VR application: the tractor's hitch system, the depth regulation mechanism, the moldboards, and the field board.

The virtual environment simulates an agricultural hangar with a realistic floor texture. Quality lighting conditions were considered to maximise immersion.

4.3. Implementation of adjustment mechanisms

The core of the adjustment functionality is based on an interactive system. Each adjustable element on the plough and tractor is implemented as a separate interactive object with corresponding scripts.

Figure 1: Training equipment such as Google Cardboard: 1 - VR-glasses; 2 - clamp and phone with the developed application.

Figure 2 shows the virtual avatar as a green capsule. The avatar is designed to move around the hangar and interact with the necessary components of the tractor and plough.

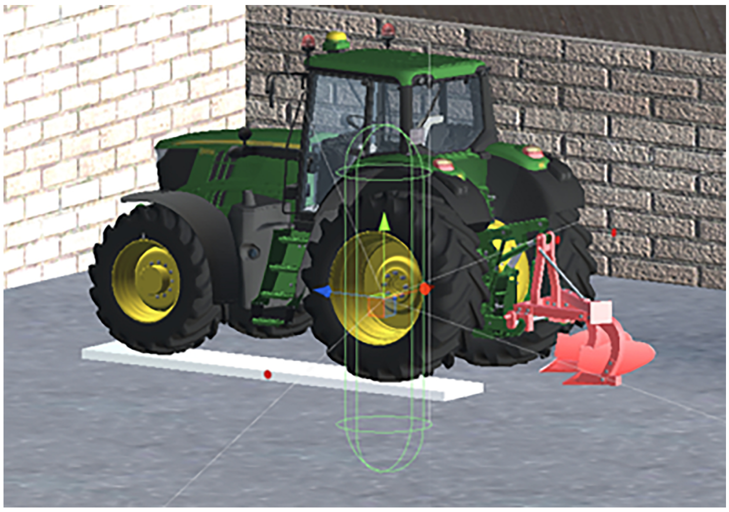

Figure 2: VR avatar layout.

To interact with the interactive components of the models, the avatar must aim its white reticle at a red marker. The red markers, indicated by red dots on the models, activate information panels at the appropriate moments for further adjustment [5]. These red markers are positioned to implement the following key adjustment operations of the tractor-machine aggregate:

- Depth of plowing adjustment (figure 3) is achieved by changing the height of the beam under the tractor's left wheels, which visually alters the penetration depth of the ploughshares.

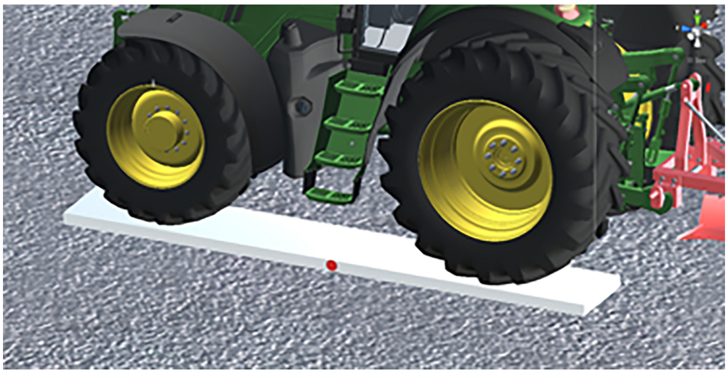

Figure 3: Ploughing depth adjustment.

- Aligning the plough horizontally in the longitudinal direction (figure 4) involves adjusting the upper link so that the plough frame is parallel to the ground along the plough frame.

Figure 4: Horizontal levelling of the plough in the longitudinal direction.

- Horizontal levelling of the plough in the transverse direction (figure 5) involves adjusting the left and right braces to ensure that the plough frame is parallel to the ground across the width of the plough.

- The working width adjustment (figure 6) involves adjusting the distance between the plough bodies.

Each user action is accompanied by visual feedback. For example, a green tick appears when the adjustment is correct, and a red cross appears when incorrect.

4.4. Development of training scenarios and evaluation system

Several training scenarios of varying difficulty levels were developed for the educational process.

Scenario 1: Initial Plough Setup.

This scenario covers basic operations such as attaching the plough to the tractor, primary adjustment of the ploughing depth, and checking the horizontal alignment.

Scenario 2: Diagnosis and Troubleshooting of Setup Issues.

This scenario simulates common setup errors (e.g., plough tilt, uneven ploughing depth), and the student must independently identify and correct them.

The evaluation system automatically records:

Figure 5: Horizontal levelling of the plough in the transverse direction.

Figure 6: Adjusting the working width of the plough.

- total time spent by the student to complete the scenario;
- number of incorrect actions performed by the student;
- correctness of completed steps and the percentage of correctly performed operations.

At the end of each scenario, the students receive a detailed report on their performance, which allows them to analyse their mistakes and improve their skills.

4.5. Program testing

The developed VR program was tested at the Poltava State Agrarian University with students of the H7 "Agroengineering" speciality during the course "Mechanisation of Agricultural Production." Two groups were formed: an experimental group (120 students) using the VR simulator for training, and a control group (129 students) that underwent traditional training methods (lectures, demonstrations on real equipment). Both groups took an initial test to assess their baseline knowledge of plough adjustment. Then, the experimental group completed two training sessions using the VR simulator (figure 1), practising all developed scenarios. During the same period, the control group received traditional practical lessons. At the end of the training cycle, both groups underwent a final assessment, which included theoretical questions and a practical task on a real plough (where possible, or through detailed description and evaluation of the student's actions). The following parameters were evaluated:

- average score on the theoretical test;
- time spent on adjusting the tractor-plough unit;
- number of errors made during the adjustment;
- quality of adjustment of the tractor-plough unit (according to expert assessment by the instructor).

To confirm the study's effectiveness, it is necessary to formulate a null hypothesis and test it. The essence of hypothesis testing lies in determining whether the results of a sample are consistent with the hypothesis and whether the observed differences are random or statistically significant. Each hypothesis testing problem begins with formulating the main and alternative hypotheses. The main hypothesis is called the null hypothesis and is denoted as H0. At the same time, an alternative hypothesis H1 is considered, which competes with the null hypothesis. The null hypothesis H0 is tested using statistical methods, which is why it is referred to as statistical hypothesis testing. The rule by which the decision is made to accept or reject the statistical hypothesis H0 is called a statistical criterion.

The Pearson's chi-square test was chosen for this study, as it ensures the lowest probability of a Type 2 error compared to other goodness-of-fit tests. The criterion is based on a comparison of theoretical and empirical frequencies.

In our study, we propose the null hypothesis H0: the developed application does not influence students' learning outcomes during the laboratory work in the course "Mechanisation of Agricultural Production." The alternative hypothesis H1 states that the developed application's use does influence the level of students' learning outcomes on the above topic.

A total of 249 students majoring in H7 "Agroengineering" at Poltava State Agrarian University participated in the experiment. Homogeneous academic groups were selected for the experiment: experimental groups (EG) and control groups (CG). The control group included 129 students, while the experimental group had 120 students.

Students in both EG and CG were categorised according to their learning achievement levels based on a 4-point grading scale:

- "High" (A) – high level;
- "Sufficient" (B, C) – sufficient level;
- "Initial" (D, E) – average level;
- "Low" (FX, F) – low level.

The experiment was conducted during the 2024–2025 academic year. During this period, many air raid alerts occurred, during which students had to leave laboratories and move to shelter areas. While in shelters, the learning process continued through distance learning technologies — students watched educational videos and took notes on theoretical material. At the same time, students from the experimental group additionally used the developed application to gain practical skills in adjusting a machine-tractor unit to the specified ploughing depth. The objectivity of the experiment was maintained by implementing a unified testing system to assess learning achievements across all students.

The data characterising the students' performance on the topic were collected after the formative stage of the experiment and are presented in table 1. It should be noted that the results in table 1 reflect only the outcomes of the first test and do not include any retakes of the topic.

In the experimental group (EG), the number of students who achieved a high level of academic performance increased by 9%. Additionally, the number of students with a low level of achievement

Table 1
Comparative analysis of students' academic performance on the topic "Adjustment of the Machine-Tractor Unit to a Specified Plowing Depth".

Group	Number of students	Levels of academic achievement								Average score
		High		Sufficient		Medium		Low		
		Num.	%	Num.	%	Num.	%	Num.	%	
CG	129	7	5%	47	36%	60	47%	15	12%	3.36
EG	120	17	14%	43	36%	55	46%	5	4%	3.60

decreased threefold. The positive trend in the average performance score among students in the experimental group indicates a higher level of learning outcomes formed during the study of the topic "Adjustment of the Machine-Tractor Unit to a Specified Plowing Depth" through the use of the VR application.

The performance level indicators of the students at the end of the topic are shown in the diagram (figure 7).

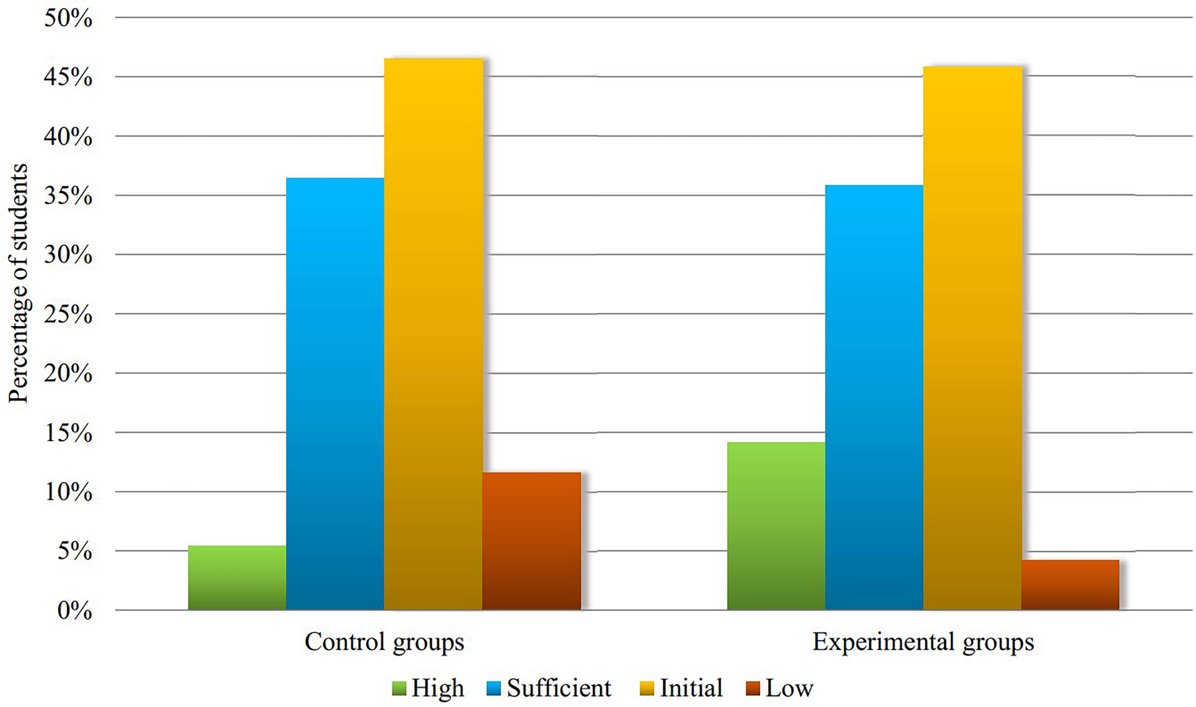

Figure 7: Diagram of students' learning achievements at the end of the pedagogical experiment.

To test the hypothesis, we conducted a pairwise comparison of the levels of academic achievement of students in the control and experimental groups. The results were processed using Pearson's criterion [30].

Find the value of the statistic χ^2_{emp} according to the formula:

$$\chi^2_{emp} = \sum \frac{(n_{ij} - np_{ij})^2}{np_{ij}}, \tag{1}$$

where n_{ij} – empirical frequency, np_{ij} – theoretical frequency:

$$np_{ij} = \sum \frac{(R_i \times C_j)}{N}, \tag{2}$$

Where R_i – total sum for row i, C_j – total sum for column j, N – total sum of all variants.

We obtained $\chi^2_{emp} = 9.25$.

According to statistical tables for the level of significance α = 0.05 degrees of freedom for k = (4 − 1)×(2 − 1) = 3 we find the critical value of the test statistic $\chi^2_{crit}(\alpha = 0.05; k = 3)$:

$$\chi^2_{crit}(0.05; 3) = 7.81.$$

We found that

$$\chi^2_{emp} > \chi^2_{crit}.$$

The calculated data are presented in table 2.

Table 2
The results of the study of the level of students' learning achievements on the topic "Adjustment of the machine-tractor unit to a given plowing depth" after the experiment are presented.

Level	EG, n_{ij}	CG, n_{ij}	EG, np_{ij}	CG, np_{ij}	EG, χ^2_{ij}	CG, χ^2_{ij}
High (A)	17	7	11.566	12.434	2.553	2.375
Sufficient (B, C)	43	47	43.373	46.627	0.003	0.003
Initial (D, E)	55	60	55.422	59.578	0.003	0.003
Low (FX, F)	5	15	9.639	10.361	2.232	2.077
Total	121	123				$\chi^2_{emp} = 9.25$

The obtained result is the basis for rejecting the null hypothesis H0 and accepting the alternative hypothesis H1 about the positive impact of the developed VR application on students' learning achievements during laboratory work in the discipline "Mechanisation of agricultural production".

5. Conclusions

The results of the pilot implementation demonstrated the significant effectiveness of the developed virtual reality (VR) program for teaching students how to adjust a plough mounted to a tractor for operation. Students in the experimental group showed higher performance in theoretical testing and significantly better practical skills compared to the control group. The average score on the theoretical test in the experimental group was 3.6, whereas in the control group it was 3.36.

The number of mistakes made during plough adjustment in the virtual environment was minimal, allowing students to experiment and learn from their errors safely without real-world consequences. The experimental group made fewer critical mistakes during the practical task using a real plough.

Students in the experimental group demonstrated a high level of interest and motivation in learning, highlighting the interactivity and realism of the VR application. The use of the VR simulator also contributes to resource savings (fuel, machinery wear, and instructor time) compared to traditional training on real agricultural equipment.

The developed software package has proven to be an effective tool for training future specialists in the agricultural sector, enabling them to acquire practical skills in a safe, controlled, and realistic environment. Future research may focus on expanding the simulator's functionality (e.g., adding other types of agricultural machinery, simulating various weather conditions), integrating it with distance learning systems, and developing adaptive learning scenarios tailored to students' individual needs.

Author contributions

Conceptualization, Oleksandr Kanivets and Irina Kanivets; methodology, Oleksandr Kanivets and Oleksii Burlaka; software, Oleksandr Kanivets and Irina Kanivets; validation, Oleksandr Kanivets, Irina Kanivets, Oleksii Burlaka, and Oleksandra Bilovod ; formal analysis, Irina Kanivets; investigation, Oleksandr Kanivets, Irina Kanivets, Oleksii Burlaka, and Oleksandra Bilovod; data curation, Sofiia

Pidhorna; writing—original draft preparation, Oleksandr Kanivets and Irina Kanivets; writing—review and editing, Sofiia Pidhorna, Oleksii Burlaka, and Oleksandra Bilovod; visualization, Oleksandr Kanivets and Irina Kanivets; project administration, Oleksandr Kanivets. All authors have read and agreed to the published version of the manuscript.

Declaration on Generative AI

During the preparation of this work, authors used GPT-4 in order to: Grammar and spelling check. After using these services, authors reviewed and edited the content as needed and takes full responsibility for the publication's content.

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