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The use of digital microscopes for studying physical phenomena: New opportunities for school education

Abstract. The modern educational process requires the introduction of the latest technologies that contribute to a better understanding of complex scientific concepts. The use of digital microscopes opens up prospects for developing practical skills, improves students' analytical thinking, and supports the integration of physical phenomena with the real world. This study was devoted to the analysis of the possibilities of using digital microscopes in teaching physics at school. A series of experiments was conducted aimed at determining the dependence of the rate of chaotic motion of particles on the viscosity of the medium. The use of video analysis software established that as the milk concentration decreases, the particle velocity increases, which is consistent with the Stokes-Einstein model. In addition to the experimental part, a survey was conducted among students and teachers to assess the effectiveness of using digital microscopes in the educational process. The results showed that 85% of students suggest that digital microscopes have made studying physics more interesting, and 78% said that observing microscopic phenomena has contributed to a deeper understanding of theoretical material. The analysis of students' academic achievements showed an increase in the level of knowledge and improved academic performance in comparison with conventional teaching methods. The results confirmed the feasibility of integrating digital microscopes into physics curricula, especially in STEM education. It was proposed to develop methodological recommendations for the introduction of digital microscopy in the school physics course. The results of the study can be used by physics teachers of general education institutions to improve the effectiveness of teaching, developers of educational programmes for integrating digital microscopy into a school physics course, and in STEM centres and scientific communities to develop practical research skills in students

Keywords: Brownian motion; molecular kinetic theory; educational technologies; methodological recommendations; STEM education

INTRODUCTION

The modern education system requires the introduction of the latest technologies to improve the efficiency of the educational process. Conventional methods of teaching physics do not always allow students to have a deep understanding of complex physical phenomena and processes. One of the main problems is that many phenomena occur at the microscopic level, and therefore, they cannot be directly observed with the unaided eye. This significantly complicates the understanding of such branches of physics as molecular physics, thermodynamics, electricity, and optics.

The use of digital microscopes opens up new possibilities for visualising and analysing physical phenomena. As noted by S.J. Pennycook *et al*. (2024), they allow researchers to directly observe microscopic structures, processes, and interactions that contribute to shaping a scientific worldview. In addition, digital microscopy provides an opportunity to record, analyse, and compare the results of observations, which is an important aspect in the current research approach to learning. The use of digital microscopes in the school physics course remains poorly understood.

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However, there is a lack of developed guidelines for using digital microscopes in physical experiments, integrating them into curricula, and creating appropriate training materials. Especially important is the issue of effective organisation of practical classes using digital microscopy and their adaptation to different levels of training of students (Yurchenko *et al.*, 2023). In the modern educational space, it is important to create an interactive learning environment that allows students to experimentally confirm theoretical knowledge and develop research skills. The use of digital microscopes can contribute to the development of critical thinking, the ability to analyse data, and skills in working with modern technologies. Given the global digitalisation of education, the integration of digital microscopy into the educational process is an important step in training future scientists and technicians.

In Ukraine and abroad, research related to the use of digital technologies in teaching academic subjects, including physics, is actively developing. R.L. Bell *et al.* (2008) proved that the use of digital microscopes contributes to better understanding by students of the molecular structure of substances. O.B. Budnyk *et al.* (2020) examined the use of digital technologies in inclusive education. The researchers analysed the current state of implementation of digital tools in the educational process for children with special educational needs, identified the main problems associated with this, and outlined the prospects for the development of such technologies in the future. Analysing the results of experimental implementation of digital microscopy in educational institutions, the researchers came to the conclusion that interactive learning increases the motivation of schoolchildren to study natural sciences. I. Doroshenko (2022) highlighted the integration of digital microscopes into optics training programmes. The researcher noted that the use of digital methods allows students to better understand the phenomena of interference and diffraction of light, and conduct experimental studies with high accuracy. The study by S. Hughes *et al.* (2019) examined the use of digital microscopes in STEM education. The researchers emphasised that their application contributes to the development of practical skills of students, helps them to apply theoretical knowledge in practice, and prepares them for future research activities.

The study by P. Whalley *et al.* (2010) analysed the possibilities of using digital microscopes in distance learning. The researchers proved that virtual laboratories based on digital microscopes help students to conduct experiments even in a remote format, while maintaining the quality of learning. O.V. Zholos (2020) examined the role of digital microscopes in the study of biophysics. The researcher noted that such technologies allow analysing the cellular structure in more detail, which is important for the integrated study of physics and biology.

The study by Y. Omelchenko (2024) examined the effectiveness of digital microscopes in the study of thermodynamics. The researcher argued that they can be used to demonstrate phase transitions and visualise the processes of evaporation and condensation. L. Potapiuk & O. Dymarchuk (2021) highlighted the adaptation of digital microscopes for students with visual impairments. The researchers offered special methods of image processing and increasing contrast, which makes teaching physics more accessible to all categories of students. Thus, researchers confirmed the effectiveness of using digital microscopes in teaching physics. However, the method of their application in the context of experimental physics remains insufficiently covered, which opens up opportunities for further research in this area. Thus, Y.T. Chien (2017) examined the effectiveness of digital microscopy in teaching natural sciences and confirmed that the integration of such technologies contributes to improving students' research skills and increases their motivation.

Despite the advantages of digital microscopes in teaching natural sciences, there is a lack of methodological developments for their effective use in physics lessons. It is necessary to determine which topics of the school physics course can be enhanced with a digital microscope, and develop specific methods for its application. Special attention should be paid to adapting digital microscopes to educational standards, preparing appropriate educational materials, and creating interactive tasks. The purpose of the study was to analyse the possibilities of using a digital microscope in physics lessons, and to develop methodological recommendations for its effective implementation in the educational process.

MATERIALS AND METHODS

The study used a comprehensive approach that included theoretical analysis of scientific sources, experimental investigation of physical phenomena using digital microscopes, sociological methods of collecting information (questionnaires), and a comparative analysis of student performance. The experiments were conducted as part of school laboratory classes in physics, where the influence of the viscosity of the medium on the speed of chaotic motion of particles (Brownian motion) was analysed. A digital microscope was used to provide video recording of particle trajectories, and the Tracker software for motion analysis. The study was conducted on milk solutions with distilled water in various concentrations (1:10, 1:15, 1:20). To assess the effectiveness of using digital microscopes in the educational process, an anonymous survey of students and teachers was conducted. The survey lasted from September to November 2024. Number of respondents: 150 students in grades 9-11 and 5 physics teachers from various educational institutions of the community. Questionnaire structure:

1. For students: the level of interest in physics before and after experiments, the impact of digital microscopy on understanding the material, the ease of use of equipment.

2. For teachers: assessment of the methodological convenience of digital microscopes, their impact on student performance, and the possibility of integration into curricula.

The study was conducted in compliance with ethical standards, including the principle of voluntary participation, anonymity, and confidentiality of responses. Prior to the survey, students and their parents received newsletters about the research objectives. The results of the survey helped to assess the feasibility of integrating digital microscopes into the educational process and their impact on students' motivation and understanding. To assess the impact of digital microscopes on the level of assimilation of the material, an experimental study was conducted, which included a comparison of two groups of students: the control group (conventional training) – studied according to the standard method, which provided for the use of textbooks, traditional demonstration experiments, and explanations of the teacher; the experimental group (digital microscopy) – worked with digital microscopes that allowed visualising and analysing physical phenomena.

Students of the control group mastered the topic of Brownian motion in the conventional way: explaining theoretical material, viewing diagrams and illustrations in the textbook, performing standard calculation tasks. Students in the experimental group additionally used digital microscopes to observe the chaotic movement of particles in solutions with different viscosities, and also analysed the data using the Tracker software. After completing the training cycle, students of both groups completed a test task that contained theoretical questions (determination of Brownian motion, factors affecting it); practical tasks (analysis of particle trajectories, calculation of their average speed based on the data obtained).

During the survey, all the necessary ethical standards specified in the Declaration of Helsinki (2013) were observed. In particular, the principle of voluntary participation was ensured – students and teachers participated in the survey at their own request. Anonymity and confidentiality of responses were guaranteed, which contributed to obtaining objective results. Before starting the survey, all respondents received newsletters explaining the goals and conditions of the survey. In addition, the students' parents were informed about the study, which allowed them to consider all aspects of ethical responsibility.

RESULTS AND DISCUSSION

Digital technologies are significantly changing the teaching methods of natural sciences, especially physics. One of the most effective tools for visual demonstration of physical phenomena is the digital microscope, which allows students to observe microscopic structures, analyse complex processes, and conduct their own research (Lavrova, 2013). The use of a digital microscope in teaching physics opens up new opportunities for improving the quality of learning, in particular: it increases the level of understanding of abstract concepts, because students can directly observe phenomena that were previously only read in textbooks; it stimulates interest in experimental work, since students can independently conduct research and analyse their results; it promotes the development of analytical thinking, because students not only observe phenomena, but also draw conclusions based on the data obtained; it increases the effectiveness of STEM education, because digital microscopy is integrated with other sciences, such as chemistry, biology, and computer science (Dickerson & Kubasko, 2007).

Conventional methods of teaching physics include the use of diagrams, illustrations, demonstration experiments, or watching videos. However, they do not always allow students to independently observe and analyse physical phenomena, which can reduce the level of understanding of the material (Banchi & Bell, 2008; Jonassen, 2011). The use of digital microscopes in the educational process allows conducting research experiments in physics lessons, combining theoretical material with practical work; involve students in active learning, because they directly interact with the material, and not just perceive it passively; use software to analyse the obtained images, which contributes to the development of skills in working with digital technologies; provide interactive learning that meets modern educational requirements (Rieber, 2005; Koehler & Mishra, 2009).

The use of digital microscopes can be effective in the following formats of the educational process: demonstration experiments (using a microscope when explaining new topics; displaying images on an interactive whiteboard or screen for analysing physical structures and phenomena; comparing the results of observations with theoretical calculations); laboratory work (visualisation of Brownian motion of particles in different environments; studying the structure and properties of thin films, optical lattices, materials; analysis of microstructures of conductors and semiconductors in the study of electricity and magnetism); project research (creating individual or group projects involving the use of digital microscopy for studying natural phenomena; study of changes in the microstructure of materials under the influence of various factors; use of digital microscopes in studies of environmental problems, such as the analysis of water micro-contamination, etc.) (Abdusselam & Kilis, 2021; Kozhevnikova & Kozhevnykov, 2024). The digital microscope was used to study physical phenomena, in particular, the Brownian motion of particles in liquids with different viscosities. Its application helped to observe microscopic processes and also quantify the movement of particles using special software (Levsheniuk & Tyshchuk, 2009). A digital microscope allowed directly observing the chaotic motion of suspended particles in each solution (Fig. 1).

1. At a high concentration of milk (1:10), the particles moved slowly, their trajectories were short due to the high viscosity of the medium.

2. At an average concentration (1:15), the movement of particles became more active, and their trajectories became longer.

3. At a low concentration (1:20), the particles moved rapidly, randomly changing direction.

Brownian motion at concentration 1:10 Brownian motion at concentration 1:15 Brownian motion at concentration 1:20

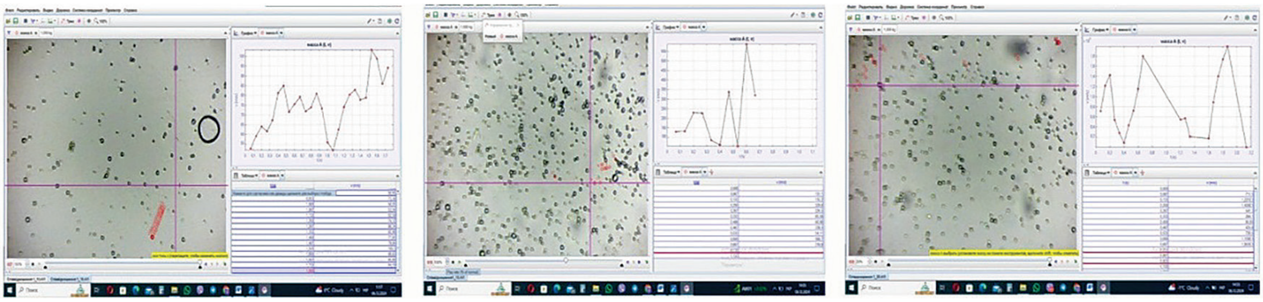

Figure 1. Visualisation of Brownian motion at different particle concentrations

Source: developed by the author based on the conducted research

The results of the study corresponded to the Stokes-Einstein model, according to which the velocity of particles in Brownian motion is inversely proportional to the viscosity of the medium. To assess the impact of a digital microscope on the educational process, a survey was conducted among students. Aspects such as the level of interest in physics before and after using a digital microscope; understanding of the topic "Molecular kinetic theory"; confidence in conducting laboratory research; ability to perform tasks for analysing experimental data were evaluated. The results are presented in Table 1.

Table 1. Influence of a digital microscope on the quality of learning material assimilation

Parameter	Before using a digital microscope (%)	After using a digital microscope (%)
Level of interest in physics	52	85
Understanding the topic "Molecular kinetic theory"	60	82
Confidence in laboratory work	45	78
Performing tasks for analysing experimental data	48	80

Source: developed by the author based on the survey conducted

The data show that after the integration of the digital microscope, the level of interest in physics increased by 33% – students began to perceive the subject not only as a set of formulas and theoretical concepts, but also as a science that can be directly studied. Understanding of the topic of molecular kinetic theory has improved by 22% – due to the ability to observe the chaotic motion of particles in different environments. Confidence in conducting laboratory tests increased by 33% – students were able to work with real experiments and analyse the results. The ability of students to analyse the results of experiments increased by 32%, which confirms the development of critical thinking skills and practical application of knowledge.

To evaluate the effectiveness of the digital microscope compared to other training methods, an additional study was conducted. Students were divided into two groups: control and experimental. After completing the study of the topic, students of both groups completed test tasks. The results obtained indicate a significant advantage of digital microscopy: conventional methods – 68 points, the use of a digital microscope – 86 points. The data confirm that students in the experimental group learned the material 26% better than those who studied in the conventional way. Student reviews confirmed the effectiveness of digital microscopy:

- "I never thought physics could be so interesting! We did not just learn theory, we explored the microcosm ourselves".
- "I did not like lab work before, because it seemed complicated. But the digital microscope has made them interesting and understandable".
- "It was very interesting to observe the chaotic movement of particles and draw conclusions yourself. Now I know exactly how molecular kinetic theory works".

Digital microscopes allow teachers to significantly improve the quality of teaching physics, as they provide visibility of educational material, make laboratory work more accessible, and help to increase students' motivation. Respondents noted the following key aspects of the impact of digital microscopes on the educational process: increasing student motivation (85% of respondents), because students showed a greater interest in performing experimental tasks, since they could directly observe physical phenomena; reducing the complexity of teaching physical topics (78%), when teachers noted that explaining complex topics, such as molecular kinetic theory or wave phenomena, became much easier due to visualisation; developing students' practical skills (80%), because the use of digital microscopes allowed students to acquire skills in working with scientific equipment, which is an important element of STEM education; improving the ability to work with scientific equipment, which is an important element of STEM education; academic performance (75%), since students who worked with digital microscopes showed better results during tests, as they learned the material more deeply and at a practical level. To evaluate the effectiveness of digital microscopes in teaching physics, a comparative analysis of various teaching methods was performed (Table 2).

Table 2. Results of comparative analysis of various teaching methods

Training method	Improved understanding of the material (%)	Increased interest (%)
Conventional lectures	50	45
Demonstrations without interaction	60	55
Laboratory work without a digital microscope	70	65
Using a digital microscope	85	82

Source: developed by the author based on the survey conducted

These results show that the use of a digital microscope is the most effective method among those analysed. This is conditioned by the fact that students not only listen to theoretical material, but also have the opportunity to actively work with experimental data. In addition to statistics, comments were collected from teachers who implemented digital microscopes in their physics lessons:

- "Students became more attentive during laboratory work, as they were interested in observing microscopic processes with their own eyes".
- "Previously, it was difficult for scientists to imagine exactly how Brownian motion occurs, but now they can observe it independently. This greatly improved the understanding of the material".
- "Digital microscopes enable students to work with modern technologies, which is an important factor in preparing for future professions in science and technology".
- "I noticed that students who worked with digital microscopes became more confident in conducting research and analysing the results".

From a pedagogical standpoint, the digital microscope has the following advantages: simplification of the process of teaching complex topics (teachers can quickly demonstrate physical phenomena to students in real time; the use of interactive technologies increases the effectiveness of lessons); optimisation of laboratory work (digital microscopes allow for detailed analysis of the results obtained; teachers can record the results of experiments in digital format for further analysis); the possibility of individual and group training (students can work both independently and in groups, discussing the results obtained; this contributes to the development of communication and teamwork skills); compliance with modern educational standards (digital technologies are a key component of STEM education; the use of digital microscopes contributes to the preparation of students to modern technological challenges). Given the positive feedback from teachers and the high learning outcomes of students, digital microscopes have great potential for further development in the field of education.

For the effective implementation of digital microscopes, it is advisable to develop methodological recommendations for their use in school physics courses; conduct trainings and advanced training courses for teachers to help them use digital technologies effectively; integrate digital microscopes into STEM education, creating interdisciplinary projects that combine physics, biology, chemistry and computer science; provide schools with the necessary equipment and maintain its maintenance. The results of our study on the impact of digital microscopes on the quality of physics teaching demonstrate a significant improvement in understanding the material, increasing students' motivation, and developing their research skills. The data obtained correlate with the results of other researchers who also analysed the effectiveness of digital technologies in school education. Thus, this study showed that the level of interest of students in physics after using a digital microscope increased from 52% to 85%, which is consistent with the conclusions of R. Kuznetsov (2022), who analysed the impact of digital technologies on teaching physics in secondary schools. The researcher showed that the integration of interactive learning tools helps to increase students' motivation to study complex topics in physics.

The study by S. Hughes *et al.* (2019) also confirmed that the use of digital microscopes in STEM education encourages students' interest in experimental work. The researcher noted that the interaction of students with real physical processes contributes to their active participation in the educational process. The above results support this conclusion, as 85% of students indicated that observing phenomena through a digital microscope made physics lessons more interesting and accessible. The data obtained show that understanding of the topic "Molecular kinetic theory" improved by 22% (from 60% to 82%). Similar conclusions were obtained by E.S. Statnik *et al.* (2020) in the study of the effect of digital microscopy on the teaching of mechanical properties of materials. The researcher noted that visualisation of microstructures using a digital microscope contributed to an increase in the academic performance of students of technical specialities by 19-23%. J. Dickerson & D. Kubasko (2007) investigated the use of digital microscopes in the optics course and recorded an increase in the level of understanding of the topic by 20-25% due to the ability to visualise the phenomena of interference and diffraction of light, which correlates with the results of the current study and confirms the overall effectiveness of digital microscopes in explaining complex concepts of physics.

The study showed that students' confidence in conducting laboratory work increased from 45% to 78%, and their ability to analyse experimental data increased from 48% to 80%. The obtained indicators are consistent with the findings of I.S. Ivanenko (2021), who investigated methodological aspects of the use of digital microscopy in secondary schools. He recorded an increase in the level of practical skills of students by 30-35% compared to conventional teaching methods. L. Tarangul & S. Romaniuk (2022) confirmed that the use of digital technologies in the educational process contributes to the development of analytical thinking skills and independent research. The study supports this conclusion, as students who worked with digital microscopes performed 20% better on tests than their peers who were trained using conventional methods.

Despite the obvious advantages of digital microscopes, there are a number of limitations that require further research: not all schools are provided with a sufficient number of digital microscopes, which may limit their use; additional teacher training is required to effectively implement digital technologies in the educational process; further research should focus on integrating digital microscopy into cross-subject STEM projects.

CONCLUSIONS

The study confirmed the effectiveness of using digital microscopes in teaching physics. They significantly improve the assimilation of educational material, increase students' interest in the subject and develop their research skills. The main results of the study indicate an increase in students' motivation: 85% of respondents noted that learning has become more interesting due to the possibility of independent observation of microscopic processes. The level of understanding of complex physical topics (in particular, molecular kinetic theory) increased by 22%, which confirms the effectiveness of visualising physical phenomena. Students' practical skills improved significantly: their confidence in performing laboratory tests increased by 33%, which indicates an increase in competence in conducting experiments. The test results showed that students who used a digital microscope scored an average of 20% higher than those who studied using conventional methods. Teachers highly appreciated the methodology: 92% of teachers confirmed that digital microscopes help to make learning more visual, simplify the explanation of complex topics and increase student achievement.

There are also some challenges that require further study, such as the development of methodological recommendations for integrating digital microscopy into the educational process, training teachers to use digital technologies in teaching physics, expanding the scope of use of digital microscopes in cross-subject STEM projects, and technical support for schools for wider adoption of digital technologies. Thus, digital microscopy is a promising area in teaching physics, which not only improves the quality of the educational process, but also contributes to the development of students' research competencies, preparing them for future challenges in the field of science and technology. Further research should be aimed at developing methodological recommendations for integrating digital microscopy into the educational process and expanding the possibilities of using this method in STEM education.

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Використання цифрових мікроскопів для вивчення фізичних явищ: нові можливості для шкільного навчання

Анотація. Сучасний освітній процес вимагає впровадження новітніх технологій, які сприяють кращому розумінню складних наукових концепцій. Використання цифрових мікроскопів відкриває перспективи для розвитку практичних навичок, покращує аналітичне мислення учнів та підтримує інтеграцію фізичних явищ із реальним світом. Дане дослідження присвячене аналізу можливостей використання цифрових мікроскопів у викладанні фізики в школі. Було проведено серію досліджень, спрямованих на визначення залежності швидкості хаотичного руху частинок від в'язкості середовища. Використання програмного забезпечення для аналізу відеозаписів дозволило встановити, що зі зменшенням концентрації молока швидкість частинок зростає, що узгоджується з моделлю Стокса-Ейнштейна. Окрім експериментальної частини, було проведено анкетування серед учнів і вчителів для оцінки ефективності використання цифрових мікроскопів у навчальному процесі. Результати показали, що 85 % учнів вважають, що цифрові мікроскопи зробили вивчення фізики більш цікавим, а 78 % зазначили, що спостереження мікроскопічних явищ сприяло глибшому розумінню теоретичного матеріалу. Аналіз академічних досягнень учнів засвідчив підвищення рівня знань і покращення успішності в порівнянні з традиційними методами викладання. Отримані результати підтверджують доцільність інтеграції цифрових мікроскопів у навчальні програми з фізики, особливо в рамках STEM-освіти. Запропоновано розробити методичні рекомендації щодо впровадження цифрової мікроскопії у шкільний курс фізики. Отримані результати дослідження можуть бути використані вчителями фізики загальноосвітніх навчальних закладів для підвищення ефективності викладання, розробниками освітніх програм для інтеграції цифрової мікроскопії у шкільний курс фізики, а також у STEM-центрах та наукових гуртках для формування практичних дослідницьких навичок учнів

Ключові слова: Броунівський рух; молекулярно-кінетична теорія; освітні технології; методичні рекомендації; STEM-освіта