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STEM-Based 3D Virtual Learning Media on Cell Biology to Enhance Conceptual Understanding and Digital Literacy

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Abstract

Conceptual understanding and digital literacy are key competencies in 21st-century learning. However, observations at SMP Negeri 10 Semarang indicate that these two skills are still not being developed to their full potential in science lessons. Consequently, there is a need for innovative teaching materials capable of enhancing students' conceptual understanding and digital literacy in an integrated manner. Cell-based material was selected because it is microscopic and complex, thus requiring learning media capable of visualising cell organelles to aid students' conceptual understanding. This study aims to analyse the effectiveness of the media in improving conceptual understanding and digital literacy in cell-based material. The research method used was the ADDIE development model of R&D with an experimental design. The research sample comprised Class VIII A as the experimental class and Class VIII D as the control class. The results of the study indicate that: 1) The STEM-based 3D virtual learning media on cell material is sufficiently effective in improving conceptual understanding, as indicated by the experimental class achieving an N-Gain score of 0.63 (moderately effective), compared to the control class using video and worksheets, which only achieved an N-Gain score of 0.20 (ineffective). 2) The results showed that the STEM-based 3D virtual learning media on cell material was sufficiently effective in improving digital literacy, as indicated by the experimental class achieving an N-Gain score of 0.70 (moderately effective), while the control class only achieved an N-Gain score of 0.18 (ineffective). This research contributes to the development of science learning media through the integration of STEM-based 3D virtual media that is able to visualize cell concepts in a more concrete, interactive, comprehensive, and accessible manner, thus supporting increased conceptual understanding and digital literacy according to the demands of 21st century competencies.

How to Cite

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INTRODUCTION

The Fourth Industrial Revolution has ushered in the era of Society 5.0, making various aspects of life easier and faster (Ziatdinov et al., 2024). The era of Society 5.0 is characterised by human driven technological innovations that further advance the integration of virtual and physical spaces (Lund et al., 2023). Consequently, in recent years, computing and technology have developed at an increasingly rapid pace, supporting the presence of artificial intelligence (AI) in human life, including within the education sector (Tzirides et al., 2024); Zhu et al., 2023).

The rapid pace of technological development in the Society 5.0 era requires students to possess the ability to access data and analyse information in order to keep pace with the flow of information and think critically about information related issues; this ability is known as digital literacy (Getenet et al., 2024). In today's information and technology era, digital literacy has become a crucial aspect of education. Digital literacy is not merely about technical skills but also involves the understanding and ability to use information effectively within a digital environment (Teknowijoyo & Marpelina, 2022). Students are expected not only to be able to access digital information but also to understand, evaluate, and produce content critically. Therefore, science lessons can be integrated with the use of technology to hone students' higher order thinking skills as a means of developing their digital literacy (Nurzhanova et al., 2024).

Digital literacy is an essential skill for students, as it enables them to collaborate effectively and articulate their ideas. Digital literacy is particularly important in today's world, as it fosters students' ability to critically evaluate information, analyse it effectively, and select credible sources (Joseph et al., 2024; Wang et al., 2023). Digital literacy skills can lead to higher order learning outcomes that foster critical, collaborative, and communicative thinking (Khan et al., 2022).

In addition to digital literacy, conceptual understanding is also one of the key competencies underpinning the Fourth Industrial Revolution and 21st-century skills (Harnani et al., 2021). This conceptual understanding forms the foundation for other skills. In other words, conceptual understanding is a key element in the learning process (Giawa et al., 2022). Conceptual understanding refers to an in depth process of acquiring knowledge about an object. A student is said to have good conceptual understanding if they are able to rephrase the concepts they have learnt in their own words and apply them in everyday life (Lathifa et al., 2025)

Observations at SMP N 10 Semarang indicate that students conceptual understanding and digital literacy in science lessons are still not optimal. This is evident from the results of the SAS test, where the average score was 51; many students have not yet achieved the required standard and are below the minimum passing mark. Preliminary pre-research data also revealed that the average scores for conceptual understanding were 36 and for digital literacy 64. Both results indicate that students' conceptual understanding and digital literacy skills still need to be improved. Furthermore, the results of interviews and teacher observations also indicate that students' conceptual understanding and digital literacy skills remain low and need to be improved.

Therefore, there is a need for teaching materials that can develop students' conceptual understanding and digital literacy in relation to cell biology. However, the teaching materials currently used in schools for cell biology do not sufficiently support the development of these skills. The teaching materials used in science lessons consist solely of printed textbooks provided by the school. The cell biology content in these textbooks is presented only in two dimensions, and not every part of the cell organelles is illustrated. The teaching of cell-related material at SMP Negeri 10 Semarang also rarely utilises 3D virtual website-based learning media, even though such media can support the skills required for the Fourth Industrial Revolution as preparation for 21st-century skills.

Therefore, the solution proposed by the author is to design STEM-based 3D virtual learning media for cell-related material to enhance conceptual understanding and digital literacy. Research by Asrizal et al. (2025) shows that STEM integration in interactive multimedia can improve conceptual understanding, but is still limited to two-dimensional visualizations without complex biological models. Research by Hutabarat (2024) also proves the effectiveness of STEM modules based on the 5E Learning Cycle, but does not yet provide an in-depth representation of cell structures. Asrizal et al. (2025) focuses more on the context of light waves and therefore does not address the need for visualization of microscopic objects in biological science. Hutabarat (2024) emphasizes that investigative science activities are not yet directed at strengthening digital literacy through high-tech visualization. Meanwhile, Khusnah & Ulfa (2024) developed an interesting 3D media based on physical materials, but the model still lacks support for digital interactivity. Muslima (2025) offers a VR-based 3D model of cell organelles, but access is limited because it requires special devices such as a VR Box. Based on this gap, the research that has been conducted combines the STEM approach with digital 3D media so that cell visualization becomes more concrete, comprehensive, and easily accessible to improve conceptual understanding and digital literacy.

Uno (2024) research shows that AR technology can improve understanding of science concepts, but its implementation still requires special devices that not all students have. Kurniasih et al., (2024) research, using authentic learning-based e-modules, successfully strengthened digital literacy, but did not yet present 3D visualizations for microscopic cell concepts. Uno (2024) emphasized visual interactivity but did not integrate the STEM framework into the learning flow. Conversely, Kurniasih et al. (2024) focused on text and two-dimensional media, thus not providing an in-depth exploratory experience. Khusnah and Ulfa (2024) research produced physical 3D models but did not support digital interaction, while Muslima (2025) presented virtual 3D models but did not explicitly integrate the STEM approach. This condition indicates that previous research has not combined conceptual understanding, digital literacy, 3D media, and the STEM approach in one integrated learning design. Therefore, the research conducted offers the integration of 3D learning media for STEM-based cell materials to provide an interactive, accessible learning experience that meets the demands of 21st-century digital competencies.

Based on the background described above, the objectives of this study are (1) to analyse the effectiveness of 3D virtual learning resources on cell-based STEM topics in enhancing conceptual understanding and (2) to analyse the effectiveness of 3D virtual learning resources on cell-based STEM topics in enhancing digital literacy.

METHOD

Participants

This study was conducted at SMP N 10 Semarang on the topic of cell biology for the odd-numbered semester. The population for this study comprised all Year 8 students at SMP Negeri 10 Semarang for the 2025/2026 academic year. From this population, two classes were selected for the study to test the effectiveness of using 3D-based virtual learning materials on cell biology with a STEM focus to improve conceptual understanding and digital literacy. The sampling technique used in this study was simple random sampling. The selection of simple random sampling in this study was possible provided that the students were homogeneous and that each class had an equal chance of being selected as a research sample. State Junior High School 10 Semarang does not have any elite classes, so all classes are relatively similar, with no strata at each grade level. Therefore, every class at State Junior High School 10 Semarang is relatively homogeneous. After conducting a homogeneity test using SPSS, two homogeneous classes were selected, namely Class VIII A as the experimental class and Class VIII D as the control class.

Tabel 1. Participants from 2 class

Experimental Class	Control Class
Class VIII A 31 students	Class VIII D 31 students

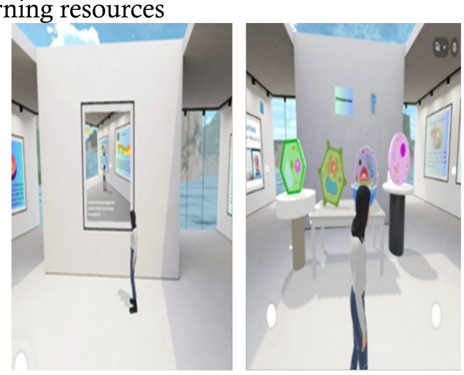
Learning using 3D virtual learning resources on cell biology based on STEM to enhance conceptual understanding and digital literacy

The STEM-based 3D Virtual Learning Resource on Cell Biology was developed using Spatial.io as the primary virtual platform, with three-dimensional objects created in SketchUp and interactive learning assets integrated using Assemblr EDU. The virtual learning environment is accessible through the Spatial application or a compatible web browser, enabling both students and teachers to engage in immersive learning activities. To ensure smooth performance, the media is compatible with Android and iOS smartphones, tablets, and desktop or laptop computers that meet Spatial.io's minimum requirements, including a stable internet connection, at least 4 GB RAM, and an up-to-date web browser or the latest version of the Spatial application. Users access the virtual environment by signing in with an active Google account and entering the learning space through a QR code or a shared access link. The learning resource incorporates several interactive features, including the Science Gallery, 3D Models, Cell Orchestra, Project Assignments, Fill in the Blanks, and Development Team and References, which collectively support STEM-oriented learning of cell biology.

Upon entering the virtual learning environment, users first read the embedded usage instructions before navigating the learning space through intuitive touchscreen or mouse-and-keyboard controls. Directional arrows guide learners systematically through each learning area to ensure that all instructional content is explored in sequence. Students can interact with multimedia resources, including science galleries, three-dimensional cell models, instructional videos, quizzes, and project-based assignments designed to strengthen conceptual understanding and scientific inquiry. The platform also enables learners to explore the environment through customizable avatars, creating an engaging and immersive learning experience while maintaining straightforward navigation across different devices. Through these technical and accessibility features, the 3D virtual learning resource provides an interactive, accessible, and technology-enhanced learning environment that supports independent and collaborative STEM learning.

The 3D Virtual Learning Resource on Cell Biology based on STEM is a virtual learning resource designed using a STEM approach and featuring 3D content on cell biology. The media developed is easily accessible to both students and teachers with features such as: Science Gallery (containing introductions, cell materials and educational videos about cells), 3D Models (containing 3D visualisations of animal and plant cells in form of QR codes and direct 3D views), Cell Orchestra (containing songs about cells), Project Assignments (containing tasks to create cell models), Fill in the Blanks (featuring a quiz to complete the names of plant cell organelles), and Development Team and References (featuring the app developers and references used to create media).

Figure 1. A display of STEM-based 3D virtual learning resources



This virtual website is designed to enable students to use avatars to explore all the activities available in the 3D room by following the instructions and navigating the room as guided by the arrows. The platform also features STEM activities and includes a STEM project that guides students to solve problems related to cell visualisation by creating models of animal or plant cells. All learning activities on the virtual platform are aligned with the Curriculum Standards (CP) and Learning Outcomes (ATP) for the cell module in Year 8, first semester. The design of the platform's activities encourages collaborative problem-solving and critical thinking as students engage with the questions and activities. We recommend that teachers divide students into small groups (4-6 students per group) to complete tasks collaboratively in class.

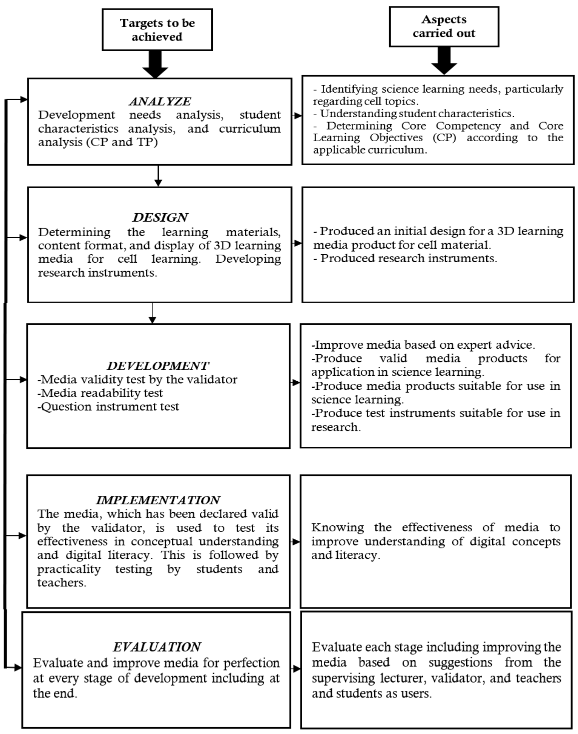


Figure 2. Research Procedure Diagram

Data Collection

The research conducted was a development study, or R&D (Research and Development). The development model used in this study was the ADDIE model, which consists of five stages: analyse, design, develop, implement, and evaluate. Furthermore, the research design for testing the effectiveness of this study employed a quasi-experimental design, specifically a Nonequivalent Control Group Design with a pre-test post-test format. The study first administered a pre-test to the pupils, after which the experimental class was treated using 3D learning media on cell-based STEM material, whilst the control class used the learning media typically employed by teachers at the school, namely educational videos and worksheets. Subsequently, at the end of the sessions, a post-test was conducted in both the control and experimental classes; the research design is presented in Table 2.

Table 2. Nonequivalent Control Group Research Design

Class	Pretest	Treatment	Postest
E	O_1	X	O_2
K	O_3	Y	O_4

Description:

E	=	Experimental group
K	=	Control group
X	=	Treatment using 3D learning materials on cells based on STEM
Y	=	Treatment using video learning materials and worksheets
O_1	=	Pretest for the experimental group
O_2	=	Posttest for the experimental group
O_3	=	Pretest for the control group
O_4	=	Posttest for the control group

Research Data

This study involved three participant groups. The first group included subject matter experts, media experts, and teachers who evaluated the suitability of the 3D STEM based learning media on cell content. The second group consisted of teachers and students participating in the media usability test. The third group involved secondary school students for readability testing and for evaluating the media's effectiveness in improving conceptual understanding and digital literacy. Details of the research subjects are presented in Table 3.

Table 3. Research Data

No	Data	Technical	Instrument	Subject
1	Digital Literacy	Questionnaire	Digital literacy questionnaire	Student
2	Conceptual Understanding	Test	Question about conseptual understanding	Student

Table 3 presents a breakdown of the research data, divided into the two tests of the effectiveness of the 3D learning media for STEM-based cell-related material: the digital literacy test and the conceptual understanding test.

Data Analysis

Normality Test

The normality test aims to determine whether data obtained in a study is normally distributed or not, prior to analysis. In this study, the Shapiro-Wilk test was used to assess normality, with the assistance of SPSS software. The study employed a significance level of 5%. If the p-value is greater than 0.05, the variable is deemed to have a normal distribution. However, if the p-value is less than 0.05, the variable is considered not to follow a normal distribution.

Homogenity Test

A homogeneity test is used to determine whether the characteristics of the sample to be used for data collection in the study are homogeneous or not. The end-of-semester assessment data from the even semester will be used for analysis. In addition, a homogeneity test is applied to determine whether the pre-test and post-test data for both sample groups namely the control class and the experimental class have equivalent variances. Conducting this test is important to ensure the characteristics of both groups are homogeneous before further statistical analysis is carried out. The analysis procedure was performed using SPSS for Windows software via Test of Homogeneity of Variances using Levene's statistic (Levene's Test). Data is deemed homogeneous if significance value obtained is greater than 0.05.

t-Test

The use of the t-test in this study aims to identify whether there are significant differences between the class that received instruction using 3D virtual media based on STEM cell material and the class that learned through video and worksheets. Through this analysis, the researcher can assess the extent to which the developed 3D

STEM cell-based media is effective in improving students' conceptual understanding and digital literacy. Thus, the t-test serves as the basis for determining the effectiveness of the learning media produced compared to the learning media commonly used.

The t-test used was the independent samples t-test to analyse whether there was a significant difference in the improvement of conceptual understanding and digital literacy between the control and experimental groups. The data analysis was carried out using SPSS software. Prior to conducting the independent samples t-test, a check of the prerequisites was required, particularly regarding normality and homogeneity. If the results of the data normality test indicated that the data were normally distributed and the data groups from the two treatments were homogeneous, the independent samples t-test was then carried out. However, if the results of both prerequisite tests were not met, the Mann-Whitney (U-Test) was then carried out. The following is the basis for the decision-making process.

- If the significance value (two-tailed) is less than 0.05, there is a significant difference in improvement between the experimental and control groups.
- If the significance value (two-tailed) is greater than 0.05, there is no significant difference in improvement between the experimental and control groups.

N-Gain Test

The effectivenes off the STEM-Based 3D Virtual Learning Media on Cell Biology to Enhance Conceptual Understanding and Digital Literacy was also examined using the N-Gain test to measure immprovements in studennts' conceptual understandunf and digital literacy from pretest to posttest. The N-Gain score provides a standardized measure of learning progress by comparing the actual gain with the maximum possible gain. The normalized gain was calculated using the following formula:

$$g = \frac{S_{post} - S_{pre}}{S_{max} - S_{pre}}$$

According to Hake (1999), the N-gain assessment categories categorized in Table 4.

Table 4. N-Gain Assessment Categories

Many factors <g>	Assessment Categories
<g> ≥ 0.7	High
0.3 ≤ <g> <0.7	Medium
<g> <0.3	Low

Based on Table 4, the N-Gain Score categories are classified into three levels: low, medium and high. An N-Gain value is considered low if it falls within the range 0.00 < g ≤ 0.30, whilst the range 0.30 < g ≤ 0.7 is categorised as moderate. If the N-Gain value falls within the range > 0.7, the improvement in student learning outcomes is categorised as high.

Having established the classification of N-Gain scores into low, medium and high categories, a further interpretation of the level of effectiveness of the improvement in learning materials is also required. Table 5 therefore presents an interpretation of N-Gain effectiveness, illustrating the extent to which such improvements can be considered effective in the context of learning.

Table 5. Interpretation of N-Gain Effectiveness

Percentage (%)	Interpretation
g < 40	Not Effective
40-55	Less Effective
56-75	Moderately effective
≥76	Effective

According to the table, the effectiveness of the N-Gain Score is divided into four categories based on the percentage achieved. Learning is deemed not effective if the N-Gain Score percentage is less than 40%. A percentage between 40% until 55% indicates the less effective category. Meanwhile, an N-Gain Score percentage in the range of 56% to 75% indicates that learning is moderately effective. A percentage of 76% or higher is categorised as effective.

Conceptual Understanding Analysis

An analysis of students conceptual understanding was conducted by examining their answers to the questions set. This study employed a quantitative descriptive analysis method, which was carried out after the students' final marks had been calculated using the marking formula presented below:

$$Value = \frac{number\ of\ scores\ obtained}{maximum\ score} x\ 100$$

Table 6. Conceptual Understanding Criteria

Value Interval	Criteria
0≤x< 34	Very Low
35≤x<54	Low
55≤x<64	Moderate
65≤ x < 84	High
85≤ x< 100	Very High

Analysis of Digital Literacy Data

This analysis was used to assess pupils' digital literacy skills via a digital literacy questionnaire. The analysis employed was descriptive statistical analysis, which serves to describe the data collected, making it easier to understand. The steps involved calculating the total scores achieved by the pupils using formula (Sugiyono, 2016):

$$Value = \frac{number\ of\ scores\ obtained}{maximum\ score}\ x\ 100$$

The criteria for digital literacy are set out in Table Tabel 7 (Dinata, 2021).

Table 7. Criteria for Digital Literacy

Value Interval	Criteria
81-100	Very Good
61-80	Good
41-60	Fair
21-40	Poor
0-20	Very Poor

RESULT AND DISCUSSION

Results of the effectiveness of 3D learning media for STEM-based cell material to improve conceptual understanding

This study was conducted to examine 3D learning media for STEM-based cell material on improving conceptual understanding using N-Gain. Based on the analysis, the experimental class experienced a significant improvement following the implementation of teaching using 3D learning media based on STEM-based cell material. When the two N-Gain scores are compared, the experimental class's N-Gain score is higher than that of the control class. This implies that the 3D learning media based on STEM cell material is more effective in improving conceptual understanding compared to video-based learning media and worksheets.

Table 8. N-Gain test for each conceptual understanding indicator

Indicator	Control Class				Experimental Class			
	Average Value			N-Gain Category	Average Value			N-Gain Category
	Pretest	Posttest	N-Gain		Pretest	Posttest	N-Gain	
Interpreting	45	52	0.13	Low	31	81	0.72	High
Exemplifying	36	56	0.31	Moderate	27	73	0.63	Moderate
Inferring	44	58	0.25	Low	49	66	0.33	Moderate
Comparring	35	48	0.20	Low	23	77	0.70	Moderate
Classifying	35	50	0.17	Low	34	80	0.70	Moderate
Explainning	35	43	0.12	Low	32	81	0.72	High

Based on the results of the independent t-test on the post-test data, a significance value of 0.000 was obtained, which is less than 0.05. This indicates that there is a significant difference between the conceptual understanding of students in the control class and the experimental class. Thus, it can be interpreted that the use of 3D learning media for STEM-based cell material in the experimental class has a more effective influence on improving conceptual understanding compared to learning using video media and worksheets in the control class.

Table 9. Results of the independent t-test of conceptual understanding data

Class	Data Type	Sig	Description
Control Eksperiment	Posttest	0.000	There is a significant difference

The interpreting skill in the 3D virtual learning environment for STEM-based cell studies is developed through the perception feature. The perception feature in the 3D virtual learning environment for cell studies is designed to develop interpreting skills, namely students' ability to transform one form of information into another specifically, interpreting the images in the perception feature into verbal explanations. In the apperception feature, students are asked to observe an image of a bowl of Kudus soto; they are then asked to interpret the image by naming the components of the Kudus soto that resemble cell organelles. Through this activity, students not only memorise information about cell material but also understand the meaning and relationships between the concepts presented. This aligns with the research by Laubscher et al. (2024), which states that 3D-based learning experiences regarding cellular structures significantly enhance the understanding of the relationship between cell structure and function, as students are asked to observe 3D models and explain them in their own words. In addition to the perception feature, the media also includes a cell worksheet feature, where the worksheet contains a section designed to practise the 'interpreting' indicator namely, interpreting images of plant cell organelles and explaining their functions. The use of 3D models can enhance students' ability to interpret complex biological structures and link them to their conceptual functions (Teplá et al., 2022).

The illustrative indicators in the learning resource are realised through interactive visual presentations that highlight the differences between unicellular and multicellular cells. This resource displays the shape and structure of each type of cell, accompanied by examples such as Amoeba and Paramecium for unicellular cells, and plants and animals for multicellular cells. Through this display, students can observe and understand the characteristics that distinguish single celled and multicellular organisms, making the concepts being studied more concrete and easier to understand. Consequently, students' ability to identify and provide examples in line with the concepts of unicellular and multicellular organisms can develop in accordance with the objectives of the exemplifying indicator, which focuses on the ability to provide accurate examples. This aligns with the statement by Takda et al. (2025), who noted that the development of 3D animation-based media for cell-related material enables students to visualise complex cell structures dynamically and more concretely than through text or 2D images alone. Activities involving the exploration of 3D models can also deepen students' understanding of the differences between unicellular and multicellular organisms. Furthermore, the exemplifying indicator is also practised through the worksheet features within the media, which include exercises where students can provide examples of organisms classified as unicellular and multicellular.

The inferring indicator refers to students' ability to draw conclusions based on the information presented. 3D virtual learning resources on cell-based STEM topics can develop inferring skills, as students can view cell models in 3D and interact with them. Through these visualisations, students learn to interpret the information they see for themselves, such as linking organelles to their functions or understanding why a particular organelle is found only in certain cells. 3D visualisation can help students focus on key parts, making it easier for them to understand and compare objects more accurately (Wang et al., 2024). As students explore 3D models and engage in STEM-based activities, they are encouraged to make predictions or draw conclusions based on their observations, rather than simply memorising the teacher's explanations. It is this process that helps students develop the ability to draw logical conclusions from the information obtained. Students become increasingly skilled at making inferences when participating in STEM activities that encourage them to deduce the reasons for the presence of specific organelles in certain cell types. This aligns with the research by Yupani & Widana (2023), which explains that exploration-based STEM activities can help build the ability to draw conclusions.

The comparing indicator in conceptual understanding refers to students' ability to identify similarities and differences between two or more concepts or objects. This ability is important in helping students analyse the relationships between concepts so that they can understand them more deeply. In the 3D learning media on cells, students are trained to compare the differences between animal and plant cells in terms of shape, structure, and the functions of their organelles. The available comparison table feature helps students review differences systematically, whilst the 3D view of animal and plant cell organelles allows them to visually observe the similarities and differences between organelles. Furthermore, activities involving the exploration of 3D models of animal and plant cell organelles also enable students to observe the differences between plant cell organelles and animal cell organelles in greater detail. This is in alignment with the study by (Teplá et al. (2022), which states that the use of 3D models and animations significantly enhances students' ability to visualise and compare biological structures, thereby deepening their conceptual understanding. Furthermore, the comparing indicator is also practised using the worksheet features included in the media, where students are presented with aspects of comparison and are able to compare animal cells with plant cells; in addition, students are also asked to compare unicellular organisms with multicellular organisms. Thus, this media not only encourages students to memorise information but also fosters analytical thinking skills through activities involving the comparison of concepts relating to an object.

Classification indicators in educational media are demonstrated through the systematic organisation of content. In the media presentation, cell organelles are grouped into those found only in animal cells, those found only in plant cells, and those found in both. Teplá et al. (2022) explain that the use of 3D models and animations in science learning can improve learning outcomes and students' conceptual understanding far more effectively than 2D images, particularly in biology. Furthermore, the room structure within the media is organised into several categories, such as unicellular versus multicellular cells, and rooms for cell organelles and their functions. This categorisation aims to help students understand concepts through guided visual classification activities, making it easier for them to recognise similarities and differences between cellular components. The classifying indicator is also practised through the worksheet feature integrated into the media, where students are asked to group organelles based on their primary functions, such as synthesis, storage, transport, or defence. Therefore, the learning process not only trains the ability to recognise cell structures but also fosters logical and conceptual thinking skills in classifying biological information scientifically.. This is supported by the findings of Arsyad & Syakhrani. (2024), who state that clearly structured materials that provide classification exercises can help students learn complex concepts and strengthen their understanding.

The explaining indicator refers to students' ability to restate a concept in their own words in a logical manner and in accordance with the concept. The explaining indicator is practised through the media by ensuring that each science gallery contains an explanation related to the cell concept. Students can understand this information and explain it in their own words. The material explanations in the media are also presented in the form of educational videos that explain a concept within the cell topic. Students can grasp the information in the educational videos about the cell topic and express the concept in their own words in line with their understanding. This is in accordance with the statement by Tondeur et al. (2024), who argue that the integration of digital tools into learning can create a more dynamic learning environment and support students' active engagement in constructing their own knowledge. The use of digital learning spaces enables students to acquire information, process data, and communicate their understanding more independently. This concept aligns with the STEM-based project approach, where the use of digital devices helps students explore concepts, document learning activities, and communicate their work more effectively, thereby developing their ability to explain the material through the activity of creating learning content. Furthermore, through the integrated worksheet feature in the media, students are trained to explain the functions of the microscope parts shown. The explaining indicator is also supported by a project feature within the platform where students explain plant or animal cells through digital content. In this project, they are trained not only to memorise information but also to convey that knowledge in a way that demonstrates understanding using their own words.

During the learning process, students were very enthusiastic and engaged with the presentation of the 3D virtual learning media on cell-based STEM material. Their interest stemmed not merely from the novelty of the medium itself, but from the various features and content it contained, and, most importantly, from the STEM activities integrated into the medium. The STEM activities within the science component helped students understand cell-related material through the science gallery; in this activity, students could access educational videos and practice questions available in the science gallery. The STEM activities in the technology component also help students understand cell material more deeply, as they can explore 3D cell organelles in greater detail, thereby facilitating an understanding of microscopic concepts. Students can rotate and view cell organelles from various angles and relate the structure of cell organelles to their functions. Furthermore, activities involving the 'Cell Orchestra' feature, supported by AI technology, help students to remember information about cell organelles and their functions through the 'Cell Orchestra' song. STEM activities in the engineering component train students to explore cell-related material in greater depth by designing animal or plant cell organelle products. STEM activities in the mathematics component can also deepen students' understanding of cell material, as they gain a deeper understanding of the subject matter by practising calculating microscope magnification. Calculating microscope magnification in the context of cell material involves adjusting the microscope's magnification to observe cell organelles.

In addition to the STEM activities explicitly included in the media, the media also features project tasks that guide students to solve problems related to cell organelles, which are microscopic in nature and therefore difficult for students to observe and understand; consequently, a product is required that can visualise these cell organelles. In the project task, students are guided to create a model of an animal cell or a plant cell, and then produce a short digital piece of content to explain the function of each organelle found in the animal or plant cell. Engaging in activities to create these STEM-based products can deepen students' understanding of cellular concepts. Thus, students do not merely understand or memorise a concept, but can apply it practically by creating a product and explain it in their own words through the creation of short digital content. This is in line with the research by Rasyid et al (2023), which states that the implementation of STEM-based project tasks can significantly improve students' conceptual understanding, as students are actively engaged in problem-solving activities and the creation of real-world products relevant to the learning material. Furthermore, activities involving the creation of products and digital content encourage students to apply concepts in a concrete manner, thereby helping them to link theory with meaningful learning practices. Consequently, the integration of STEM-based project tasks into learning materials helps students not only to memorise the material but also to understand and explain concepts in depth.

The results of the n-gain analysis indicate that an n-gain value of 0.63 in the experimental class, which falls into the 'moderately effective' category, demonstrates that the 3D learning medium for STEM-based cell material is capable of improving conceptual understanding more effectively than the control class, which achieved an n-gain of only 0.20 and was classified as ineffective. The fact that the outcomes did not reach the very high category for the developed medium was influenced by a one-week break in learning due to co-curricular activities, which led to a reduction in the continuity of learning and concept reinforcement. A sufficiently long break in learning can reduce knowledge retention, thereby impacting learning outcomes (Maceiras et al., 2025). Nevertheless, STEM-based 3D learning materials continue to demonstrate greater effectiveness, as three-dimensional visualisations and the STEM approach help students to grasp microscopic cellular concepts more quickly and thoroughly.

Another factor contributing to the suboptimal effectiveness of 3D learning materials on cell-based STEM topics in enhancing conceptual understanding is that, when analysed based on students' n-gain scores for conceptual understanding, the lowest improvement was observed in the 'inferring' indicator. This is consistent with the weakness of the media, where the section intended to train the inferring indicator is still not optimal; the features in the media, particularly the inferring indicator section, are still not explicitly designed to train the inferring indicator. Therefore, improvements were made to the media by adding features to train the inferring indicator, whereby the media was provided with a video-triggering illustration about mitochondria, after which students were asked to answer questions in the concept reinforcement gallery by drawing conclusions related to the comparison table presented and answering questions in the concept reinforcement gallery. Further research can also be conducted by addressing the media's weaknesses in training the inferring indicator.

After analysing the factors contributing to the decline in effectiveness, the researchers found that the primary cause was the intermittent nature of the research implementation, which reduced knowledge retention and consequently impacted learning outcomes. Furthermore, the extent to which students accessed various media outside of the learning context also played a role. The researchers also assume that student characteristics influence learning outcomes; therefore, further research is recommended on a larger scale to assess the effectiveness of the learning media developed to enhance conceptual understanding.

The effectiveness of 3D learning media for STEM-based cell-related content in improving digital literacy

The results of the Mann-Whitney test on the post-test digital literacy data showed an Asymp. Sig. (2-tailed) value of 0.000, suggesting that there is a significant difference between the experimental class and the control class. These results indicate that the use of 3D learning media for STEM-based cell-related material is more effective in improving students' digital literacy compared to the use of video media and worksheets in the control class. This means that learning using 3D media, which is visual in nature and allows for independent exploration, provides a stronger learning experience in developing digital literacy.

Table 10. Result Man Whitney U-test

Class	Data Type	Asymp Sig.	Description
Control Experiment	Posttest	0.000	There is a significant difference

The N-Gain scores show that, in the analysis of digital literacy skills, the experimental class experienced a significant improvement following the implementation of lessons using 3D learning materials on cells based on STEM. When the two N-Gain scores are compared, the experimental class's N-Gain score is higher than that of the control class. This implies that the 3D learning media based on STEM cell material is more effective in improving digital literacy skills compared to video media and worksheets.

Table 11. N-Gain test for each digital literacy indicator

Indicator	Control Class				Experimental Class			
	Average Value			N-Gain Category	Average Value			N-Gain Category
	Pretest	Posttest	N-Gain		Pretest	Posttest	N-Gain	
Operational	65	78	0.37	Moderate	76	90	0.58	Moderate
Thinking	65	69	0.11	Low	64	88	0.67	Moderate
Collaboration	54	60	0.13	Low	63	92	0.78	High
Awareness	67	70	0.09	Low	58	91	0.79	High

Operational indicators are assessed based on students' ability to explore information via digital media, their ability to use digital technology in learning, their ability to store information on digital media, and their ability to resolve digital technical issues. These operational indicators can be honed through the use of 3D cell learning media, where the media's avatar feature can be used to explore information in the science gallery, whilst the media's unique design can also train students to use digital technology in learning. The use of digital media in learning demonstrates that well-designed resources can help students develop technical skills and the ability to use various devices in learning (Chisunum & Nwadiokwu, 2024). The project assignment feature, which directs students to upload their work to Instagram, also helps them practise storing information on digital media. Thus, students are not only sharing information but also using technology as a means of storing it. Furthermore, the ability to resolve technical issues is evident alongside the use of 3D learning media for cell-related material. Students do not immediately ask the teacher if there is a technical error; they first attempt to resolve it themselves or consult their team. Only when they feel it is too difficult to resolve do they begin to ask the teacher. This aligns with Suganda (2022) research, which states that learning activities via digital media can enhance students' ability to operate digital devices.

Indicators of digital literacy thinking are assessed based on students' ability to interpret information contained in digital media, their ability to develop digital content, and their ability to analyse information contained in digital media. Juliana et al. (2024) state that the use of digital learning environments can enhance students' independence in seeking out and understanding visual information, thereby making them more active when exploring microscopic data. The media can be used to practise digital literacy thinking indicators through the appreciation features contained in the 3D digital media on cell material. The 3D learning media on cell material also includes projects that can train students to create digital content. In addition, the digital media also features an instructional video on calculating microscope magnification; at this stage, students can practise analysing microscope magnification calculations.

The collaboration indicator in digital literacy is assessed through the ability to work together in teams using digital technology, the ability to share information and materials via digital devices, and the ability to communicate with one another with the aid of digital technology. Digital literacy skills relating to collaboration can be supported by platforms where students can collaborate in teams using digital technology; for example, platforms featuring worksheets where the links or worksheet features are integrated with Canva. This allows students to edit documents together. Bach & Thiel (2024) state that digital learning environments designed for collaboration improve the quality of team interaction and task management, thereby enabling students to work together more effectively online. The platform also features project assignments that encourage students to share information and materials via digital devices, specifically by uploading them to the social media platform Instagram. This is in line with the statement by Annisa et al.(2025), who state that social media can support collaboration and information sharing among students. Furthermore, the platform also facilitates communication between students through audio and live chat features. The Cell Orchestra feature also supports students in terms of collaboration, allowing them to sing songs together about cell organelles and their functions.

Indicators of digital literacy awareness can be seen in students who demonstrate a balanced approach to the use of technology, understand the role and benefits of information, communication and technology, and recognise the importance of safeguarding personal security in the digital world. These awareness indicators can be honed through the use of 3D cell-based learning materials, whereby the use of technology for learning helps students strike a better balance between using media for learning and for play. Following the introduction of 3D cell-based learning materials, students no longer use electronic devices such as mobile phones or laptops solely for play but also for learning. Consequently, learning with 3D cell-based learning materials enables students to better understand the role and benefits of information, communication, and technology. Furthermore, the 'technology-savvy' features within the media also encourage students to better understand the importance of safeguarding personal security in the digital world. The ever-increasing exposure of personal data in the digital space demands the implementation of stricter privacy protections to minimise the risks of misuse and security threats (Herath et al., 2024).

Most students in the experimental class reported that they had previously encountered various difficulties in using digital learning resources, particularly in terms of their operation. The most common difficulties related to the operation of digital resources, such as confusion over how to access certain features, technical issues when opening materials, and difficulties in saving or managing digital information. Furthermore, in terms of thinking and collaboration, students tended to use digital media passively, limiting themselves to receiving information, and were not yet optimally processing information or utilising it as a means of learning communication. Regarding awareness, the majority of students also acknowledged that they had not yet fully balanced the use of technology between learning and entertainment, and were still paying insufficient attention to the security of personal data in the digital world.

Following the implementation of 3D virtual learning media based on STEM cell material in the experimental class, it was found that the media was quite effective in improving all aspects of students' digital literacy, including operational skills, collaboration, and awareness. Through the use of 3D virtual media based on STEM cell material, students became more proficient in operating learning technology and were able to explore cell structure and function in greater depth, thereby optimising the process of analysis and conceptual understanding. Furthermore, STEM-based learning activities encouraged communication and cooperation among students during discussions and problem-solving, which directly strengthened the aspect of digital collaboration. Students also demonstrated increased awareness in using technology in a balanced and responsible manner, including in safeguarding personal data during digital learning. These findings align with study Govender (2025), which states that digital literacy is closely linked to the development of 21st-century skills, such as critical thinking, collaboration, and the reflective use of technology within a digital learning context.

The results of the n-gain analysis indicate that the improvement in digital literacy in the experimental class reached 70%, falling into the 'moderately effective' and 'nearly high' categories, whilst the control class achieved an improvement of only 18%, falling into the ineffective category. These results suggest that the use of 3D virtual learning media for STEM-based cell-related content is more effective in improving students' digital literacy. This is due to the inclusion of digital media exploration activities and the creation of short digital content in the learning process, which encourages students to actively utilise technology in accessing, processing, and presenting information (Thelma et al., 2024). Furthermore, the three-dimensional visualisation and interactivity of the 3D learning media enhance student engagement in the learning process, thereby enabling digital literacy skills to develop more optimally.

This STEM-based 3D virtual learning resource on cell biology offers a number of advantages that can enrich students' learning experience. With its three-dimensional display, students can explore the space more freely, thereby gaining a deeper understanding of cell biology concepts. The 3D cell organelles in this resource are also available in two formats: via QR code scanning or in a version that can be viewed directly, allowing users to adapt their use to suit learning needs and conditions. Furthermore, the practical and portable nature of the media allows students to access it at any time, providing flexibility in learning across various situations. The engaging visualisations and interactive features provided help to stimulate students' curiosity and motivation to study cell material. Students can also explore and perform various activities, such as rotating the 3D cell organelles, to observe them in greater detail. However, this medium does have a drawback, namely its reliance on an internet connection. In conditions where the signal is unstable, the loading process can be slow and hinder the smooth running of the learning process. Thus, although 3D virtual media on cell material based on STEM offers a more engaging learning experience, the availability of an internet connection is a crucial factor that must be considered in its implementation. Alternative solutions proposed by researchers to address the limitations of digital learning media related to internet dependency include: (1) teachers can provide printed worksheets by downloading them via the 'Worksheets' feature on the platform; (2) rather than relying entirely on the school's Wi-Fi, teachers can also provide a personal hotspot; (3) If implemented in schools in remote areas where internet access is very limited or constrained, teachers can record media usage, which can then be saved as an offline record of media browsing; thus, even without an internet connection, the media can still be used. Apart from the limitation of the media's dependence on the internet, another limitation lies in the fact that the 3D representations of cell organelles used do not yet reach the molecular level; however, this is not a significant issue as the nature of cell-related material at lower secondary school level is limited to understanding cell organelles and their functions, without delving into the detailed molecular structure of each organelle. Nevertheless, this could present an opportunity for further research to be refined, serving as inspiration for the development of learning materials on cell biology with more detailed depictions of cell organelles down to the molecular level. If implemented, this would enrich the learning resources for cell biology and represent an innovation in research and development of cell biology materials.

CONCLUSION

3D virtual learning media for STEM-based cell material has a significant effect in improving conceptual understanding. This is indicated by the results of the t-test and n-gain in the experimental class, which experienced a more rapid increase. Based on the results of the n-gain interpretation of 3D learning media for STEM-based cell material, it was stated that it was quite effective in improving conceptual understanding. In addition, 3D virtual learning media for STEM-based cell material has a significant effect in improving digital literacy skills. This is indicated by the results of the man-whitney u-test and n-gain in the experimental class, which experienced a more rapid increase. Based on the results of the n-gain interpretation of 3D learning media for STEM-based cell material, it was stated that it was quite effective in improving digital literacy. This study also has limitations where the 3D shape of organelles does not reach the molecular level. For more detailed observation of the shape of cell organelles, further research can be conducted by developing 3D virtual learning media on cell material with detailed depictions down to the molecular level. In addition, to make the learning experience feel more real, further research can add a more comprehensive Virtual Reality (VR) feature using VR glasses so that 3D space exploration can be felt more realistically.

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REFERENCES

Annisa, L. A., Alya, D., & Bahri, S. (2025). Penggunaan Media Sosial Sebagai Sumber Pembelajaran yang Efektif di Kalangan Pelajar. *Jurnal Multidisiplin Ilmu Akademik*, 2(2), 15-22.

Arsyad, M., & Syakhrani, A. W. (2024). The efficiency of using visual learning media in improving the understanding of science concepts in elementary school students. *Indonesian Journal of Education (INJOE)*, 4(1), 775-787.

Asrizal, A., N, A., Ahzari, S., & Helma, H. (2025). Interactive Multimedia Sound and Light Waves Integrated Stem to Develop Concept Understanding and Literacy Skills of Students. *Journal of Turkish Science Education*, 22(1), 18–32.

Bach, A. (2024). Collaborative online learning in higher education quality of digital interaction and associations with individual and group-related factors, 1–12.

Chisunum, J. I., & Nwadiokwu, C. N. (2024). Enhancing Student Engagement through Practical Production and Utilization of Instructional Materials in an Educational Technology Class : A Multifaceted Approach. 10(2), 81–89.

Getenet, S., Cantle, R., Redmond, P., & Albion, P. (2024). Students ' digital technology attitude , literacy and self - efficacy and their effect on online learning engagement. *International Journal of Educational Technology in Higher Education.* https://doi.org/10.1186/s41239-023-00437-y

Giawa, L., Gee, E., & Harefa, D. (2022). Analisis Kemampuan Pemahaman Konsep Matematis Siswa Pada Materi Bentuk Pangkat Dan Akar Di Kelas Xi Sma Negeri 1 Ulususua Tahunpembelajaran 2021/2022. 1(12), 2439–2450.

Govender, I. (2025). Digital literacy and STEM skills–What is the connection? A systematic review. *Technology, Knowledge and Learning*, 1-22.

Harnani, N., Amijaya, D. T., & Setiadiwibawa, L. (2021). Digital literacy competences in improving the problem-solving skills in facing the industrial revolution 4.0. 2, 290–298.

Hutabarat, C. E. M. (2024). Pengembangan Media Pembelajaran Modul STEM dengan Model

Learning Cycle 5E Pada Pelajaran IPA di Kelas 8 Sekolah Menengah Pertama. *Didaktika: Jurnal Kependidikan,* 13(1), 1063–1070.

Joseph, G. V., Athira, P., Anit Thomas, M., Jose, D., Roy, T. V., & Prasad, M. (2024). Impact of Digital Literacy, Use of AI tools and Peer Collaboration on AI Assisted Learning: Perceptions of the University students. *Digital Education Review*, 45, 43–49.

Juliana, N., Ampera, D., & Sinukaban, V. Y. (2024). Digital Student Worksheets to Improving Students ' Learning Independence. 8(1), 31–41.

Khan, N., Sarwar, A., Chen, T. B., & Khan, S. (2022). Connecting digital literacy in higher education to the 21st century workforce Nasreen Khan Abdullah Sarwar Tan Booi Chen Recommended citation : Connecting digital literacy in higher education to the 21st century workforce. *Knowledge Management & E-Learning*, 14(1), 46–61.

Khusnah, L., & Ulfa, Y. (2024). Validitas dan Respon Peserta Didik terhadap Alat Peraga 3D Menggunakan Bahan Bekas pada Materi Sel Hewan dan Sel Tumbuhan di MTs Zainul Hasan Balung Jember. *JagoMIPA: Jurnal Pendidikan Matematika Dan IPA*, 4(3), 501–511.

Kurniasih, T., Suryajaya, S., Suyidno, S., & Fahmi, F. (2024). E-modul IPA berbasis authentic learning untuk meningkatkan literasi digital peserta didik. *Journal of Banua Science Education*, 5(1).

Lathifa, F. W., Fakhriyah, F., & Khamdun, K. (2025). Efektivitas Model Problem Based Learning Bermetode Eksperimen dengan Media PAREPIA untuk Meningkatkan Pemahaman Konsep IPAS Materi Sistem Pernapasan Manusia. 5, 247–258.

Laubscher, H., Loos, B., & Theart, R. P. (2024). Engage and learn: Improved learning of cellular structures using a virtual reality-based learning experience. *Computers & Education: X Reality,* 5, 100089.

Lund, B. D., Wang, T., Mannuru, N. R., Nie, B., Shimray, S., & Wang, Z. (2023). ChatGPT and a new academic reality: Artificial Intelligence-written research papers and the ethics of the large language models in scholarly publishing. *Journal of the Association for Information Science and Technology,* 74(5), 570-581.

Maceiras, R., Feijoo, J., Alfonsin, V., & Perez-Rial, L. (2025). Effectiveness of active learning techniques in knowledge retention among engineering students. *Education for Chemical Engineers,* 51, 1–8.

Muslima, A. H. (2025). Perancangan Media Pembelajaran Organel Sel Berbasis Virtual Reality. *BARIK*, 7(1), 113–127.

Nurzhanova, S., Stambekova, A., Zhaxylikova, K., Tatarinova, G., Aitenova, E., & Zhumabayeva, Z. (2024). Investigation of Future Teachers' Digital Literacy and Technology Use Skills. *International Journal of Education in Mathematics, Science and Technology,* 12(2), 387-405.

Rasyid, A., Rinto, R., & Susanti, M. (2023). Project-Based Learning through the STEM Approach in Elementary Schools : How to Improve Problem-Solving Ability. 1(1), 1–8.

Suganda, P. I. (2022). The Use Of Digital Media To Improve Students'literacy In English Learning In Junior High School. 02(02).

Takda, A., Hunaidah, M., & Halidun, W. O. N. S. (2025). Pembuatan Media Pembelajaran Sains Berbasis Augmented Reality dengan Animasi 3D. *Amal Ilmiah: Jurnal Pengabdian Kepada Masyarakat*, 6(3), 848–863.

Teknowijoyo, F., & Marpelina, L. (2022). Relevansi Industri 4.0 dan Society 5.0 Terhadap Pendidikan Di Indonesia. *Educatio*, 16(2),173–184.

Teplá, M., Teplý, P., & Šmejkal, P. (2022). Influence of 3D models and animations on students in natural subjects. *International Journal of STEM Education*. 1(2).

Thelma, C. C., Sain, Z. H., Shogbesan, Y. O., Phiri, E. V, & Akpan, W. M. (2024). Digital literacy in education: Preparing students for the future workforce. *International Journal of Research,* 11(8), 327–343.

Tondeur, J., Howard, S., Amélia, A., & Marijke, C. (2024). The DTALE Model : Designing Digital and Physical Spaces for Integrated Learning Environments. *Technology, Knowledge and Learning*, 29(4), 1767–1789.

Tzirides, A. O. O., Zapata, G., Kastania, N. P., Saini, A. K., Castro, V., Ismael, S. A., You, Y., dos Santos, T. A., Searsmith, D., & O'Brien, C. (2024). Combining human and artificial intelligence for enhanced AI literacy in higher education. *Computers and Education Open*, 6, 100184.

Uno, W. A. (2024). Pengembangan media pembelajaran interaktif berbasis augmented reality untuk meningkatkan pemahaman konsep IPA. *Jurnal Pendidikan Dan Pembelajaran*, 4(1), 28–33.

Wang, J., Li, W., Dun, A., Zhong, N., & Ye, Z. (2024). 3D visualization technology for Learning human anatomy among medical students and residents : a meta- and regression analysis. 1–12.

Wang, X., Liu, Q., Pang, H., Tan, S. C., Lei, J., Wallace, M. P., & Li, L. (2023). What matters in AI-supported learning: A study of human-AI interactions in language learning using cluster analysis and epistemic network analysis. *Computers & Education*, 194, 104703.

Yupani, E. V. I., & Widana, I. W. (2023). The Impacts of the Stem-Based Inquiry Learning Models on Critical Thinking and Concept Mastery. 7(1), 171–184.

Zhu, C., Sun, M., Luo, J., Li, T., & Wang, M. (2023). How to harness the potential of ChatGPT in education? *Knowledge Management & E-Learning,* 15(2), 133–152.

Ziatdinov, R., Atteraya, M. S., & Nabiyev, R. (2024). The fifth industrial revolution as a transformative step towards society 5.0. Societies, 14(2), 19.