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Article

Theoretical Foundations of Using AR/VR Technologies to Develop Ecological Competencies in School Education

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Abstract: Global environmental challenges require school education to develop not only students' ecological knowledge, but also their values, decision-making skills, and responsible behavior toward nature. Traditional text- and image-based instruction does not always allow learners to understand complex, long-term, or hardly observable ecological processes. Objective. This article aims to substantiate the theoretical foundations for using augmented reality (AR) and virtual reality (VR) technologies in the development of ecological competencies in school education. Methods. The study is designed as a conceptual and theoretical analysis. Pedagogical, methodological, and psychological sources on ecological competence, digital education, AR/VR tools, constructivist learning, visual learning, activity-based learning, and immersive learning were analyzed, compared, generalized, and systematized. Results. The analysis identifies four structural components of ecological competence: cognitive, activity-based, value-motivational, and behavioral. AR/VR technologies can support these components by visualizing ecological objects, modeling cause-and-effect relations, strengthening ecological empathy, and organizing practice-oriented decision-making tasks. Conclusion. AR/VR technologies should not be treated as a decorative digital supplement. Their educational value depends on alignment with lesson objectives, age-appropriate design, teacher readiness, reflection, and the integration of virtual tasks with real ecological actions.

Keywords: *ecological competence, augmented reality, virtual reality, school education, environmental education, digital learning, interactive teaching.*

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1. Introduction

Contemporary school education is increasingly influenced by global environmental problems such as climate change, decreasing water resources, air pollution, biodiversity loss, and waste accumulation [1]. These challenges require the education system to form students' ecological knowledge, practical skills, values, and sense of responsibility. For this reason, the development of ecological competencies has become a relevant direction in pedagogy and subject methodology [2].

Ecological competence refers to a learner's ability to understand the interdependence between nature and society, recognize environmental problems, approach their solution consciously, and make ecologically responsible decisions [3]. This competence is not limited to theoretical knowledge. It also includes ecological culture, practical activity, responsible behavior, and readiness to act in everyday life [4].

Traditional teaching methods are not always sufficient for explaining ecological phenomena in a complete and emotionally meaningful way. Many ecological processes are complex, long-term, or difficult to observe directly [5]. For example, the consequences of climate change, ecosystem imbalance, or the long-term impact of waste may remain abstract when they are presented only through written explanations, static pictures, or isolated examples [6].

In this context, AR and VR technologies offer new opportunities for environmental education. AR enriches the real environment by placing digital objects, images, models, and information layers over it [7]. VR places the learner in a fully simulated yet realistic environment, allowing ecological processes and situations to be experienced from within. These technologies can strengthen observation, analytical thinking, ecological awareness, and decision-making in problem situations [8].

The purpose of this article is to analyze the theoretical foundations of AR/VR technologies in the development of ecological competencies in school education, identify their didactic potential, and justify the pedagogical conditions for their effective use [9].

2. Methods

This study has a conceptual and theoretical design. It does not report an experimental intervention, a survey, or statistical testing. Therefore, the findings are presented as theoretically grounded propositions, implementation principles, and pedagogical conditions rather than as measured empirical outcomes.

The methodological basis of the study includes analysis, comparison, generalization, and systematization of pedagogical, psychological, and methodological sources related to ecological competence, digital education technologies, and AR/VR tools in education. The analysis also relied on constructivist learning, activity-based learning, visual learning, and immersive learning approaches.

The analytical procedure consisted of four stages. First, the concept and structure of ecological competence were clarified. Second, the educational potential of AR and VR technologies was examined from the perspective of learner activity, visualization, and immersion. Third, a conceptual model for using AR/VR in ecological topics was formulated. Fourth, the possible influence of AR/VR technologies on ecological competence was evaluated according to four criteria: acquisition of ecological knowledge, ability to analyze problem situations, attitude toward nature, and readiness for responsible ecological behavior.

The study also identified pedagogical conditions that must be considered in school practice: relevance of digital content to curriculum objectives, teachers' digital and methodological competence, availability of technical equipment, safety requirements, time limits, and age-appropriate design.

3. Results

The theoretical analysis shows that AR/VR technologies can contribute to ecological competence when they are integrated into lesson design as purposeful didactic tools. Their main value lies in transforming abstract ecological concepts into observable, interactive, and practice-oriented learning situations [10].

Table 1. Structural components of ecological competence and AR/VR-supported learning opportunities

Component of ecological competence	Content	AR/VR-supported learning opportunity
Cognitive component	Understanding concepts such as ecosystem, biosphere, natural resources, pollution, biodiversity, and sustainable development.	Three-dimensional models, interactive maps, virtual ecosystems, and visual explanations of ecological processes.
Activity-based component	Analyzing ecological situations, identifying problems, proposing solutions, and completing practical tasks.	Scenario-based tasks such as waste sorting, water-saving decisions, ecosystem restoration, and risk reduction.
Value-motivational component	Developing careful attitudes toward nature, ecological culture, internal motivation, and personal responsibility.	Immersive experiences that show polluted rivers, damaged forests, endangered species, or consequences of unsustainable behavior.
Behavioral component	Choosing environmentally responsible actions in everyday life, such as reducing waste, saving water and energy, and protecting nature.	Reflection tasks, virtual decision-making, and transfer of virtual experience into real-life ecological actions.

First, AR/VR technologies support the visual and interactive acquisition of ecological knowledge. Instead of receiving information only through text or pictures, students can work with three-dimensional models, virtual field trips, and simulated ecological environments. This helps them understand ecological concepts more consciously and retain them more firmly [11].

Second, AR/VR technologies make it possible to model ecological phenomena that are difficult to observe in real time. Deforestation, air pollution, water contamination, climate change, biodiversity loss, and ecosystem imbalance can be represented in a virtual environment. As a result, students can more clearly understand cause-and-effect relationships [12].

Third, VR can strengthen ecological empathy. When students virtually observe a polluted river, a drying forest, or an area filled with waste, they are more likely to perceive the problem not only intellectually but also emotionally. This experience can support the formation of ecological values and responsibility[13].

Fourth, AR/VR technologies can develop practical ecological decision-making. Scenario-based tasks such as sorting waste, reducing water consumption, selecting safe behavior during ecological risk, or planning a small ecological project encourage active thinking and responsible choice [14].

Fifth, AR/VR technologies support differentiated and learner-centered instruction. Students can study complex ecological objects at an individual pace and return to difficult fragments when necessary. This is especially important in heterogeneous classrooms where learners differ in prior knowledge, visual perception, and learning speed [15].

The most appropriate ecological topics for AR/VR-based instruction include ecosystems and food chains, climate change, waste management, protection of water resources, biodiversity, atmospheric and soil pollution, and the relationship between human activity and nature.

4. Discussion

The findings indicate that the role of AR/VR technologies in environmental education cannot be reduced to technical novelty. Their main pedagogical function is to make ecological content more visible, emotionally meaningful, and practically connected to learners' decisions. This corresponds to constructivist principles because students do not passively receive information; they interact with a simulated or augmented environment and build understanding through activity.

In the development of ecological competence, it is important that students not only understand an environmental situation but also express a personal attitude toward it. VR is particularly useful in this regard because it places the learner at the center of a situation. For example, observing a virtual forest fire, melting glaciers, or an area polluted by waste may stimulate emotional and moral responses to environmental problems.

AR has a different but equally important function. It connects digital information with the real classroom environment. For example, a textbook illustration may be supplemented by a three-dimensional model, a plant or animal may be presented together with information about its ecological role, and pollution zones may be displayed on a map. Such use is relatively easier to implement in school settings and can be combined with ordinary lessons.

At the same time, AR/VR implementation has limitations. Not all schools have sufficient technical resources. Teachers may also lack methodological preparation for designing AR/VR-based lessons. In addition, students' age characteristics, eye health, time limits, psychological comfort, and safety requirements must be considered. For this reason, AR/VR activities should be short, purposeful, and followed by discussion and reflection.

Effective use of AR/VR technologies requires several pedagogical conditions. The tools must be selected according to the lesson objective; students must be involved as active participants rather than passive viewers; virtual activities must be connected with analysis, discussion, and reflection; teachers need methodological recommendations and training; and digital technologies must be integrated with traditional methods, field observations, practical ecological actions, and project-based learning.

The theoretical value of AR/VR technologies can be summarized through the sequence "seeing experiencing understanding deciding." This sequence supports not only superficial memorization but also deeper and more stable formation of ecological competence.

5. Conclusion

AR/VR technologies have a strong theoretical and didactic basis for developing ecological competencies in school education. They help visualize ecological knowledge, model complex environmental phenomena, form ecological values and responsibility, and develop practical decision-making skills.

Their educational potential is especially evident in bringing environmental problems closer to real life, strengthening students' emotional and intellectual participation, and supporting interdisciplinary integration. However, these technologies can be effective only when they are methodologically justified, technically accessible, safe, age-appropriate, and connected with reflection and real-life ecological behavior.

Further research should include experimental testing of AR/VR-based ecological lesson modules, development of age-specific digital resources, and practical assessment of their effectiveness in forming students' ecological competencies.

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