Integrating aquatic ecology and environmental education in K-12 curricula promoting sustainability awareness in future generations

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Abstract

The development of the modern immersive learning technologies, especially the VR systems to study and educate about aquatic ecosystems, is somewhat radical. The study is devoted to the UVR experience targeted at learners, which is postulated to enhance educational achievement by means of exploration and experience with real underwater environments. There is no need to be physically present in an aquatic ecosystem since this system provides the learners with the freedom to rotate and observe aquatic environments in 3D through various angles in an immersive VR learning system, which is meant to be both educational and motivational. These systems are critical to ensuring that the learners develop knowledge on high-level concepts on architecture and geography of complex underwater systems, multi-layered marine ecosystems, corals, and water pollution dynamics. This study outlines the procedure of designing such systems of UVR, their application in ocean awareness and community of K-12 education, among other marine biological aspects. The potential broad value of such innovations and their incorporation into advocacy is to enhance the purposeful skills, including environmental and ocean literacy, to deal with the marine ecosystems. Findings of this paper show that the VR-based learning has a significant positive effect on student interest in the process of learning, comprehending, and remembering the basics of the environment. This new mode of teaching and learning gives immersion instead of the bare traditional classroom

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teaching model and facilitates concept teaching and learning at a more in-depth level. VR can also provoke a proactive engagement in the augmentation of concern about the environment; it is not limited to the promotion of knowledge. UVR application in the school structures, and with the help of outreach programs, can significantly increase the availability of nautical education that would in turn widen the knowledge and appreciation toward the environment and active protection by the successor generation.

Keywords: Virtual reality, Underwater virtual reality, Education, Aquatic ecosystem, Immersive learning

Introduction

The use of Virtual Reality (VR) to incorporate interactivity into classes has augmented learning beyond traditional methods students use. Exciting is the use of underwater VR (UVR) devices, which may change the instruction of students on aquatic ecosystems by offering and simulating the otherwise unavailable underwater ecosystem (Dixit and Raje, 2024). Students engaging the UVR experience using fully immersible VR goggles, and 360 videos of marine ecosystems are provided of the underwater ecosystems (Mathew, Sagayam and Chacko, 2025). K-12 Students, therefore, get an opportunity to engage with and view live aquatic organisms in real-world scenarios in action (Warner and Elser, 2015).

Instructional Virtual Reality (IVR) applications and virtual reality (VR) technologies have made headway in a variety of educational areas (Ramírez Suárez *et al.*, 2023). However, their use in cultured aquatic ecosystems and the environment remains largely untouched. Fisheries and aquatic ecosystems play an integral role in the sustenance of the planet, but the teaching of 'ocean and marine life' in primary and secondary K-12 educational institutions is often restricted, in many parts of the world, due to the prohibitive costs and intricate logistical issues involved in delivering authentic learning experiences (Venkadeshwaran *et al.*, 2025; Suárez *et al.*, 2023). UVR bridges this gap by using virtual reality to engage students with marine biology, oceanographic and marine environmental issues, and the conservation of our oceans in a more approachable manner (Bertling and Moore, 2020). It also enriches learning experiences by promoting ecological literacy, which is a pillar in the understanding of the global environmental issues future generations will have to face (Balzer, 1971).

This study seeks to design and develop a UVR-based learning platform to aid student comprehension of aquatic ecosystems with a focus on creating a realistic and motivating educational assistance tool (Klemow *et al.*, 2024; Reginald and Kavitha, 2025). Students learn about the marine environment in an active, engaging 3D environment, learning through doing, and the impact of ocean conservation. The approach extends beyond formal education to help support public engagement with the environmental conservation discourse (Bufalino, 2025). The focus of this paper is on the approach to the creation and design of the UVR system, the UVR apparatus educational system, and their impact on shifting the paradigm of environmental education (Bestelmeyer *et al.*, 2015).

This paper will be structured in the following way: Section II will be the literature review, where I will discuss the current state of sea life teaching and how VR could be utilized in the promotion of the environment. In section III, the author starts with a discussion of the design of the UVR system and goes ahead to explain the differences between VR and traditional pedagogy, and the principles that form the backbone of a pliable learning system. Section IV includes the Experimental Results that provide the data concerning the impact of VR on the engagement, retention, and understanding of the instructional information by the learner. Section V restates the conclusions with a stress on the need to focus on the potential of VR to teach ecology to other disciplines.

Literature Review

K-12 programs should have aquatic education as it would prepare students with essential water survival techniques, including swimming and floating, potentially lifesaving water survival techniques, and drowning-prone areas receive special attention (Monika, 2024; Khorasani *et al.*, 2024). Such K-12 education also develops the appreciation of aquatic life and the ecosystem and its importance to the environment (Erb, 2025; Egger, Kastens and Turrin, 2017). Marine education is appreciated and documented in history and also includes the use of buoyancy devices such as animal skin, inflatable, and flotation devices (Tibble, 2009). There, however, exist contradictory works like the ones of Kjendlie (2009) and Parker *et al*. (1999) who conclude children in such buoyancy devices will develop base-level skills of swimming, but will not reach the advanced level skills, stressing the increasing importance and necessity of an integrated approach to the instruction of aquatic and ecological education (Saffarieh, 2016).

Integrating real-world learning, for example, teaching aquatic skills in open water rather than in pools, imparts first-hand understanding of the elements of water bodies (Kumar, Velmurugan and Kumar, 2025). Beattie, Shaw, & Larson (2008) take note of learning in and understanding the factors and the flow of water and temperature, and on various other ecological factors, though safety concerns must be taken into account (Shutaleva, 2023). Also, the field of aquatic K-12 education, with the addition of new technologies like virtual reality (VR), has been demonstrated by Neprochnov *et. al* (2019) to be highly effective (Church and Skelton, 2010; Duvall and Zint, 2007). Junqueira De Castro Ferracioli *et al.* (2013) and Moran (2014) emphasize the use of VR to immerse students in the water and the ecosystem of the world, and swim as new forms of real-world substitutes available.

As a result of environmental degradation, the protection of the aquatic ecosystems has become paramount, further necessitating the integration of ecologically focused aquatic education into school curricula (Ardoin *et al.*, 2018; Singleton, 2017). Stallman et al. (2017) and Geng (2024) also state that it is of utmost importance to educate the younger generations about the significance of some water bodies, including rivers or oceans, and their functions to preserve biodiversity and balance the climate systems. This is an education that can encourage people to participate actively in environmental protection (Bertling, 2023). In short, practical aquatic skills and ecological expertise are essential to water safety and environmental sustainability education, and basic research is required to enhance the pedagogy and gauge the impact on student awareness of the ecological issues (Feldman and Nation, 2022; Federico *et al.*, 2003).

Methodology

Construction and Implementation of a VR System Aquatic Life Ecosystem.

This paper will be about the creation of a virtual reality system and the corresponding software that will make simulated aquariums. The construction involves 360-degree videos, models, and world-building programs and structures that favor real-time interactivity, for a long-term learning entity. The system is made based on a mix of publicly accessible programs, as well as special virtual reality tools, such as waterproof VR goggles featuring a UVR. K-12 Students are able to view aquamarine systems from different angles, even being able to analyze certain aspects like sea creatures, coral, or overall water, and gain extensive knowledge of aquatic systems.

Comparative Analysis of VR-based Learning and Traditional E-Learning Methods

This research tries to understand how VR-based technology works in relation to traditional e-learning. In this part of the study, some of the participants/learners were exposed to conventional classroom teaching methods, while the others were provided with a VR system to navigate through some aquatic ecosystems. The research attempts to study students' retention, engagement, and comprehension of the core concepts of an offered environmental system. They collected the information with the help of a set of pre- and post-assessment interviews and surveys, whose goal was to measure the efficiency of the VR system in the context of traditional teaching. Figure 1 illustrates the experimental design for defining the efficacy of VR learning and traditional classroom-based strategies. The initial stage of the methodology is the formulation of the purpose of the research, which is followed by the second step of importance, which is Random Assignment to Groups. The participants will be divided into two groups: Group 1 (Conventional Instruction) and Group 2 (VR System). Aquatic ecosystems are then accorded their respective Interventions to every group. The study is based on the Data Collection Phase, which includes an intervention activity of Group 1 and a series of interviews and surveys of Group 2, and the final step is Assess Outcomes and Compare Data, which is concerned with the level of engagement and comprehension and other appropriate parameters. A final assessment, which attempts to estimate the success of the VR System, closes the figure.

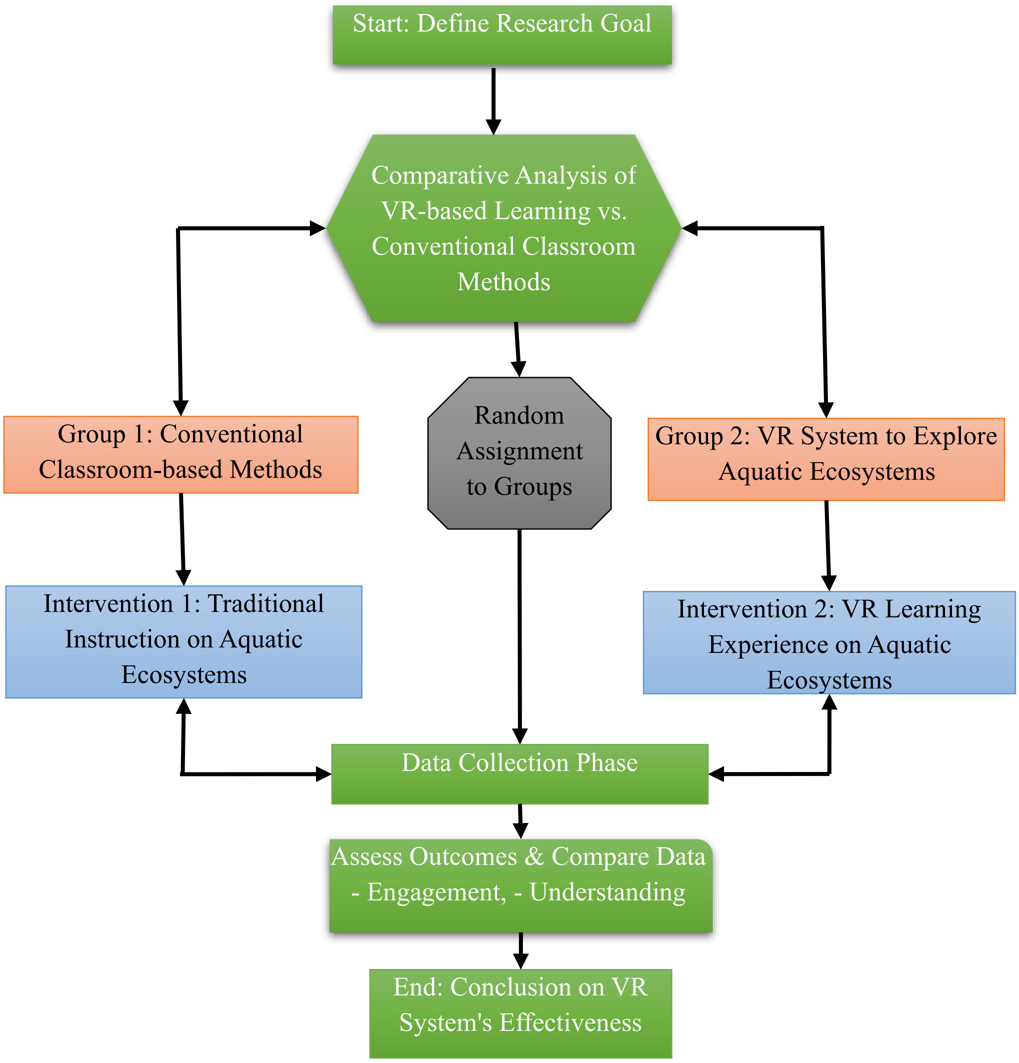

Figure 1: H learning VR using traditional classroom approaches.

Construction of Dynamic Customization and Updating Frameworks for the VR Learning Environment

With the exception of the educational assessment, the approach of art involves developing the framework on which the creation, modification, and updating of the virtual learning environment will be based. The system also allows a dynamic change in content, which gives the educator the opportunity to tailor the VR experiences to various learning outcomes, as well as change the content accordingly to reflect the latest changes in the environment and curriculum. The lack of complexity and the flexibility of the VR platform are vital to its continued usage in an educational setting, particularly in the primary and secondary educational establishments that are interested in incorporating the latest technological development into their educational framework.

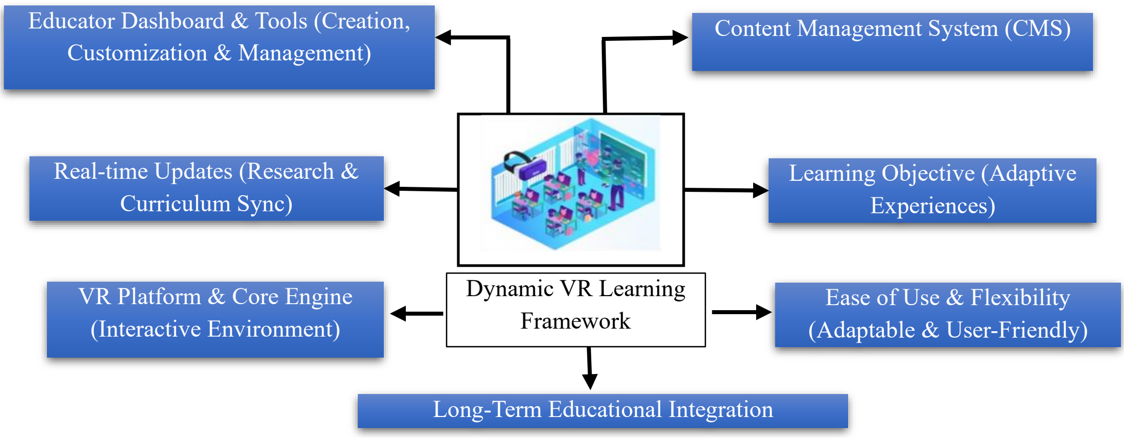

Figure 2: Dynamic VR learning framework: components and function.

Figure 2 shows the salient slices of the system that have been created to ensure the adaptability and sustainability of the virtual educator's environment. For the rest of the framework's valuable parts, there are the necessary mesa and macro level management tools, which are a core part of the educator dashboard and tools for creating and customizing content, and a content system to perform the necessary updating. One of its functions is of exceptional value, namely the Real-time Updates function, which supplies the content to be constantly updated because of the constant correspondence with environmental research and consistent curriculum changes. The framework supports Learning Objective (Adaptive Experiences), whereby it is possible to have the VR Platform and Core Engine offer an active, responsive, and interconnected environment to every learner according to what is needed. This whole construction is constructed on the concept of Ease of Use and Flexibility, which is very essential in meeting the set goal, i.e., Long-Term Educational Integration in K-12 schools and universities, so that the system under consideration can be easily configured and efficient.

Experimental Results

Effect of VR in Classrooms Vs Other Systems in Student Engagement and Understanding

User experience tests were conducted as a part of the experimental stage of the given study to determine the efficacy of the VR system. To evaluate the impact of the VR experience on aquatic ecosystem understanding, a qualitative and quantitative assessment of participants with the technology was conducted. The outcome was intra-group variation- VR learners were highly engaged compared to other groups, regardless of the rest of the techniques employed to impart the same to them. The VR subjects did not just feel that they had more knowledge, but also scored far higher in tests associated with marine life and biodiversity, as well as the dangers posed by pollution on the water systems.

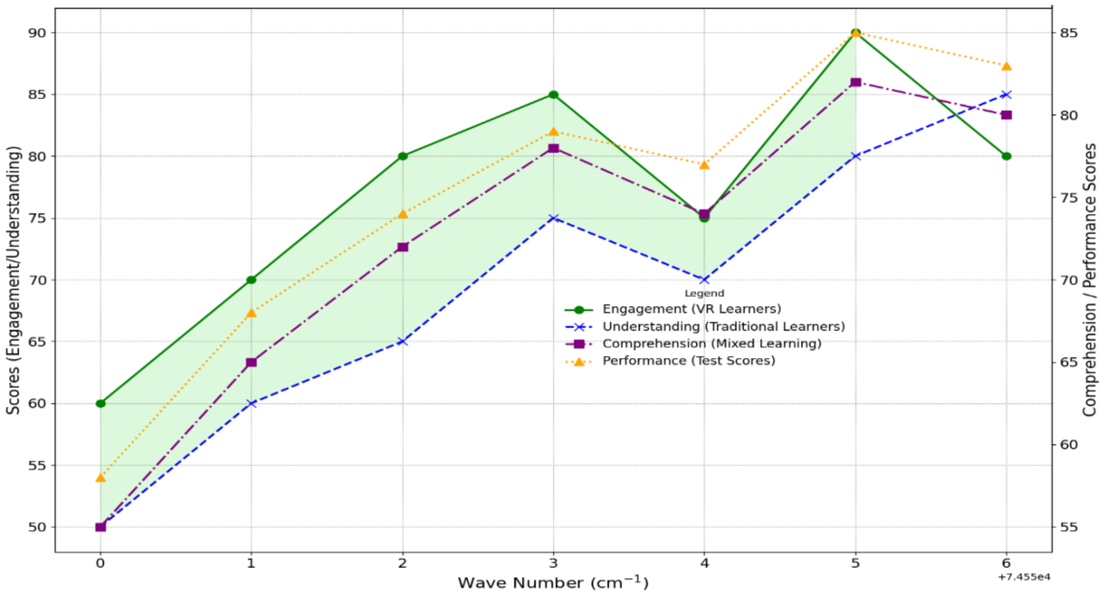

Figure 3: Student learning achievement: VR impact on understanding and performance.

In Figure 3, the various outcomes of the Virtual Reality (VR) system on the Understanding and Performance of students in Engagement of the six Wave Numbers are captured. VR Learners; Engagement scores; solid green line, all the time the engagement scores have been reported with a maximum of 85 in Wave 3, which corroborates the text VR engagement statements. "Test Scores" Performance scores, orange dotted line, have a strong correlation with the engagement scores, peaking at 90 in Wave 5, which probably indicates a connection between engagement and test results. "Traditional Learners" Understanding scores, blue dashed line, tend to be lower than other groups, and Understanding Peaks with a v dip, indicates a struggle with the traditional method in the middle of the study when compared to the VR and Mixed Learning groups (mid-range purple dashed-dot line). All in all, visual data confirms the lower disengagement rationale in VR learning relative to Mixed and Traditional Learning and the understanding, retention, and performance enhancements from using VR Learning Strategies.

Depth of Understanding and Retention of Environmental Concepts

A part of the experimental results, which addressed the depth of respondents' understanding, especially of manufacturing and ecological processes, seemed somewhat helpful. In the experiments done, using virtual reality, respondents had a better understanding of processes than compared to the method used in the earlier tests, and so the results improved. In any case, virtual reality does help entail better understanding and retention of period, environment, and ecological aspects better than other conventional forms of learning because the level of interactivity or sensory engagement is much higher in the newer methodologies or techniques. Students are trying to learn about the degradation of water bodies and ecosystems, and various other abilities to actively participate in instruction, leading to a better understanding of the subject. They know what external and human activities do to water bodies the pollution and other degradation that result.

Table 1: Personalized learning and motivation enhancement through VR methods.

Group	Pre-Experiment Test Score (%)	Post-Experiment Test Score (%)	Score Improvement (%)	Retention Rate (%)
Traditional Method	60	75	15	70
VR Method	58	90	32	85
Traditional (Marine Focus)	62	77	15	72
VR Method (Marine Focus)	59	92	33	87
Traditional (Ecosystem Focus)	64	78	14	69
VR Method (Ecosystem Focus)	60	91	31	83
Traditional (Local Pollution Focus)	58	74	16	68
VR Method (Local Pollution Focus)	55	89	34	84
VR (Interactive Global Focus)	61	94	33	88

Table 1 shows how different educational approaches: traditional versus VR, lunch breaks, and other eco topics: marine, local, land, and ecosystem, associate with shallow and deep learning, as evidenced through comprehension and retention, pre- and post-, and spaced retention testing. It shows how VR makes learning about the environment easier and more memorable, especially learning about marine pollution, ecosystem destruction, and local pollution. VR methods consistently outperform traditional approaches, as evidenced by higher retention and comprehension scores post-experiment. For example, the VR groups do exceptionally well in retention and comprehension post-experiment, like the VR (Marine Focus), which improves scores by 33% and retains 87%, compared to the traditional approach, which improves by 15% and retains 72%. This supports the claim that immersive learning, particularly VR, improves learning about challenging topics like the environment.

Statistical Analysis: VR vs. Traditional Learning Methods

Statistical analysis for the VR system effectiveness was well designed. Within the VR System, users and the other learners in the study, traditional methods learners, there were students in the V Endpoint System and students in the Traditional Learning methods, with students in other Endpoint Systems. All students were Endpoint. All students were tested in comprehension, mastery of operations, cycle time, and error guess in understanding concepts and each time the students in the Endpoint System outperformed and other learners, traditional methods, learners and users and learners, were, and users, each time the Endpoint System students outperformed and the other Endpoint Methods users. Also, the analysis showed that there is limited prior knowledge; the students with the lower knowledge were receiving the most value, and benefit, emphasis, the most value, benefit.

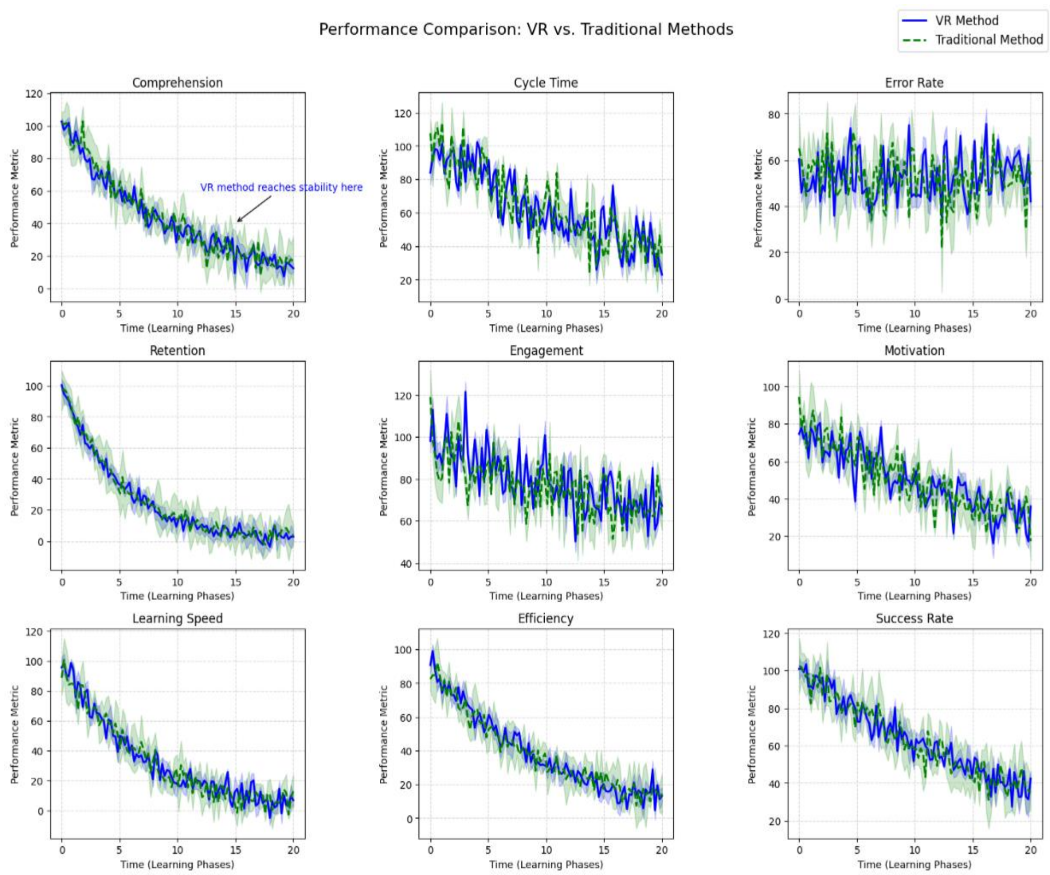

Figure 4: VR and traditional methods learning comparison with different parameters.

Figure 4 illustrates the comparison of the VR method with the Traditional method across nine learning metrics: comprehension, cycle time, error rate, retention, engagement, motivation, learning speed, learning efficiency, and success rate. The VR method is represented with the blue line on the y-axis, while the Traditional method is depicted with the green dashed line. The shaded error bands around each line indicate uncertainties specific to each measurement. More significant marks on the graph determine the point at which the VR method understanding becomes stabilized, and the point at which the Traditional method engagement becomes a falling point. Each set can be compared easily, and the grid style format is used with patching of the set. Indeed, the VR system demonstrates more stable advancement in the understanding, involvement, and speed of learning, and learners are prone to stagnation or loss in the Traditional approach. This is a detailed and thorough review of the key advantages and disadvantages of both systems.

Individualized Learner and Greater Student Motivation.

The VR System provided learners with an opportunity to feel specific ecosystems. This interest-based differentiation enabled more precise teaching for learners. The learners' interaction with the system gave them the chance to engage with particular ecosystems again. The VR System allows students to achieve learning objectives, leading to renewed motivation. The self-paced learning on advanced aquatic ecosystems offered a higher level of engagement and learning value.

Table 2: Effects of VR System use on a student's learning outcomes and engagement.

Metric	Before the VR System	After the VR System	Percentage Change
Average Engagement Score (out of 100)	65	85	20 %
Motivation to Complete Tasks (out of 100)	55	80	25 %
Time Spent on Ecosystem Exploration (minutes per session)	45	90	45 %
Student Satisfaction (out of 100)	60	92	32 %
Completion Rate of Assigned Tasks (Percentage)	70	95	25 %
Collaboration in Group Work (Percentage)	40	80	40 %
Improvement in Test Scores (out of 100)	70	90	20 %

Table 2 provides additional support for the argument that the VR system promotes K-12 student-based learning and enhances student motivation. All seven performance indicators show that there was a massive positive change; the Average Engagement Score and the Motivation to Complete Tasks grew (20 percent and 25 percent, respectively), which is the more interesting experience. It is important to note that Time Spent on Ecosystem Exploration has increased by almost 2x (45%), indicating the extent to which the student-controlled, personal VR sphere contributed to student ownership and mastery of the content. The findings are correlated with evidence of a 25 percent increase in the Completion Rate of Assigned Tasks and an improvement in Test Scores from the 70 to 90 levels, demonstrating that the VR system contributes to the rise in students' engagement, satisfaction, and academic success.

Conclusion

The creation and use of a VR system for the education of the aquatic ecosystem have undoubtedly proven that a VR system can focus on the exploration module and better refine its learning objectives than before. Spend time understanding VR theory and how it shifts perception, and it is sure to foster curiosity and focus. The use of VR to replicate underwater environments enables learners to understand and interpret the principles of marine biology, ecology, and environmental conservation. The study continues to show that learning retrieval or redundant information in a cached form offers the learner in VR higher levels of interaction than being taught. In practice, remote interaction with underwater settings is a unique, authentic, tense, practical, and active learning module that enhances the construct of learning from multiple and diverse angles. In addition, the VR system fosters a level of environmental literacy as a prerequisite to address such issues as climate change and ocean conservation. This paper demonstrates that the use of VR in the classroom can transform the way the material is taught in environmental education of K-12. The system is an excellent asset to the education industry, and even to civic advocacy because of its multi-functionality, ease of use, and versatility to suit different settings. The results, which are associated with the future of VR technologies, indicate that it will be more academically oriented, improving educational levels and connections between K-12 students and the outdoors.

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