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*Original Article*

# Multiplatform Virtual Simulation of Immersive Environmental Impact using Mixed Reality and 360° Camera

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***Abstract*** - *Environmental awareness and sustainable waste management by human actions is a great important challenge that is faced today, even educational institutions being so busy daily, some of the individuals do not respect their environment, causing their space to look sometimes poorly cared for or have a bad appearance. Therefore, the objective of the present study was to develop and evaluate an immersive multiplatform system for visualizing environmental impact through the integration of 360° panoramic images, mixed reality technologies and the WebXR environment. For this, it was selected to use the spaces of the University of Sciences and Humanities (UCH) in Lima, Peru. The methodology used was Extreme Programming (XP), because it allows adapting to changes in functional requirements. In addition, the study employed tools such as a Kandao QooCam 8K Enterprise camera, aerial photographs obtained with a DJI Mini 2 drone and then deployed on a multiplatform platform based on WebXR. The system allows the user to be able to walk around as if they were physically in that environment under different environmental conditions, including scenes with proper handling of garbage waste and other types of visible accumulation. In addition, as part of the results, an expert validation survey was carried out, where the results proved to be mostly positive in both accessibility and usability. In addition, they confirmed the viability of the developed system, which guarantees the usefulness of the system to educate people about their environmental environment. As future work, it is suggested to carry out tests with a large number of scenarios and in other types of spaces.*

***Keywords*** - *WebXR, Civil engineering informatics, WebXR, 360° imaging, Mixed Reality, Environmental awareness.*

## 1. Introduction

In recent years, accelerated urbanization and the growth of people's activity have caused environmental problems to increase in urban areas [1, 2]. Likewise, pollution, accumulation of garbage waste, the deterioration of green spaces and loss of public spaces have become many of these factors that have a direct impact on the quality of life of the population [3]. But, although there are environmental programs and information campaigns, many of the negative impacts that still persist are going unnoticed on a day-to-day basis. Most people think that environmental issues are far away, which makes it difficult to change habits or ways of acting more responsibly [4, 5].

Traditional methods of evidencing environmental information, such as photos, videos and two-dimensional graphics, only allow limitations to be presented, since they only show the parts of the problem, without showing that citizens can fully assess the interrelationships between the various environmental elements [6, 7]. In addition, in cities where everything is connected, such as traffic, buildings, green areas, sources of pollution. All these influences at the same time, it is for this reason that traditional forms fail to capture this complexity [8].

In this sense, immersive technologies such as virtual reality, augmented reality and mixed reality are increasingly capturing the attention of researchers. Because of this, recent research shows that the use of immersive environments is promoting greater environmental awareness among citizens, showing a better understanding of environmental processes and a more responsible attitude towards sustainable development issues [9, 10]. Thanks to immersive technologies, people can see and feel the reality of their environment, as if they were inside it.

Along with all these technologies, the use of panoramic images and 360° video is rapidly imposing more presence

[11]. They allow you to show a complete and realistic omnidirectional view of the environment, visualize the spatial characteristics of objects without the limitations of a traditional frame [12, 13]. They use it for monitoring urban areas, for education, and even to create replicas of real spaces.

On the other hand, there is WebXR, it is a technology that makes it easy to create an immersive experience directly from the web browser without the need to install specialized software. All this guarantees cross-platform compatibility between other computers, mobile devices and immersive viewers, which extends the accessibility of virtual environments to a greater number of users [14]. However, although these technologies have grown rapidly separately, the scientific literature shows little research where the combination of all these technologies together to address these types of environmental problems can be visualized.

Therefore, the present study was carried out at the University of Sciences and Humanities (UCH), which is located in the district of Los Olivos, Lima, Peru. The objective was to develop and evaluate an immersive multiplatform system for visualizing environmental impact through the integration of 360° panoramic images, mixed reality technologies and the WebXR environment.

Despite the existence of immersive technologies, previous research on the visualization of environmental problems is still characterized by the fragmented use of virtual reality and panoramic imaging technologies. Likewise, most of the solutions proposed by other researchers only focus on educational visualization or environmental documentation, but do not consider a unified multiplatform architecture capable of integrating real-time environmental data on multiple screens in which it can be accessed directly through a web browser. On the other hand, it has been shown that there are few studies in which work has been done on this integration that can provide the same accessibility on desktop computers, mobile devices and immersive viewers without requiring the installation of specialized software. Therefore, the need arises to develop and evaluate a unified WebXR system that can combine 360° visualization of real-world spaces with immersive interaction and thus facilitate the comparison of different ecophilological environments.

## 2. Related Works

### *2.1. Immersive Technologies for Environmental Awareness*

In recent times, Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR) technologies have been increasingly employed in the field of environmental education and sustainability. Recent studies indicate that immersive environments promote a much deeper understanding of environmental problems that persist even compared to conventional learning methods, as they help people become aware of the environment, develop better habits for the benefit of their environment, and become more responsible [15, 16].

However, despite the positive results, most of the existing research only focuses on educational virtual reality scenarios and very few consider exploring the integration of mixed reality with 360° panoramic images and web technologies for different devices [19]. From this arises the need to continue researching to create more innovative environmental visualization systems that are immersive and accessible, through real-world environmental data and allow them to be accessible to all types of devices.

### *2.2. 360° Imaging and Environmental Visualization*

Advances in 360° panoramic imaging technologies have opened up new possibilities for interpreting, studying, and documenting the environment. Unlike traditional images and videos, this type of panoramic image allows you to capture the entire space in all directions simultaneously; In this way, it helps to have a better understanding of the space being analyzed [20]. Thanks to the accessibility of modern 360° cameras, this type of data is increasingly used in environmental environment research, monitoring of urban spaces, green space assessment, and recording spatial environmental change.

In addition, recent research shows that panoramic visualization allows users to have a deeper perception of the spatial context compared to what traditional visual materials offer, because it allows people to explore the environment independently and thus observe details that sometimes go unnoticed [21]. It should be mentioned that the integration of panoramic data with drones, geospatial technologies, and sensor systems allows for the creation of more detailed and informative digital representations of real-world objects and territories [22].

However, while 360 technologies have great potential, most existing research focuses on environmental monitoring or educational virtual tours. According to the scientific literature, there are limitations in research that integrates 360° images with mixed reality technologies and web platforms for the creation of immersive environmental scenarios based on spaces of reality [23]. This leaves the door open for users to increasingly innovate by developing new solutions capable of combining the benefits of panoramic photography, ambient visualization and access within a single system.

### *2.3. WebXR for Immersive and Multiplatform*

Experiences The advancement of technologies has led to the emergence of the WebXR standard, as it allows virtual, augmented and mixed reality applications to be created directly from the browser, without the need to install specialized software. On the other hand, one of the benefits is compatibility with modern web standards. According to recent research on educational technology, web-based XR systems have reported high levels of usability and good acceptance by students, as they are simple to use [24].

WebXR has been actively applied in educational platforms, engineering simulations, geographic data visualization, and collaborative learning systems. Likewise, a systematic review analyzed more than 38 immersive learning studies; the majority of users indicated greater engagement, motivation, and understanding when working in XR environments compared to traditional digital resources [25]. Similarly, some research on WebXR in educational environments also reported high rates of user satisfaction and participation, which would confirm the great potential of this technology for the creation of immersive and accessible learning and viewing environments [26].

While there is a growth in research into the use of WebXR, most of the solutions that already exist are only focused on medical training, engineering education, and virtual labs. On the other hand, the use of WebXR for the analysis of real environmental spaces from 360° panoramic images is still scarce, since it is an area that is little studied [27]. Therefore, in the present study, the use of WebXR has been considered for the creation of a cross-platform environmental visualization system that can be accessible and capable of facilitating an immersive interaction of the user with real spatial data.

Unlike other studies that were reviewed, in which they used WebXR and immersive technologies to perform educational simulations, virtual labs, or individual XR scenarios, the present study uses WebXR as a unified cross-platform environment for the visualization of real-world 360° panoramic data. Also, the proposed system makes it possible to access the same environment from a desktop computer, a mobile device, and a virtual reality headset, thus expanding the reach of its WebXR application beyond traditional educational solutions.

### *2.4. Environmental Perception and Presence in Virtual Environments*

One of the benefits of immersive technologies is their ability to transform the perception of the environment, generating in the person a sensation as if they were really in that place. This allows the user's attention to be captured by focusing not only on individual objects, but also by relating to environmental elements, which is important for analysing the environmental conditions of urban spaces [28]. Unlike traditional photographs and videos, immersive environments allow for a better interpretation and understanding of the spatial context and the impact of human activity on the environment.

This approach is relevant and very significant in environmental education and awareness programs. Some of the studies in recent years have shown that users who interact with immersive environmental scenarios show a greater understanding of environmental issues and a more marked emotional response compared to users who use traditional multimedia materials. For example, a study of 142 participants, which visualized the melting of a glacier, revealed that the use of virtual reality contributes to a more significant increase in environmental awareness compared to text and video materials [28]. Similarly, a meta-analysis of educational virtual reality systems revealed a statistically significant increase in participation, motivation and information retention in immersive environments [29].

To visualize the environmental space of urban areas, the combination of immersive experiences of real 360° panoramic images is relevant, because it allows people to observe not a virtual scene as if it were fictitious, but a digital representation of an existing place, preserving its characteristics and spatial relationships of the real environment. This translates into an authentic perception of the environmental conditions of the area studied, which would strengthen greater environmental awareness and turn immersive technologies into a promising tool for visualizing environmental problems in both university and urban spaces. It has been observed that existing studies analyze only the effects of the presence and perception of the environment in virtual scenarios. On the other hand, the approach proposed by the study uses real panoramic images of the university environment and, in this way, allows comparisons of different environmental conditions within the same space, thus establishing a direct link between the immersive experience and the environmental conditions of the real world.

### *2.5. Research Gap*

A review of the literature has shown that modern research confirms that, although immersive technologies have great potential and effectiveness to disseminate and improve environmental awareness, they reveal an important potential in 360° panoramic images for the visualization of real spaces and for monitoring the environment [30]. On the other hand, WebXR technologies are increasingly used to create virtual environments accessible to different devices, such as computers, mobile devices and immersive viewers. However, the vast majority of existing research explores these areas separately, some focusing on environmental education in virtual reality, others on the use of panoramic images to document spaces or the development of XR applications through the web.

Despite the fact that progress has been seen, the number of studies that carried out the integration of mixed reality technologies, 360° panoramic images and the WebXR platform for the visualization of environmental conditions in university environments of reality is still limited. In particular, for the creation of accessible immersive systems based on real spatial data, aimed at strengthening the person's environmental awareness, they have not yet been explored in depth [31]. Likewise, the gap in the research served as a starting point for the development of the proposed multiplatform environmental impact visualization system, which is proposed in this study, implemented on the campus of the University of Sciences and Humanities (UCH) in Lima, Peru.

Unlike technological solutions already existing by other researchers, in which WebXR, panoramic visualization and immersive technologies are applied separately, the system proposed in the present study combines these components in a unified multiplatform architecture. Likewise, its main technical contribution lies in the integration of real-world 360° panoramic scenes with WebXR to visualize them on desktop computers, mobile devices and immersive virtual reality glasses without requiring the installation of specialized programs. On the other hand, the proposed system differs from others since it allows a comparison of the different environmental conditions of the same real space in an interactive environment, which extends the application of WebXR from a simple visualization to a tool of environmental scientific analysis.

## 3. Materials and Methods

### *3.1. Study Area and Ethical Considerations*

This present study was carried out on the campus of the University of Sciences and Humanities (UCH), located in Los Olivos, Lima, Peru, which is an educational space in an urban area where a large number of students, teachers and administrative staff circulate daily. On the other hand, the choice of this campus was due to the fact that, being a large space and being used daily, as well as being used daily, as well as it was necessary, including academic buildings, pedestrian routes, recreational areas and adjacent public spaces, to create nearby scenarios. It also presents environmental conditions in relation to waste management, the state of common spaces and the interaction of users with their academic environment. Therefore, due to the combination of spatial characteristics of the real environment and the constant high flow of people, the UCH campus provides an ideal space to develop and evaluate a multiplatform environmental visualization system based on mixed reality technologies and 360° panoramic images. Likewise, for the taking of photos and visual records of the university environment, the corresponding authorization was obtained from the University's Research Directorate, which approved both the protocol for capturing common spaces and the processing of visual data. It should be mentioned that the people who appear in the photographs taken incidentally in the panoramic shots were recorded in an unidentifiable way.

### *3.2. Data Collection Equipment*

For the capture of panoramic images and the creation of immersive environmental scenarios, a set of equipment was used, which included a Kandao QooCam 8K Enterprise camera, a DJI Mini 2 drone and a DJI Osmo Mobile 6 stabilizer. The devices were also selected to be able to capture high-quality images of the study area from both the observer's perspective and an aerial view. Thanks to all the specialized equipment, the panoramic scenes of great detail, stable recording and complete spatial coverage of the university space were guaranteed. For this, the technical specifications of each device used are presented in Tables 1 to 3.

**Table 1. Technical specifications of the Kandao QooCam 8K Enterprise 360° camera**

| Parameter | Specification |
|---|---|
| Type | Dual-lens 360° panoramic camera |
| Sensors | 2 x 1/1.7" CMOS ×, 20 MP per Sensor |
| Lenses | Lenses Dual lens F2.0, FOV 200° per Lens |
| Video Resolution | 8K (7680 × 3840) at 30 fps; 4K at 120fps |
| Color Depth | 10-bit video; SuperHDR DNG photo up to 16-bit |
| Bitrate/codec | Bitrate/codec Up to 150–200 Mbps; H.265 / H.264 (MP4) |
| Stabilization | Integrated 6-axis gyro |
| Connectivity | Wi-Fi 2.4/5G, Ethernet (8K live streaming) |
| Display | 2.4" touch |

Table 1 shows the technical specifications of the Kandao QooCam 8K Enterprise camera, which the team mainly used to capture panoramic images. Due to the 8k resolution, its dual optical system and its compatibility with HDR ensured that the 360° images can preserve their spatial characteristics of the study area and can create immersive and very realistic scenarios for their subsequent visualization phase.

**Table 2. DJI Mini 2 drone technical specifications (overhead views / context)**

| Parameter | Specification |
|---|---|
| Take-off weight | < 249g (includes battery and microSD) |
| Camera sensor | 1/2.3" CMOS, 12 MP |
| Lens | FOV 83°, 24 mm equivalent, F2.8 Fixed aperture |
| Video Resolution | 4K at 24/25/30 fps; 2.7K and 1080p |
| Photo Resolution | 4000 × 3000 (4:3); JPEG and RAW (DNG) |
| Stabilization | 3-axis mechanical gimbal |
| Flight autonomy | Up to 31 min per charge |
| Transmission / Control | OcuSync 2.0; DJI Fly app; Wind resistance level 5 |
| ISO | 100–3200 |

On the other hand, Table 2 shows all the technical specifications about the DJI Mini 2 drone, which was used for the photographic shots of the area and thus can obtain an overview of the university area. The photographs complemented the panoramic images at the dream level, which provided context on the layout of the buildings, green areas and infrastructure of the surrounding urban area.

**Table 3. Technical specifications of the DJI Osmo Mobile 6 stabilizer**

| Parameter | Specification |
|---|---|
| Type | 3-axis handheld stabilizer (gimbal) |
| Weight | 305 g (gimbal); Magnetic clamp ≈ 25 g |
| Stabilization | 3-axis mechanical, anti-vibration |
| Extension rod | Integrated, extendable up to 215 mm |
| Mechanical Range | Motorized panning, rocking, and tilting |
| Battery life | ≈ 6 h 24 min |
| Charging Time | ≈ 1 hr 24 min (USB-C, 10W) |
| Function | Stable support for shake-Free 360° Shooting |

Finally, Table 3 presents the specifications of the DJI Osmo Mobile 6 stabilizer, which was used to improve the stability of the DJI Osmo Mobile 6. Its three-axis system allowed for the minimization of unwanted movements and vibrations during image capture. This process ensured that all captured images look of better quality for post-processing within the immersive environment.

### 3.3. Software Platform and Multiplatform Deployment

The processing of the images taken consisted of adjustment, preparation and export as 360° scenes for subsequent integration into the virtual environment. In addition, SimLab 360, the Three.js library and WebXR were used to build the immersive web platform, which allowed interactive 3D scenes to be created directly in the browser. Varnish software was also used to improve performance and optimize the delivery of multimedia content.

Table 4 below presents the configuration of the hardware and software used in both the development and deployment stages of the system.

**Table 4. Cross-platform capture, processing, and deployment configuration**

| Stage | Hardware | Software/format |
|---|---|---|
| 360° Capture | QooCam 8K Enterprise + Osmo Mobile 6 | Equirectangular 8K, 10-bit |
| Overhead capture | DJI Mini 2 Drone | 4K / RAW (DNG) |
| Processing | Desktop Station | Manufacturer Software + Image Editing |
| Desktop Deployment | PC / WebXR browser | A-Frame 1.7.x (HTML, <a-sky>) |
| Mobile deployment | Smartphone/tablet | A-Frame (device gyroscope) |
| Immersive Deployment | VR Headset (Meta Quest / PICO) | A-Frame + WebXR |
| Overhead capture | DJI Mini 2 Drone | 4K / RAW (DNG) |

### 3.4. XP-based Development Methodology

The methodology followed for this study was Extreme Programming (XP), since it allows adapting to the change in requirements thanks to its flexibility, adding new functionalities and continuously testing each stage of the system components [32]. On the other hand, XP facilitated a better organization in the development in successive cycles, in order to be able to create, test and improve the web platform for visualization of the environmental area based on 360 images and WebXR technology. To this end, the cycle of the phases of the XP methodology is presented in the following Figure 1.

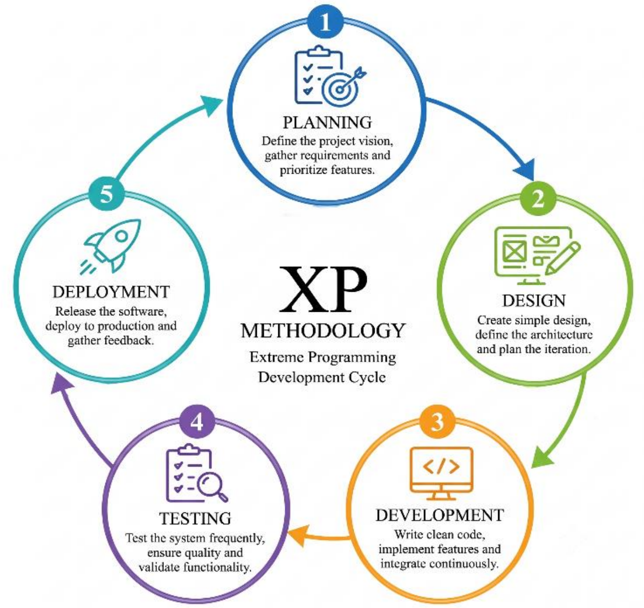


**Fig. 1 XP methodology phase cycle**

In order to carry out the study, the planning stage first defined the approach to the environmental problem to be addressed, the objectives and the requirements of the project. Then, in the design phase, he focused on the structuring of the virtual environment, definition of the visualization scenes and the design of the user interface. In addition, in the development phase, it was carried out thanks to the Three.js library and WebXR technology for the construction of the system. Then, the system was tested, performing the analysis.

### *3.5. Systematic Capture Procedure and Justification of Night Hours*

To carry out the process of creating the immersive platform, it involved several phases, such as the selection of the study area, the capture of panoramic images, data processing, protection of personal information, design of environmental scenarios and integration of these within the WebXR environment. This entire process allowed the preparation of the visual content and the development of the system to be systematically addressed. To this end, Figure 2 presents the diagram that explains in detail how this workflow was carried out in a general way.

On the other hand, the panoramic images were captured during the afternoon and night shift. Likewise, they were selected from a preliminary survey that was carried out on students, which indicated that it is during this time when the campus has the highest concentration of visitors due to the schedule of classes and university activities that are carried out daily. For this reason, night photographs made it possible to capture the real conditions of the studio space and create scenarios about the environment. Figure 3 and Figure 4 show an example of a panoramic image obtained during data collection. Both images formed the basis for the data processing phases, creation of the environmental scenarios and the development of the system.

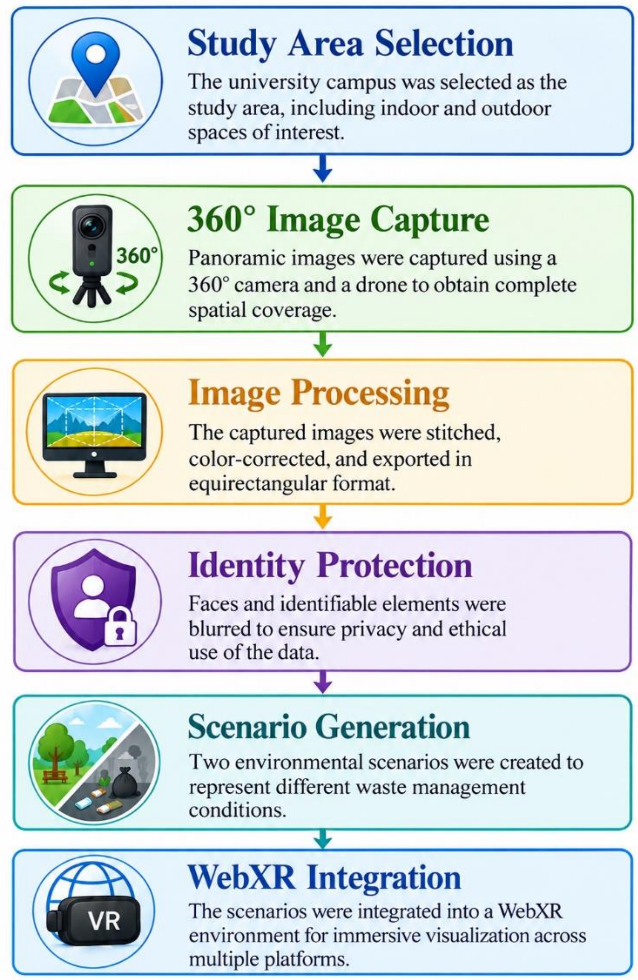


**Fig. 2 Workflow used for environmental data acquisition, processing, scenario generation and WebXR integration**


**Fig. 3 Aerial view of the UCH campus obtained using DJI Mini 2**

**Fig. 4 360° panoramic image captured with Kandao QooCam 8K Enterprise**

### *3.6. Environmental Conditions for Immersive Visualization*

To strengthen environmental awareness, different environmental conditions were incorporated that reflect how waste management is being handled within the university campus. In this way, people can observe and make a comparison of an area under different situations, which favors the perception of the impact that human activity has on the environment. To this end, a work was carried out under two contrasting scenarios, the first shows a space that is in constant maintenance, preserves a clean and pleasant educational environment for students. However, the second image shows the presence of garbage waste, which generates visual pollution, which could negatively affect how people can perceive the educational space and their own environmental culture. Both scenes were integrated as a comparison within the immersive WebXR educational environment, ensuring that the user can explore different points of view and encourage reflection on the different ways of managing waste. Figure 5 shows one of the examples of both conditions incorporated into the platform.

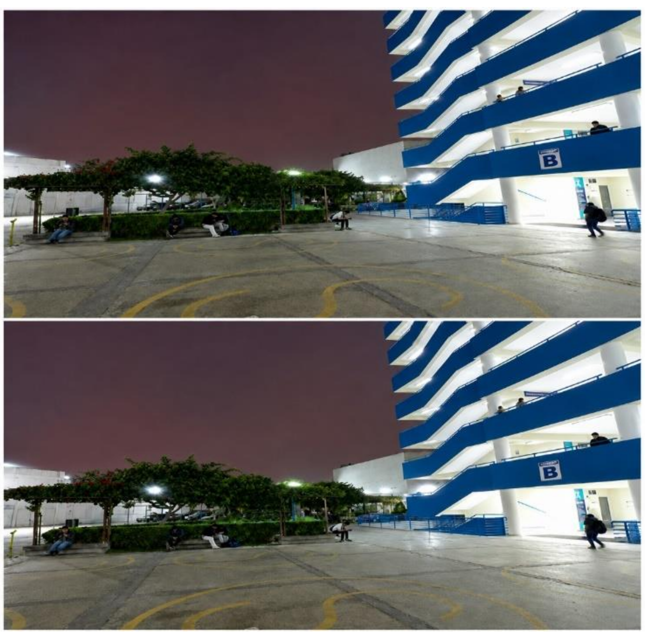

**Fig. 5 Comparative environmental conditions considered for immersive visualization within the university campus**

### *3.7. Quantitative Evaluation Model*

A five-point Likert scale was used to quantify the system, where 1 corresponded to the minimum score and 5 to the maximum. Likewise, for each characteristic that was evaluated, the mean value was determined as follows:

$$\bar{x}_{d,m} = \frac{1}{N}\sum_{i=1}^{N} x_{i,d,m}$$

In which $x_{i,d,m}$ It represents the score obtained by the expert $i$ for the dimension for the deployment mode, while it is the one that corresponds to the number of the total experts who evaluated the system. Likewise, to obtain an overall assessment of each dimension considering the three deployment modes, the following expression was used:

$$S_d = \frac{\bar{x}_{d,D} + \bar{x}_{d,M} + \bar{x}_{d,V}}{3}$$

In which D, M and V specifically represent the desktop computer, mobile device and the virtual reality viewer. In addition, the value obtained could allow the environmental realism, the feeling of immersion, the usability and the potential it has to promote environmental awareness among the different modalities of access to the proposed system of the study to be quantitatively purchased.

It should be mentioned that the study did not use a mathematical model for the prediction of physical or environmental processes, since the system is focused on the visualization and comparison of environmental scenarios of the real environment. Therefore, the mathematical formalization focused on quantitatively evaluating the characteristics and perceptions of the developed multiplatform system.

### *3.8. Experimental Protocol and Reproducibility*

In order to ensure the reproducibility of the study, the experimental procedure was carried out in sequential steps. First, the locations on the university campus of the University of Science and Humanities were selected that represented different environmental conditions. To do this, visual data was collected using a Kandao QooCam 8K Enterprise camera to obtain 360° panoramic images, the DJI Mini 2 drone for aerial photography and a MoJI 6 stabilizer for the control of movements during the capture of the images.

The resulting material was processed and prepared in equidistant panoramic format so that it can later be integrated with the web environment. Likewise, the system was implemented using A-Frame, Three.js and WebXR, and the tests were carried out in three deployment modes: first, through a desktop computer, then on a mobile device through the gyroscope and with the virtual reality viewer. In all modes, the accuracy of the visualization of the panoramic scenes, the navigation between points, the user's interaction with the interface and the access to the comparative environmental scenarios were evaluated.

On the other hand, to evaluate the perception of the system, 40 students from the University of Sciences and Humanities participated voluntarily, 10 from systems engineering, 14 from electronic engineering and 16 from environmental engineering in the first cycles. After interacting with the developed platform, they responded to a survey through the 5-point Likert scale and left their perceptions of what they visualized.

The system was also evaluated by 5 specialists in the study of the Likert scale. The evaluations were carried out using the same scenario for all participants, which was able to ensure that the scores were compared between the different modes of implementation obtained from the survey.

## 4. Results and Discussion

### 4.1. Results of the Instrument on the Capture Schedule

The results of the survey were obtained with the voluntary participation of 40 engineering students from the University of Sciences and Humanities, since the objective of the study at this stage was not to obtain a statistical sample, but to confirm two aspects of the scenario: to determine at what time of the day there was a greater influx of people on campus and how they perceived the environmental conditions. To this end, Table 5 shows the results.

**Table 5. Descriptive results of the instrument applied to students**

| Item | Statement (summary) | Media | % agreement |
|---|---|---|---|
| I1 | Greater influx at night | 4.3 | 82 % |
| I2 | Less Noticeable pollution at night | 4.0 | 75 % |
| I3 | 360° simulation promotes awareness | 4.5 | 88 % |

With the results obtained, it was evident that the busiest time and environmental problems are shown at night. On the other hand, the best evaluations were related to the potential of immersive 360° visualization to increase environmental awareness and to highlight waste management problems.

### 4.2. Developed WebXR Environmental Awareness Platform

As a result of the development of the Web System, it combined the possibility for users to move between the different key points of the University of Sciences and Humanities, panoramic scenario viewers and tools that allowed visual comparison of the different environmental conditions.

In addition, users can easily move around each area of the campus, learn about each element of the university environment in relation to the environmental status related to waste management. In this way, it favors the person to interact and can make a better and deeper understanding of environmental problems, thanks to the system made, since the user can have the feeling of presence and participation that it offers.

As shown in Figure 6, the system's interface has a navigation bar, an environmental status module for each area, full-screen display options and a virtual reality mode.

It also has a button to compare different environmental conditions, which makes the web platform not only a visualization tool, but also a resource to educate people about environmental education and disseminate the most responsible attitudes towards the environment.

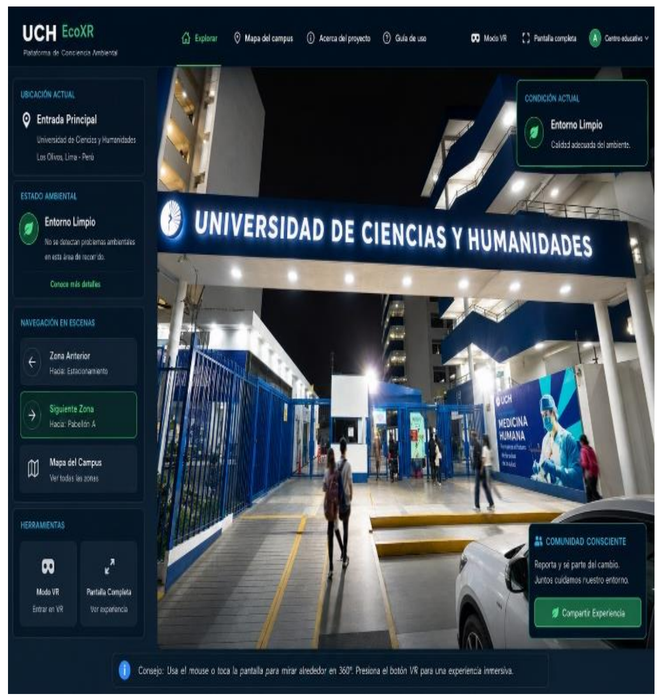


**Fig. 6 Developed WebXR environmental awareness platform for immersive exploration of the university campus**

### 4.3. Environmental Visualization Scenarios

As mentioned earlier, the platform shows the user two viewing scenarios. An example of this can be seen in Figure 7 and Figure 8, where it shows the same space in two different types of these. Likewise, this mode of presentation allows the user in 360° format, as well as to experience the effects of the different practices of waste management.

This immersive experience allows both scenarios of reflection to be perceived more easily. It should be noted that the main intention of this study is to be able to promote environmental responsibility in people and to promote a better conscious attitude towards the care of their environment, maintaining a cleaner university environment.

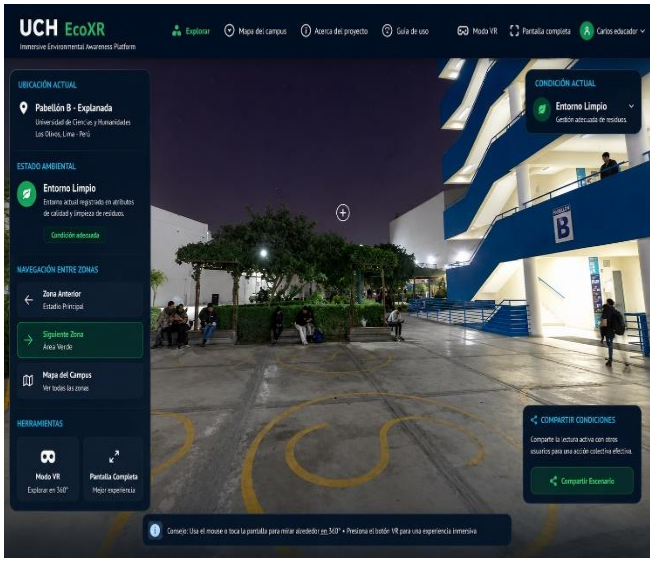


**Fig. 7 Clean environmental scenario implemented in the WebXR platform**

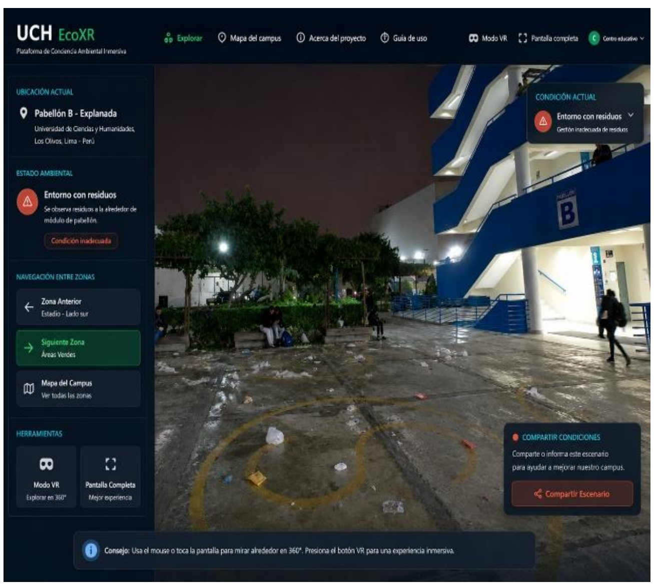


**Fig. 8 Environmental scenario showing visible waste accumulation in the university environment**

### *4.4. Immersive Visualization through Virtual Reality Devices*

To see the correct functioning of what the system offers, as evidenced in Figure 9, using an augmented reality viewer was used to make the appropriate tests of the system and check if the user really allows him to have a sensation as if he were physically present in the environment in a natural way. Unlike just observing images through a device, either computers or cell phones, the experience offered to the user is immersive, which allows a higher level of involvement to be achieved, which is particularly valuable to be able to promote environmental education. This would confirm that the system developed allows easy access to educational content through different forms of interaction.

**Fig. 9 User interacting with the EcoXR platform through a virtual reality headset**

### *4.5. Expert Validation*

Once the development was completed and functional tests were carried out, the system was presented to five specialized experts for evaluation in three deployment modes, i.e., desktop, mobile, and with virtual reality glasses. The experts rated the system on a five-point Likert scale, the results of which are shown in detail in Table 6.

**Table 6. Base test with expert jury: averages by deployment modality (scale 1–5)**

| Dimension | Desktop | Mobile | VR Headset | Media |
|---|---|---|---|---|
| Environmental realism | 4.0 | 3.7 | 4.7 | 4.13 |
| Immersive feeling | 3.7 | 4.0 | 4.8 | 4.17 |
| Usability | 4.3 | 4.5 | 4.0 | 4.27 |
| Awareness Potential | 4.0 | 4.2 | 4.7 | 4.30 |

From the results obtained from Table 6, it can be seen that environmental realism, immersion and awareness potential obtained the highest score in the immersive viewer modality, while the desktop and mobile modalities stood out in usability and accessibility. All of this, it can be confirmed that the relevance of the cross-platform approach, the viewer maximizes a deep experience, both on desktop and mobile.

## 5. Discussion

### *5.1. Contribution of Immersive Visualization to Environmental Awareness*

The findings coincide with what the research suggests about environmental education and immersive technologies. For example, one study [33] indicated that the virtual reality environment has great potential for people to participate and facilitate a better interpretation and understanding of environmental impact. On the other hand, another study [34] agrees that thanks to immersive experiences it favors the promotion of a deep understanding of environmental problems compared to traditional methods such as photographs or videos, which are sometimes ignored.

In this context, the WebXR platform that was developed shows different scenarios, which makes it an innovative system for users since it demonstrated through the evaluation results a high percentage of usability, which shows that any user can test the system without having to have such technical knowledge. Therefore, the results obtained in the study support what has been pointed out by recent scientific literature, that augmented and mixed reality technologies can be of great potential to promote environmental reflection.

### *5.2. Comparison with Previous Digital Environmental Platforms*

The web system developed in this study is different from most of the existing digital solutions aimed at environmental monitoring and citizen participation. For example, Study [35] reported that a web platform is more beneficial than a mobile app, as it does not require installation or other specialized apps. Also, in this way, it allows you to reach a greater number of people. On the other hand, [36] they analyzed international citizen science platforms, but they only concentrate most of them on data collection and the recording of observations, but they do not pay attention to details such as the experience that the user may have with the proposed system. Unlike these proposed systems, the WebXR platform allows the user to participate by showing them different panoramas of their daily reality in 360° format. It also adapts to any type of device, which highlights its level of accessibility, as well as offering an innovative and thoughtful experience on environmental content.

Likewise, in the previous studies analyzed, they have shown that virtual reality makes it easier for users to directly perceive the impacts of environmental change and thus to be able to interact with the environmental conditions represented visually [33, 34]. In the present study, a similar trend could be seen in the expert evaluation of the developed system, since the potential to promote environmental awareness received an average rating of 4.30 out of 5, usability 4.27 and the sensation of immersion 4.17.

Although the results obtained do not allow us to affirm the statistical superiority of the system over existing systems, because a direct experimental comparison with other solutions was not made, however, they do show that the multiplatform architecture that was developed obtained high scores with respect to usability, immersion and potential to improve the perception of the environment, while incorporating real-world panoramic data and various modes of access in a single WebXR platform.

### *5.3. Limitations and Future Work*

Although the results were mostly positive, the study has limitations. Since the system was evaluated only on a university campus and in a number of environmental scenarios, the results obtained cannot be directly extrapolated to other types of urban environments. Also, the study did not include a longitudinal evaluation of the changes in the environmental behavior of users after interacting with the system.

On the other hand, the scalability of the system requires additional verification of performance by increasing the number of panoramic scenes, the amount of multimedia data and the number of users connected simultaneously, in addition. It is necessary to be able to consider the differences in the processing capacity of mobile devices and virtual reality headsets, the quality of the internet connection and also the conditions of use in the field. Therefore, in future studies, it is recommended to plan to expand the number of spaces investigated, include other types of environmental problems that exist, and to be able to evaluate the system with other diverse groups of wider users.

## 6. Conclusion

The studio developed an immersive platform. based on WebXR in order to promote environmental awareness within the environment of the University of Sciences and Humanities (UCH), the proposal made a combination of 360° panoramic images, WebXR technology and environmental scenarios in an interactive way, all in a single web system accessible by different devices. Part of the results obtained showed that recreating realistic scenes with different conditions on waste management offers users a better way of visualizing environmental problems due to their incorrect responsibility ofTheir Actions with their environment, spreading a deep reflection to promote change, Likewise, a survey evaluated by specialized experts confirms that the system developed is very accessible and easy to use. In the future, it is proposed that the scenarios can be expanded by taking other spaces of the studied environment to show an environmental impact, as well as new forms of participation of people, In summary, the results obtained confirmed that modern technologies such as WebXR are very useful tools to support environmental education and can promote better practices for the care of their environment.

## Conflicts of Interest

The authors declare that they have no conflicts of interest.

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