THE APPLICATION OF AUGMENTED REALITY FOR THE UNDERSTANDING OF CHEMISTRY

Alicia Gabriela Paredes Benavides[1]
Arelys García Chávez [2]
José Enrique Martínez Serra [3]

UNIVERSIDAD NACIONAL DE EDUCACIÓN UNAE

Author contribution:
The 3 authors of this research article have actively contributed to the development of each of its component parts.

Conflict of interest
There are no conflicts of interest.

ABSTRACT

This research was developed in response to the need for new ways of teaching Chemistry in order to improve the understanding of molecular geometry. As the development of technology advances, it is also considered that it should be applied within the educational environment, as it will prepare students for the future. This work was carried out using an action-research methodology and both quantitative (statistical) and qualitative (ideas or opinions) data were analyzed. In addition, Blender and Unity software were used to build the augmented reality (AR) application. Results showed an increase on the levels of creativity, innovation, motivation displayed by the participating students, as well as a better academic performance in the chemical subject of molecular geometry. Thus, it can be concluded that the teaching-learning process can be positively influenced using new tools. This research implies that the application of immersive technologies such as AR in education favors the development of a meaningful learning and allows students to better understand the usefulness of knowledge and its applicability in the contexts of their daily lives. Such investigations are especially valuable in STEM disciplines, since they allow the students to enjoy lessons while staying in touch with new technologies that are already native to them.

Keywords: Chemistry, augmented reality (AR), teaching-learning process, education.

[1] Universidad Nacional de Educación, Cañar, Azogues, Ecuador. E-mail: alicia.paredes@unae.edu.ec
Orcid: https://orcid.org/0000-0001-7643-1067
[2] Universidad Nacional de Educación, Cañar, Azogues, Ecuador. E-mail: arelys.garcia@unae.edu.ec
Orcid: https://orcid.org/0000-0003-3730-0499
[3] Universidad Nacional de Educación, Cañar, Azogues, Ecuador. E-mail: jose.martinez@unae.edu.ec
Orcid https://orcid.org/0000-0002-0274-0649

1 INTRODUCTION

In the 21st century, considered as the age of technology, several didactic resources have been developed to improve the teaching-learning of chemical, mathematical, biological and physical sciences. In this sense, technology is considered as an essential element that is integrated into everyday life.

Thus, as the development of technology advances, it is also considered that it should be applied within the educational environment, as it will prepare students for the future (Alcívar & Alcívar, 2021). By using various technological resources within the educational area, the acquisition of digital competences is encouraged, facilitating digital literacy and allowing them to adapt to new forms of lifelong learning.

Among the highlights of the use of technology in education is that most educational resources are globally accessible, i.e., students have access to a wide variety of information and learning resources from all over the world (universal tools).

Technology facilitates the exposure to diverse perspectives, cultures, knowledge, learning experiences and the development of curiosity as part of intellectual formation.

Similarly, implementing technology in education promotes innovation, critical thinking and creativity (Mendoza & Loor, 2022). Digital resources enable students to develop multimedia content, structure interactive projects and present their ideas in a novel way. Thus, such resources link thinking and creativity, greatly facilitating the expression of knowledge in unique and enterprising ways.

In addition, when technology is used in the classroom, inclusion and equity in education are practiced. This is because, by overcoming boundaries of access, there is equality in opportunities, learning environments and circumstances.

In Ecuador, the technology applied in the classroom has increased significantly in recent years (Pimentel, *et al*, 2023). This has led to the implementation of various programs and projects that facilitate the integration of technological teaching resources in the teaching-learning process.

It should be noted that there are still challenges to overcome, such as the digital divide and the lack of training of teachers with respect to technological tools. Therefore, as measures, continuing education should be encouraged for all teachers, in order to guarantee equitable access to technology and promote educational innovation.

On the other hand, the teaching-learning of chemical sciences, both in secondary education and at university, generally deals with abstract content that is difficult to understand,

as it is not perceived with the naked eye and its application in everyday life is scarce or nonexistent.

Chemistry is considered to be a disciplinary subject and it does not deal much with the problems that arise in everyday life and particular interests, which makes them lose interest and feel that this subject is far from the context, making it irrelevant for today's young people.

When teaching chemistry classes, the teacher has the obligation to incorporate changes in didactics and structure different proposals that facilitate the learning of this subject.

Therefore, different challenges can be identified in the teaching of chemistry, such as: creating spaces for students to learn through theoretical content that is contextualized (Souza & Selpa, 2020); enabling students to understand the applicability, usefulness and benefits of chemistry knowledge; and facilitating educators and educational centers to incorporate the content in didactic models and proposals.

The aim of this research is to design teaching resources that facilitate the understanding of the molecular geometry of all the atoms that make up a molecule in order to improve the teaching-learning process in chemistry.

This is due to the identification of the scarce applicability of didactic resources to develop the teaching-learning process in chemistry, in this case molecular geometry (Granados, *et al*, 2020). Emphasizing that this is a basic subject in the chemical sciences, it should be a priority to understand and comprehend the usefulness of this knowledge in everyday life.

After analyzing that technology is a necessary tool to change the focus of education, it is proposed to create augmented reality models that allow students to understand the topic of molecular geometry.

Therefore, when developing an application that facilitates the learning of the aforementioned topic, it should be taken into account that augmented reality allows students to observe molecular geometry from various angles, in addition to understanding the more abstract chemistry concepts present in the aforementioned topic.

AR has contributed with 3D models of molecules, geometry, bonds, orbitals, polarities, and structural relationships, in order to connect macro, micro, and symbolic processes, which has contributed to guided learning interpretation. AR laboratories have also been created to generate step-by-step methodological procedures. This is to ensure safety, reduce risks, and visualize experiments without exposing oneself to danger. It is evident that periodic tables have been created that focus on the elements and their properties, with gamified elements.

However, after an exhaustive literature review, there is no evidence of the direct contribution of AR within learning spaces, as no standardized tests or objective evaluations are

carried out on this subject; the focus is only on subjective aspects. When using AR, several studies also fail to show the relationship between the macro, micro, and symbolic, which leads to misconceptions about teaching and learning processes. There are significant gaps in the use of AR in spaces with low connectivity, with large groups, in teacher evaluations, and in planning.

The applications may be interesting, but they must be linked to teaching-learning processes with results, various rubrics, evidence, teaching sequences, and assessment tools. There is no evidence of clear learning paths or personalized feedback. Issues such as when AR adds value in socio-educational contexts and how these contribute directly to collaborative work have not been addressed. Teachers have also not identified whether AR serves as a reinforcement space or as a net process of connection between theory and practice.

The AR application used in chemistry to learn the molecular geometry of chemical bonds, described in this research article, has a teaching sequence because, before using the application, an initial diagnosis was made, then the AR application was introduced consistently with guided activities, followed by work with various chemical compounds and a practical exercise to understand the type of molecular geometry of each of the chemical compounds. This research includes a pre-test and post-test to demonstrate the direct contribution of the application within the teaching-learning processes. In addition, it was applied consecutively in the classroom in order to strengthen teamwork and make the connection between theory and practice.

This application showed that students, upon observing the different types of molecular geometry within chemical compounds, were then able to characterize the number of bonds in each compound, the shape of the bond, the type, and the angles that existed in each one. Finally, they wrote down the angles, graphed the bonds in 2D, and symbolically showed the types of molecular geometries of each of the compounds. It should also be noted that the application works directly on the cell phone without the need for internet access. All that is required is to download the application, install it on the cell phone, and project the 3D objects with sound using a trigger image, making it applicable in any educational environment.

2 THEORETICAL FRAMEWORKS

This section describes several works that serve as a guide for the development of the application and the research. Key concepts are identified to ensure that the research is structured correctly and coherently.

2.1 Technology in education

Nowadays we talk about a digital era, therefore, this aspect has changed everyday life, so in the educational field it cannot be different. This phenomenon is referred to as the digital transformation that basically incorporates technology into education in order to contextualize and personalize learning for each of the students, also known as educational technology.

By introducing new technological resources in educational centers (initial, secondary, higher, etc.), teaching-learning methods are changed in order to create both formal and informal instructional spaces (Peña & Otálora, 2018); i.e., a digital and technological culture is developed within the classroom.

Thus, technology allows creative and innovative solutions to educational problems to be found through the use of computers, storage equipment, data sharing and management, focusing on educational technologies.

In other words, educational technology is understood to focus on the use of various technological resources that encourage or enable technology to develop (Montecé, *et al*, 2017*)* Currently, most educational centers have the possibility of accessing the Internet, digital whiteboards, computers, mobile phones and tablets, which facilitate the sharing of knowledge and the organization of both homework and classes.

Among the advantages identified when using technology in education, the following are described:

Students have the facility to play, interact and learn through the use of various platforms, allowing a participatory environment to develop within the classroom (Sánchez & Suárez, 2019). At the same time, learning from a distance is facilitated through flexible schedules and the personalization of tasks that adapt to the needs of learners.

For teachers, work is automated through the use of organizational tools, teaching and planning, allowing the time taken to review topics to serve as a space for reflection and development of new skills or abilities.

It should be noted that most of the platforms that use technology can be incorporated at all levels of compulsory education, which makes it easier for students to have spaces to resolve their concerns, for teachers to organize groups and for administrators to identify the learning achievements that are being obtained with each of the classes (Ávila, *et al*, 2021).

Technology in education allows all the needs of students to be met, avoids the risk of dropout and provides information and knowledge support for the development of various skills.

Thus, educational technology serves to identify and address each learning style in order to develop a self-directed way of learning. By using it, target competences are fostered according to the characteristics of the learners. In addition, the use of various technological resources fosters creativity and innovation.

2.2 Teaching and learning chemistry

Chemistry is considered as a complex subject that facilitates the understanding in detail of the facts that occur in nature, it is not considered a discipline distant from the other subjects, since, being considered of an interdisciplinary nature, it has facilitated the description of various processes that occur in people's daily lives.

Therefore, its teaching in both secondary and higher education is of great relevance. However, at present there is still a predominance of teaching that focuses on lectures, most frequently in chemistry classes (Taber, 2015), this type of teaching focuses on a type of learning that simply allows the repetition of concepts and content that the teacher has given in his classes; undoubtedly favoring memorization.

When describing the teaching-learning process in chemistry, it is evident that most of the contents of this subject are taught through strategies that the educator deems convenient, which leads to the design of meaningful learning being inappropriate or non-existent.

Therefore, this type of didactic strategies loses their meaning or purpose, because the student is obtaining a minimum of meaningful learning. After analyzing the above ideas, it can be seen that the learning resources are not focused on the development of knowledge, but rather on strengthening the traditional, rote teaching model.

However, in the subject of chemistry, the teacher is responsible for analyzing the various conditions and sets of requirements that must be met so that the teaching-learning process of the subject is framed in the development of meaningful learning.

Chemistry focuses on the development of methods and characteristics necessary for living in the modern world, because, in order for the quality of life to be optimal, various supplies of food, medicines and, above all, large amounts of energy must be developed (Taber, 2019). This leads to the conclusion that absolutely all life depends on chemistry.

Chemistry is involved in the food we eat, as most of it contains preservatives that extend the shelf life and prevent spoilage. It is used in fertilizers and pesticides, which are used to improve the quality of crops. Chemistry is also involved in the production of synthetic fibres and elastomers used in footwear and clothing.

Chemistry is also involved in transport, analyzing the composition of petrol and diesel (or biodiesel), how engines work, the usefulness of lubricants and other additives required in means of transport.

In order to have a clear idea of the scope of chemistry in the daily life of all people, it is described that the materials that are made from polymers are: plastics, varnishes, foams, paints, fibres, among others (Kozlitin, *et al*, 2021). The elements that are used on a daily basis such as metals, plastics and ceramic materials have been produced after going through a chemical process.

Absolutely all the advances that have been made in medicine are based on and created from various chemical processes, since special materials are used for the construction and disinfection of medical equipment; dentists use resins to perform dental cures, vision is improved thanks to the development of lenses.

In conclusion, chemistry is present in all the tools and elements used in everyday life, and this discipline has the capacity to help solve the problems of global warming, the ozone layer and the waste generated, water quality, among others (Ghobadi, *et al*, 2023). Chemistry is the discipline that can contribute efficiently and effectively to solving the problems mentioned above.

Therefore, the teaching-learning of chemistry is considered as a space that facilitates simulation, experimentation and understanding of chemical phenomena through practice, i.e. to learn this subject it is necessary to apply knowledge to events and occurrences that happen in everyday life.

2.3 Augmented reality

Augmented reality (AR) is a space that allows students to analyze various elements or scientific facts from all possible angles, allowing them to effectively visualize how these facts or events are organized and produced in order to understand all the abstract and essential concepts to the human eye.

Curiosity in education allows us to imagine and create various didactic resources that facilitate the understanding of different subjects. AR is an element that facilitates the representation of the three-dimensional reality in which we live. In education, the way of teaching through the use of books and blackboards has become obsolete; as they are two-dimensional spaces, they do not reflect the reality of life.

The three-dimensional vision is incorporated in various educational resources that favor the understanding of subjects, as technology is increasingly used in educational centers (Fernández, *et al*, 2022). The various technological resources provide considerable enrichment

to the teaching-learning process and one of the proposals is augmented reality within the educational field.

AR actively promotes autonomy, practical problem solving, critical thinking and motivation. The main characteristic of this type of resource is to develop a metacognitive process that facilitates learning through the practice and use of knowledge, which in turn greatly favors the approach of different ways of solving a real or practical problem.

Augmented reality has only recently been incorporated into education, but its effects on education have been positive (Iatsyshyn, *et al,* 2020). In addition, this resource promotes meaningful learning at all levels of education, whether at primary, secondary or university level.

Applying AR in the classroom promotes the acquisition of new concepts, skills, language, abilities, among others. This resource incorporates activities that are considered exploratory and that encourage continuous discovery, as students begin to ask themselves what can be done with this knowledge, as well as applying motor activities that contribute to the active development of students.

Augmented reality focuses on a constructivist type of learning, due to the fact that education is adapting to new learning environments, which are considered more interactive, participatory and motivating (Toala, *et al*, 2020). With this resource, the student has the ability to try out new ideas, build them, modify them and become actively involved in making effective decisions to solve everyday problems.

Moreover, in order for meaningful learning to take place, teachers must teach through interactive methods, since 75% of the population retains 75% of what they observe, listen and perform (Martínez, *et al,* 2021). Thus, AR is a tool that facilitates learners to highly interact with theoretical and practical content, in other words, it provides the space for teaching to have a "learning by doing" approach.

One of the most relevant advantages of AR is that it creates a learning space that is attractive to the learner. This resource within education facilitates the handling of various 3D objects (Paredes, 2023), various virtual environments are observed and content is experienced in a more realistic (immersive) way, which significantly favors the interest and curiosity of learners.

In short, an inclusive learning environment is developed, allowing students to acquire diverse preferences and to develop relevant, coherent and long-lasting subject knowledge (Godoy, 2021). Whereas, it also serves as an essential resource to support teaching practice.

Thus, one of the most effective ways of acquiring and retaining information is through the observation of more realistic facts, which are coupled with the everyday situations that

students experience. AR in education allows these obstacles to the understanding of subjects to be removed.

2.4 Augmented reality in chemistry teaching and learning

Chemistry focuses on a kind of understanding that facilitates the comprehension of the most invisible parts of matter, so that macroscopic models can be explained by means of a symbolic representation. To facilitate this type of understanding, the ability to visualize and understand the three-dimensional structure of atoms or molecules, the way in which particles act in atomic and molecular orbital states, must be activated in order to implement new theoretical cognitions within the teaching-learning process.

Based on these reasons, the need is identified to develop in some way the spatial intelligence of Chemistry students (Fernández, *et al,* 2022), in order to verify spatial relationships, cognitively reproduce the facts or events that have been observed, observe in three-dimensional form the elements that are in two-dimensional form (images, drawings, etc.).

AR also allows the learner to anticipate consequences (symmetry exercises), to observe similarities between elements that look different (isomerism), in order to develop a constructivist approach to the teaching-learning process. In other words, learners should have the ability to deduce or induce through active construction of knowledge.

In the digital era, the virtual 3D modelling of not only molecular models, but also of various graphs representing charge density, orbitals, among others, which are of daily use in the teaching-learning process of chemistry, is spreading in the digital era.

Thus, digital devices are of permanent use for both teachers and students, at absolutely all levels of education (Mendoza, *et al,* 2022). This causes education to incorporate technologies within the experiential context of students, so that various technological tools are used in order to strengthen the didactic action.

AR is a new form of technology; therefore, it offers a large number of educational elements that enhance and improve the quality of the teaching-learning process (Zaragoza & Cueva, 2020). In the teaching of chemistry at all levels, various programs should be used in order to strengthen and improve the quality of education.

By using technological resources, as is the case of AR, spaces are created that allow the development of learning that focuses on one's own experiences, strengthens knowledge and facilitates the observation of various molecular elements such as orbitals, crystallines, representations and structures.

In conclusion, AR is a tool that facilitates the observation of facts and phenomena that are not visible to the naked eye. In addition, this resource allows experimentation and putting

into practice all the knowledge acquired theoretically.

3 METHODOLOGY

This research has been developed through the analysis of both qualitative (numerical) and quantitative (opinion) data, i.e., it is a mixed research. This is in order to carry out a more complete analysis of the application of AR in education, specifically to improve the teaching-learning process in chemistry.

By interpreting the data obtained through the application of tests, observation guides and surveys, it is possible to verify whether the proposal has a positive impact within the educational environment and whether, by using it, meaningful, experimental and experiential learning has been developed, as well as to verify whether it improves the assimilation of theoretical content.

This enquiry is considered as an action-research, because it allows a problem to be identified, then studied in order to develop a possible solution and try to improve or fix the identified problematic situation.

Action research allows the analysis of all the people who are involved in the study problem, i.e., research is carried out within the community (Hernández & Mendoza, 2018). In this type of research, several data collection tools are used, such as interviews, surveys, observation and evaluations. It facilitates the understanding of the data as it allows for representations to be made through graphs or structured tables.

This study involved 62 university students enrolled in the Experimental Sciences Education program at the National University of Education (UNAE) and was applied directly to the high school chemistry course.

- Average age: 19.8 years (SD = 1.4).
- Gender: 38 women (61.3%) and 24 men (38.7%).
- Degree program and academic level: Experimental Science Education, third cycle.
- Selection criteria: be officially enrolled, have a minimum attendance of 80% during the application process, and sign the informed consent form.
- Exclusion criteria: having taken other chemistry courses, not completing the pretest and posttest, and/or voluntary withdrawal during the intervention.

This research was conducted using a mixed design, employing a pre-posttest (quantitative) and focus groups (qualitative). The intervention variables focus on augmented reality, and the dependent variable is the level of theoretical-conceptual understanding of molecular geometry (chemistry).

The instruments used in this investigation were: conceptual tests in chemistry, consisting of 24 multiple-choice questions that assessed the dimensions of: macroscopic, submicroscopic, symbolic, and representational levels. The scoring was 1 point per correct answer, with a maximum score of 24 points.

In turn, focus groups were used to identify and delve deeper into the students' experience, perception, and cognitive processes during the application of augmented reality. Participants were chosen at random with a balance based on academic performance (high, medium, and low), and participation was voluntary. The focus group lasted between 60 and 75 minutes, was conducted in person at UNAE, moderated by the researchers, and audio recorded and transcribed for later analysis.

When analyzing the data, emerging categories were identified and the information obtained was refined using ATLAS.ti version 23 software, while quantitative data were examined using SPSS version 29 software in order to ensure the greatest possible rigor.

The reliability of the research was assessed using internal consistency, which was: Cronbach's alpha ($\alpha = .87$). In summary, the pre- and post-test data were triangulated with the focus group data, and peer reviews and expert validation (5) were carried out within the field of chemistry teaching. Therefore, the content validity index is: (IVC = .91).

Procedure

The AR intervention lasted 6 weeks, i.e., 12 sessions, equivalent to 2 sessions per week. The following activities were carried out in these sessions:

- Application of the structured teaching sequence.
- Macro, micro, and symbolic translation activities.
- Use of Android mobile phones.
- Laboratory simulations and reflective spaces.
- Application of a pretest in the first session and a posttest plus focus group in the last session.

3.1 Defining the themes for the development of the application

This research describes the development of an application for cell phones with Android operating system in order to improve and enhance the teaching-learning of chemistry, specifically molecular geometry. This application will allow observing 3D elements that represent models of the aforementioned subject, i.e., augmented reality will be used.

Then, by identifying that students have a poor understanding of the topic of molecular geometry in the subject of chemistry, a mobile application is developed that focuses on the use of AR, and that allows the student to learn this topic through practice and use of knowledge.

Emphasizing that AR has the ability to convert a theoretical class into practice and create learning environments (formal and informal) that allow students to understand chemical phenomena in a more realistic way.

Thus, as part of this research, a mobile application has been developed that can be used in chemistry classes so that students can observe the different structures, shapes and angles that molecules have in relation to their molecular geometry and how these should be represented in each of the cases.

It should be noted that, in order to develop the application of AR, it was identified among several topics, the topic in which students have a lower understanding, considering also that the topic of molecular geometry is a basic topic of chemistry. In this sense, this theoretical content must be understood, reinforced and practiced arduously in order for them to possess a solid knowledge on the subject and thus be able to understand the topics of Chemistry.

In short, the subject of chemistry is not liked by students, therefore, few people are interested in learning this subject, specifically because of the complexity of the basic concepts and the structure of the subject. However, AR motivates students to want to learn more about the subject and begin to explore more relevant concepts, practices and theories of chemistry.

3.2 Creating the application

When developing applications to visualize AR, what is done first is to identify the subject to be represented, then a sketch of how you want the application to be elaborated is made, and finally you start to develop step by step the application to visualize AR.

At first, the modeling part is developed in the program called Blender, in this space is given the shape, structure, color, design, movements and utility of the 3D models that are being produced. In this case, what was done was to create spheres and rods and then join them together and give the different forms that are presented in the molecular geometry, such as: linear, two spheres and rods were used in order to join them and give the space for the formation of an angle of 180 °. In planar trigonal geometry, spheres and rods were used in the same way, but a triangle shape was created in order to represent the 120° angle.

For the angular form, spheres and rods were joined in the same way, giving it a triangle shape, but with an angle of less than 120°, due to the free pairs. In the tetrahedral shape, spheres and rods are also used, a tetrahedron shape is used and its angle is 109.5° and for the pyramidal structure, spheres and molded rods are also used, giving it a tetrahedron shape, but with an angle smaller than 109.5° due to the presence of free pairs.

When we have the 3D elements modeled in Blender, we proceed to export them in the FBX version, in order to introduce them in the Unity application and proceed to create the application.

Next, a new project is started in Unity, this must be centered in AR, from there the files are imported in FBX version. Then each shape of the molecular geometry is associated with a representative image (trigger). The 3D elements are placed on the images and finally we proceed to create the application for cell phones with Android operating system.

The representative images will be different molecules or elements present in nature, once the cell phone camera is focused on these images it will be clearly observed what is its molecular geometry structure, what angle it should form and the value of the same, in addition to the name of the molecular geometry it has.

This type of activities is developed in groups and facilitate the practice of learning that is acquired theoretically to practice, in short, relate various elements of everyday life with the shape, structure, angle and name that each of the molecules according to the molecular geometry.

3.3 Proposal characteristics

This proposal is characterized by using AR elements for learning molecular geometry, focusing on developing meaningful and lasting learning in students through the use of immersive technologies. In turn, it seeks to develop several skills and abilities such as: creativity, innovation, knowledge, practice, motivation and meaningful learning as described in the results.

The implementation of AR in chemistry classes focuses on developing learning in which the student is considered as the protagonist of their learning, in addition to using the AR application with the objective of understanding abstract topics such as molecular geometry.

It also allows the student to get to know the similarities and differences that exist within molecules. For this reason, the molecular geometry application was used through the use of AR. *Table 1* describes the characteristics of the AR application.

Table 1

Features of the AR application

Features	Utility	Skills development
Interactive	The student actively participates in the assignment	Motivation Class participation
Intuitive	The student quickly understands how the application works	Knowledgeable Practice
Dynamic	The application presents molecular geometry in a spontaneous way	Motivation Meaningful learning Creativity
Visible	Awakening student interest and curiosity	Motivation Creativity Experimental

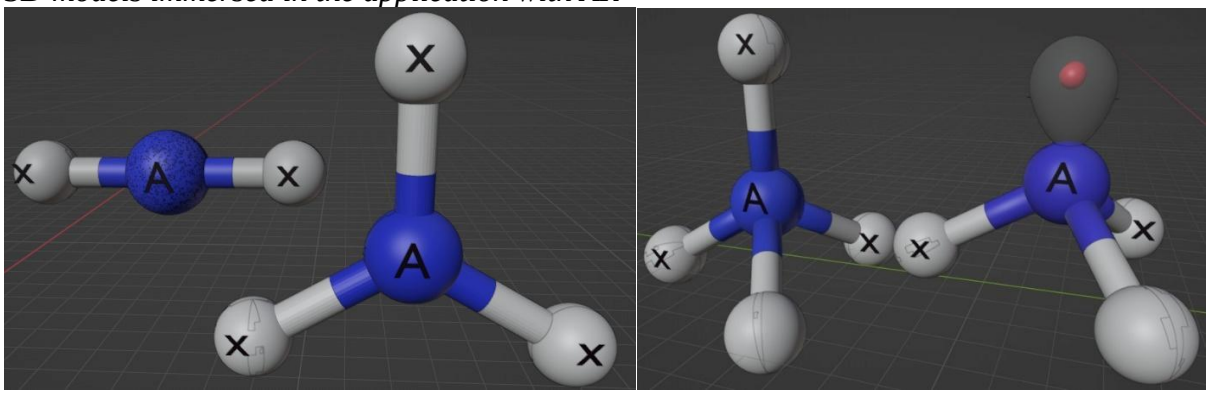
Source: own elaboration

Table 1 shows the different characteristics of the application that allows visualizing AR, as well as specifying its usefulness in the teaching-learning process of chemistry, and finally describes the skills that will be developed by using the AR application

Below are images of the models used in the application:

Figure 1

3D models immersed in the application with AR



Source: own elaboration

4 RESULTS AND DISCUSSIONS

When using this proposal to strengthen the teaching-learning process in Chemistry, it is highlighted that: the topic of molecular geometry is a basic topic in Chemistry, however, at the beginning the students had learning difficulties with respect to this topic. However, after using AR as part of a learning tool that favors and improves the understanding of this topic, their level of knowledge increased significantly by 50%, this with respect to the category of knowledge about molecular geometry.

In the category of the application of knowledge, when AR was not used for the learning of molecular geometry when applied in the resolution of problems, it was relatively low, but

when AR was applied, it increased considerably by 31%; also, in the creation of similar models for the understanding of the topic after applying AR, an increase of 45% was evidenced (*Figure 1*).

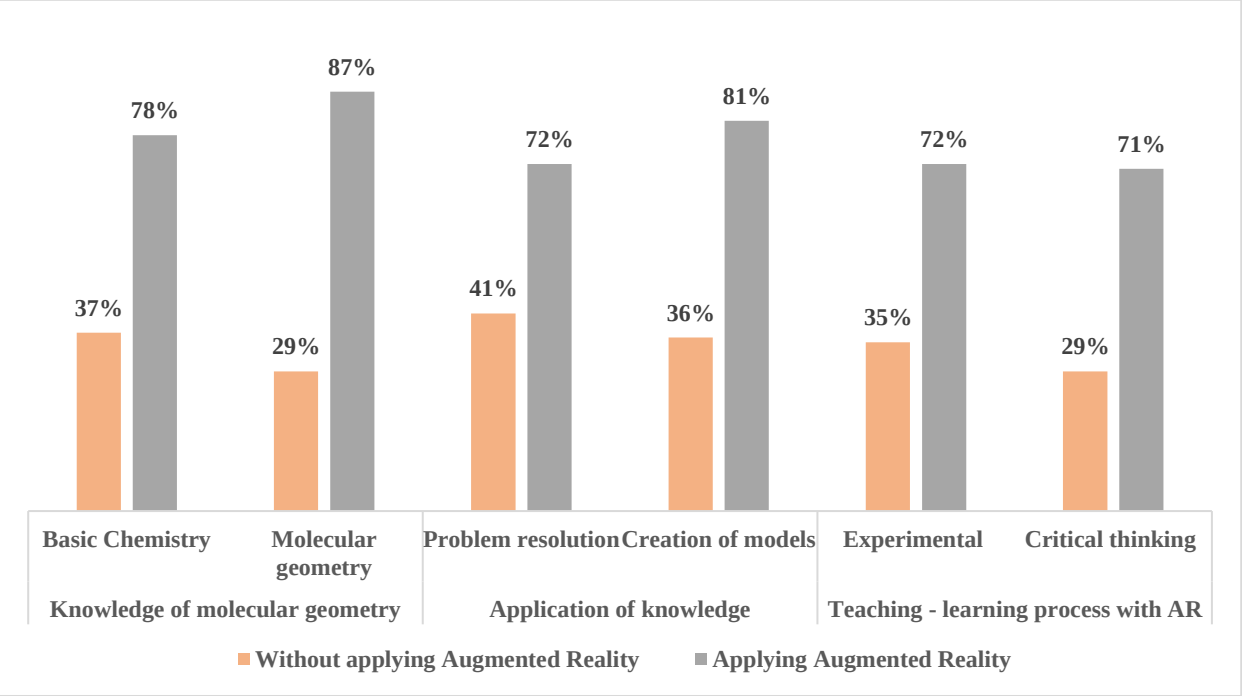
In the category of the teaching-learning process through AR, at the beginning the experimental part within this process is relatively low, while, after applying AR in the classroom in order to develop practices and apply knowledge to decision-making and problem solving, it increases by 37%.

And finally, the development of significant learning at the beginning was relatively low and was not developed correctly, but using the application of AR has increased the development of significant learning by 42% (*Figure 1*). In addition, the element that has increased the most in the knowledge possessed on the subject of molecular geometry, this increased by 58%.

Thus, it is evident that in general the categories of: knowledge of chemistry, the application of knowledge and the development of the teaching-learning process through AR, in all these categories after using the application with AR, has increased significantly and has improved both the learning environment and the knowledge, skills and abilities of the students, specifically in the subject of chemistry in the topic of molecular geometry.

Figure 2

Results when applying augmented reality



Source: own elaboration

In addition, after using AR in chemistry classes, specifically in the topic of molecular geometry, a survey was conducted with the students in order to know their level of satisfaction

with the application of AR. Most of the responses were positive and showed that the students are happy with the application of AR to learn molecular geometry.

Eighty-two percent of the students agreed that the application of AR favors and strengthens the way they learn and understand the topics of chemistry, considerably improves their teaching-learning process and above all allows them to practice the topics that are acquired theoretically.

In addition, according to the students' opinions, the application of AR in education promotes innovation spaces (new ways of teaching and learning), this type of resource favors experimental processes and all theoretical knowledge is put into practice (*Figure 2*). Also, meaningful, critical and reflective learning is developed, which in turn allows the development of metacognition on the subject of molecular geometry in order to make decisions and solve various problems that arise in everyday life.

Figure 3

Students' views on the application of augmented reality in the teaching-learning process



Source: own elaboration

Then, by using the application with AR, several skills and abilities have been developed in the student, among which we can highlight: the aspect of creativity, at the beginning it was considerably low, but after applying this proposal this aspect increased by 55%.

The aspect of innovation is of utmost importance and should be developed in each of the students, so that they can create creative solutions to the various problems of everyday life, this aspect increased by 43%. The knowledge element is the one that has increased the most, this in relation to the other aspects and its value is 50%.

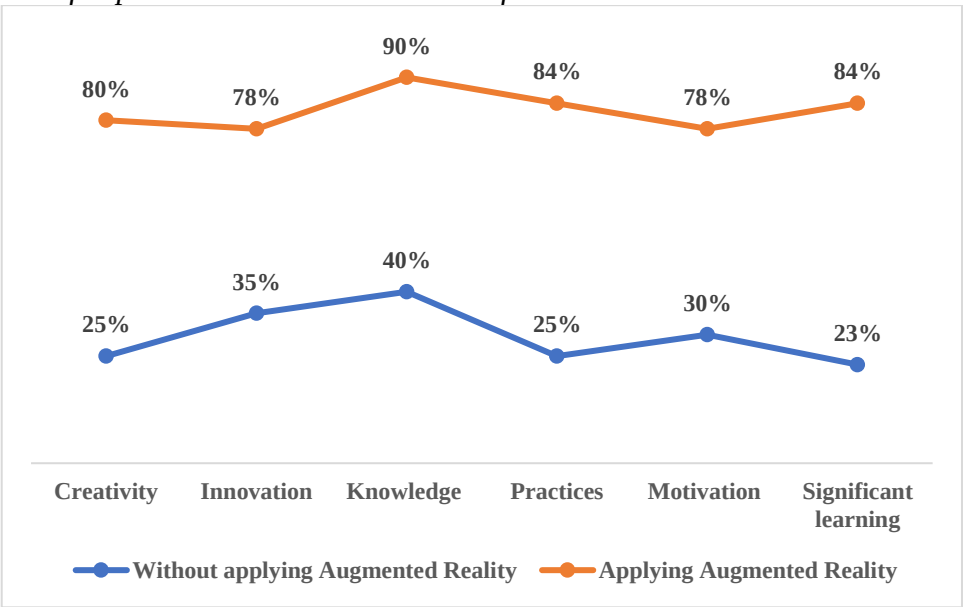
Another element to highlight is the practices, this space allows students to analyze various contexts, problems or activities and thus think of possible solutions that involve the use of learning that has been acquired within the educational centers, this has improved by 59% (*Figure 3*).

The aspect of motivation is fundamental for the student to feel that learning is necessary for his or her personal and/or professional development. In this sense, both intrinsic motivation (personal improvement) and extrinsic motivation (group improvement) should be developed. Thus, in this area there is an increase of 48%.

Finally, the aspect of meaningful learning has increased by 61%, which shows that students, through the application of AR (*Figure 3*), have acquired knowledge in a spontaneous way and are using it in the various contexts in which they develop in order to provide solutions or problems or simply to understand why and the usefulness of the topics they teach in educational centers.

Figure 4

Development of capacities and skills in the use of AR



Source: own elaboration

In conclusion, it is evident that the use of AR in education significantly favors the teaching-learning process of chemistry, specifically in the topic of molecular geometry. In the case of the development of skills and abilities that focus on the promotion of curiosity and interest of students, a significant increase and progressive development is evidenced.

Furthermore, in the opinion of the students, education using AR is participatory, influential, inclusive and, above all, practical. In this way, it is also evident that the students'

knowledge of molecular geometry and how to apply the knowledge to solve problems found in the environment in which the student lives (contextualization) has increased.

The results clearly show that students' knowledge of the topics covered in AR achieved better results and demonstrated that learning was consolidated and applied to everyday life (Figure 4). This is evident in: understanding basic chemistry, molecular geometry, problem-solving spaces and processes, model creation or replication, experimentation, and critical thinking. For example, in the post-test, the percentage was between 71% and 87%, while initially the percentages were between 20% and 41%. The most visible categories were:

- Molecular geometry (87% vs. 20%)
- Model creation (81% vs. 36%)
- Critical thinking (71% vs. 29%)

When analyzing these results, it is clear that augmented reality has contributed significantly to the understanding of theoretical concepts, as these three-dimensional models can be observed.

Some noteworthy statistical data include:

- The pretest mean score was $M = 5.21$ ($SD = 1.45$), while on the posttest, the mean score was $M = 7.85$ ($SD = 1.12$).
- The probability that the difference in data occurred randomly was $p = .001$. This shows that the research was highly significant.
- The effect size (Cohen's $d = 1.15$) was large, representing a substantial change.

The results confirm that the incorporation of AR has had a significant impact on the teaching and learning of chemistry. The improvement is relevant in molecular geometry and model creation, whose representation is more mental and submicroscopic, which is reflected in AR. Similarly, there is evidence of an increase in critical thinking and meaningful learning, since AR not only had a motivational impact but also served as a cognitive mediator that favors mental processes and a deep understanding of theoretical content. This is because the effect size is greater than 1 and the intervention was a high-quality pedagogical measure, as it far exceeds the effects generated by traditional methodology.

In terms of quality, a thematic analysis was carried out, focusing on the approach proposed by Braun and Clarke (2006), which allowed for the identification, analysis, and reporting of themes within the data. The focus groups were intentionally selected based on student performance levels, with half of the population participating in total. The duration of this meeting was 70 minutes, with informed consent obtained to proceed with the correct transcription of the information collected.

To code the information, the data was first familiarized, then the most relevant spaces and categories were identified, and then groupings and verifications of the data obtained and its relevance within the categories were created (Table 2). The results were then interpreted and verified to see if the data was related to the quantitative information. For the interpretation of qualitative results, a table was created that focuses on understanding the most relevant thematic analyses.

Table 2.

Relevant aspects identified within the focus group

Topic	Description	Text example
Submicroscopic data visualization	Understanding focused on three-dimensional structures and intangible processes	"I can imagine more clearly how molecules are organized."
Macro, micro, and symbolic integration	There is greater consistency between the observable, molecular, and symbolic	"I understood the chemical equation when I directly observed what was happening with the molecules."
Reduction in cognitive abstractions	Conceptual difficulty decreased	"The topics were abstract, but with the application everything became easier."
Increased cognitive engagement	Increased participation and reflection	"These processes forced students to focus on critical thinking rather than memorization."

Source: own elaboration, based on Braun and Clarke (2006)

Furthermore, qualitative data is closely related to quantitative data. Among other aspects, the following are mentioned:

- Submicroscopic visualization is directly related to a significant increase in molecular geometry (87%).
- The category of macro, micro, and symbolic integration is evident in improved problem solving and model creation.
- Cognitive engagement is reflected in high levels of meaningful learning (84%).
- The data has high credibility due to the triangulation of qualitative and quantitative information.

In this sense, the contribution of this research is not only focused on the technical development of the AR application, but is also closely related to the pedagogical and structured integration of these educational tools within the chemistry teaching-learning process. In

contrast to other research focused solely on three-dimensional visualization, this study incorporates the following components:

- Several guided activities are used that focus on the macro, micro, and symbolic.
- Structured teaching sequences.
- Integration of various formative assessments.
- These AR activities were carried out with programmed laboratory activities.
- Conceptual elements focusing on critical thinking were designed.

This contributes to the application being a mediator of the cognitive process and allows for its application as it is based on a pedagogical model.

This application incorporates interaction and manipulation that enables students to: explore molecular structures in 3D, modify various angles and understand geometry, observe dynamic changes, and relate representations to symbolic equations, which significantly promotes constructivist and experiential learning.

The instructional design of this application is based on constructivism, which allows learning to occur when students actively construct their knowledge through interaction and manipulation of meaningful representations. In addition, it is based on positive load theory, due to its level of abstraction, so AR reduces this load to: the externalization of submicroscopic representations, the spatial visualization of content, and a reduction in complex mental rotation, which significantly increases cognitive processing.

The TPACK model focuses on the design of conceptual content knowledge (molecular chemistry), pedagogical knowledge (teaching sequences), and technological knowledge (augmented reality). Interaction is balanced across these three components to ensure that technology does not replace the pedagogical component but rather enhances learning.

The learning outcomes of this research show that the effect size is large ($d > 1$), which is slightly higher than international studies on AR within the chemistry teaching-learning process. Some comparisons include:

- Several studies in Europe and Asia report improvements in spatial understanding and molecular geometry, with effect sizes between $d = 0.5$ and $d = 0.8$.
- Several studies focus only on molecular visualization rather than on significant increases in motivation and perception; these effects are slightly lower in academic performance.

Therefore, the effect observed in this research is greater because:

1. The macro, micro, and symbolic processes of the teaching sequences are explicitly integrated.

2. This application is based on a structured pedagogical approach and is not limited to observation processes alone.
3. AR is combined with guided activities and shared reflection processes.
4. Evaluation is carried out using validated instruments and rigorous methodological triangulation.

However, this effect may be influenced by the specific context of implementation and the profile of the participating group.

The difference in results compared to several previous studies can be explained by several factors:

- Interaction levels: this study focused on active manipulation, not just observation.
- Pedagogical design: it was based on constructivism and cognitive load theory.
- Duration: this study was implemented over several weeks, not just as a one-off experience.
- Evaluation: data collection instruments such as pre- and post-tests with inferential analysis and based on effect size were used.

It is considered that previous studies were limited because they were an isolated visual complement to the teaching-learning processes, without structured and properly applied curricular integration.

The limitations of this study include the sample size, which is relatively small (62 participating students), meaning that the results cannot be generalized. Studies with larger samples contribute directly to the stability of the observed effect. The research was conducted in a unique context, at a single university and within a specific statistics course, so the interpretations of the results are only valid in that particular context. In future research, it is recommended that this study be applied to various educational levels and sociocultural contexts. Another limitation is the duration of the intervention, which lasted six weeks and did not allow for the evaluation of long-term impact or retention of the knowledge acquired.

5 CONCLUSIONS

The integration of Augmented Reality (AR) into the chemistry teaching-learning process demonstrated a significant impact on students' understanding of molecular geometry, specifically in tasks focused on spatial visualization and the interpretation of chemical structures. It differs from traditional approaches to basic instruction in that AR facilitated dynamic student interaction with various structural and three-dimensional models, promoting the transformation of abstract chemical concepts into manipulable and observable representations.

The development of this mobile application has an exclusive design that works only with the Android operating system and is structured through Blender for 3D modeling and Unity for the integration of pedagogical functionalities in relation to the complexity of the topics. Image markers contextualized within everyday life are incorporated in order to actively collaborate in the understanding of the topics through situated learning. This made it easier for students to recognize the presence of the principles of molecular geometry within their own environment, promoting cognitive processes and connections in relation to theoretical concepts and the application of this knowledge in everyday practice.

Based on the didactic perspective, the application has been structured with the aim of enhancing interactivity, intuitive navigation, and adaptation within socio-educational contexts.

The design is based on constructivist principles, as it reinforces active experimentation, guided exploration, and immediate visual feedback. The instructional dynamics emphasize the core content of molecular geometry, encouraging learning that focuses on inquiry and reflective reasoning.

Quantitative data show a significant statistical improvement in learning outcomes after the application of AR, which has increased by 53% in performance indicators closely related to conceptual understanding and the various forms of knowledge application. Analysis of the dimensions “knowledge of molecular geometry,” “application of knowledge,” and “perceived influence of AR within the teaching-learning process” showed that they have increased by 44%, effectively supported by immersive visualization tools in conceptual consolidation.

In addition to improving academic performance, the implementation of AR has promoted the development of higher-order cognitive skills, such as analytical reasoning, problem solving, and creativity. These results suggest that AR has not only increased student motivation and engagement, but also contributes significantly to the teaching and learning processes in relation to chemistry.

In conclusion, when augmented reality is integrated in a pedagogical and structured way, it constitutes and develops an instructional strategy that promotes and strengthens the understanding of molecular geometry, favoring conceptual mastery that is integrated into experiential learning. The results reinforce the potential of immersive technologies as tools that transform education in the experimental sciences, when implementation is based on a solid pedagogical design and rigorous empirical validation.

REFERENCES

Alcívar – Alcívar, F.; & Alcívar – Alcívar, D. (2021). Uso de las Tecnologías de la Información y Comunicación (TIC) en el proceso de enseñanza – aprendizaje de Biología. *Dominio de las Ciencias*, Vol. 7, No. 6, pp. 1585 – 1598. https://bit.ly/41OP4ts

Ávila – Garzón, C.; Bacca – Acosta, J.; Kinshuk, K.; Duarte, J.; & Betancourt, J. (2021). Augmented Reality in Education: An Overview of Twenty-Five Years of Research. *Contemporary Educational Technology*. Vol. 13, No. 3, pp. 1 – 29. https://doi.org/10.30935/cedtech/10865

Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. Qualitative Research in Psychology, 3(2), 77–101. https://doi.org/10.1191/1478088706qp063oa

Fernández – Batanero, J.; Montenegro – Rueda, M:, & Fernández – Cerero, J. (2022). Use of Augmented Reality for Students with Educational Needs: A Systematic Review (2016–2021). *Societies*. Vol. 12, No. 36, pp. 1 – 11. https://doi.org/10.3390/soc12020036

Ghobadi, M.; Shirowzhan, S.; Mehdi – Ghiai, M.; Mohammad – Ebrahimzadeh, F.; & Tahmasebinia, F. (2023). Augmented Reality Applications in Education and Examining Key Factors Affecting the Users' Behaviors. *Educ. Sci*. Vol. 13, No. 10, pp. 1 – 16. https://bit.ly/3Sv3kVn

Godoy – Jr, C. (2021). Augmented Reality for Education: A Review. *International Journal of Innovative Science and Research Technology*. Vol. 5, No. 6, 39 – 45. https://bit.ly/495gvls

Granados – Maguiño, M.; Romero – Vela, S.; Rengifo – Lozano, R.; Garcia – Mendocilla, G. (2020). Tecnología en el proceso educativo: nuevos escenarios. *Revista Venezolana de Gerencia*, Vol. 25, No. 92, pp. 1809 – 1819. https://bit.ly/3FKO3IZ

Hernández – Sampiere, R.; & Mendoza – Torres, C. (2018). Metodología de la investigación. Las rutas cuantitativa, cualitativa y mixta. *McGRAW-HILL INTERAMERICANA EDITORES. Primera edición*, pp. 1 – 753. https://bit.ly/3IAKmqf

Iatsyshyn, A.; Kovach, V.; Lyubchak, V.; Zuban, Y.; Piven, A.; Sokolyuk, O.; Iatsyshyn, A.; Popov, O.; Artemchuk, B.; & Shyshkina, M. (2020). Application of augmented reality technologies for education projects preparation. *CTE Workshop Proceedings [Online]*. Vol. 7, pp. 134 – 160. https://doi.org/10.55056/cte.318

Kozlitin, D.; Kozak, L.; Krystopchuk, T.; & Kochmar, D. (2021). The Application of Augmented Reality in Education and Development of Students Cognitive Activity. *CEUR Workshop Proceedings*. Vol. 1, pp. 1 – 10. https://bit.ly/3vLAes2

Martínez – Pérez, S.; Fernández – Robles, B.; & Barroso – Osuna, J. (2021). La realidad aumentada como recurso para la formación en la educación superior. *Campus Virtuales*, Vol. 10, No. 1, pp. 9 – 19. https://bit.ly/3Iy3uVJ

Mendoza – Melazco, D.; Flores – Hinostroza, E.; Paredes – Benavides, A.; & Sanango – Guallpa, C. (2022). Realidad aumentada en la enseñanza y el aprendizaje de la biología y la química universitaria: una revisión sistemática. *RECIMA21 - Revista Científica Multidisciplinar - ISSN 2675-6218*, Vol. 3, No. 8, pp. e381766. https://doi.org/10.47820/recima21.v3i8.1766

Mendoza – Mendoza, R.; & Loor – Colamarco, I. (2022). Estrategias Didácticas para la Enseñanza de las Ciencias Naturales y Desarrollo del Pensamiento Científico. *Dialnet*, Vol. 8, No. 1, pp. 1 – 12. https://bit.ly/3XVwVqF

Montecé – Mosquera, F.; Verdesoto – Arguello, A.; & Montecé – Mosquera, C. (2017). Impacto de la realidad aumentada en la educación del siglo XXI. *European Scientific Journal,* Vol. 13, No. 25, pp. 129 – 137. http://dx.doi.org/10.19044/esj.2017.v13n25p129

Paredes – Benavides, A. (2023). La realidad aumentada para reforzar la enseñanza – aprendizaje de los colores, pronombres y números. *Revista Iberoamericana De Investigación En Educación*, No. 7, pp. 1 – 14. https://doi.org/10.58663/riied.vi7.111

Peña – Rodríguez, F.; & Otálora – Porras, N. (2018). Educación y tecnología: problemas y relaciones. Pedagogía y Saberes, No. 48. *Universidad Pedagógica Nacional. Facultad de Educación*, pp. 59 – 70. https://bit.ly/3u67Wrr

Pimentel – Elbert, M.; Zambrano – Mendoza, B.; Mazzini – Aguirre, K.; & Villamar – Cárdenas, M. (2023). Realidad virtual, realidad aumentada y realidad extendida en la educación. *Revista Científica Mundo de la Investigación y el Conocimiento*, No. 7, pp. 74 – 88. https://bit.ly/47s2c9a

Sánchez – Córtes, I.; & Suárez – Riverio, J. (2019). Métodos de enseñanza, compromiso y metas del profesorado en modalidad b-learning. *Universidad de Ovideo*, Vol. 48, No. 3, pp. 311 – 320. https://bit.ly/3XEyvgc

Souza – Schilichting, T.; & Selpa – Heinzle, M. (2020). Metodologías activas de aprendizaje en la educación superior: aspectos históricos, principios e implementaciones. *Revista curriculum. Educa*, Vol. 18, No. 1, pp. 1 – 10. https://doi.org/10.23925/1809-3876.2020v18i1p10-39

Taber, K. (2015). Ase Sciencie practice teaching secondary Chemestry. *New Edition. Hooder Education. Five Edition*, pp. 1 – 41. https://bit.ly/3HCahNW

Taber, K. (2019). Foundations for Teaching Chemistry: Chemical Knowledge for Teaching. *Routledge. Education. Fist Edition*, pp.1 – 176. https://bit.ly/3HuV4ya

Toala – Palma, J.; Arteaga – Mera, J.; Quintana – Loor, J.; & Santana – Vergara, M. (2020). La Realidad Virtual como herramienta de innovación educativa. *EPISTEME KOINONIA.* Vol. 3, No. 5, pp. 1 – 10. https://bit.ly/3StH0tD

Zaragoza – Pérez, R.; & Cueva – Escudero, A. (2020). Realidad aumentada en la enseñanza. *Revista Digital Universitaria*, Vol. 21, No. 6, pp. 1 – 8. https://bit.ly/3kwB8mI