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Strategies for improving secondary school students' understanding of chemical concepts: A case study in Ecuador

Estrategias para mejorar la comprensión de conceptos químicos en estudiantes de secundaria: Un estudio de caso en Ecuador

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ABSTRACT

The aim of this research is to analyse strategies for improving secondary school students' understanding of chemical concepts, based on a case study in Ecuador. To produce this article, which takes the form of a mixed-methods case study, a quasi-experimental design was implemented, involving a comparison group and pre-test/post-test measurements, applied to 70 first-year sixth-form students. A teaching intervention was developed, structured in three phases: concrete molecular models, contextualised problem-solving and the use of digital simulations. The results showed a significant improvement in the academic performance of the experimental group, as well as an increase in motivation and conceptual understanding. It is concluded that the integration of active strategies promotes meaningful learning and constitutes a viable alternative in educational contexts with limited resources.

Descriptors: chemistry teaching; active learning; pedagogical innovation. (Source: UNESCO Thesaurus).

RESUMEN

Se prescribe como objetivo de investigación analizar las estrategias para mejorar la comprensión de conceptos químicos en estudiantes de secundaria desde un estudio de caso en Ecuador. Para la elaboración de este artículo en modalidad de estudio de caso con enfoque mixto, se implementó un diseño cuasiexperimental con grupo de comparación y medición pretest-postest, aplicado a 70 estudiantes de primero de bachillerato. Se desarrolló una intervención didáctica estructurada en tres fases: modelos moleculares concretos, resolución de problemas contextualizados y uso de simulaciones digitales. Los resultados evidenciaron una mejora significativa en el rendimiento académico del grupo experimental, así como un incremento en la motivación y comprensión conceptual. Se concluye que la articulación de estrategias activas favorece un aprendizaje significativo y constituye una alternativa viable en contextos educativos con recursos limitados.

Descriptores: enseñanza de la química; aprendizaje activo; innovación pedagógica. (Fuente: Tesauro UNESCO).

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Research articles

INTRODUCTION

The teaching of chemistry at secondary school level represents one of the most persistent pedagogical challenges in Latin American education systems; particularly when the study of the abstract nature of its fundamental concepts, such as chemical bonding, stoichiometry and acid-base equilibrium, requires higher-order cognitive processes that are often not fostered by lecture-based methodologies focused on the transmission of content, as noted by Chonillo-Sislema et al. (2024); this gap between declarative knowledge and conceptual understanding results in failure rates that exceed the average in several regions of the continent, with a particular impact on public institutions with limited teaching resources.

In Ecuador, the Ministry of Education (MINEDUC) has consistently acknowledged the difficulties students face with the exact sciences; within this framework, the 'Oswaldo Lombeyda' Municipal Educational Unit, located in the parish of Guamaní, in the south of the Metropolitan District of Quito, recorded a failure rate of 36.4% in chemistry for the first and second years of the unified general upper secondary programme (BGU) during the 2023–2024 academic year, a figure that exceeded the national average for the same educational level by twelve percentage points. This context prompted the design of a pedagogical intervention aimed at methodological diversification.

The international literature indicates that learning difficulties in chemistry are largely associated with an overload of symbolic content not grounded in concrete experiences, according to Garritz and Trinidad-Velasco (2003); in contrast, the incorporation of active strategies, such as model-based learning, contextualised problem-solving and the use of digital simulations, has shown favourable results in research of varying scope (Espinosa-Ríos et al., 2016; García-Gruezo et al., 2025). However, evidence regarding the coordinated implementation of these

three strategies in public education contexts with material constraints remains scarce, particularly in Ecuador.

Thus, the present study specifically sought to: (a) describe the strategies implemented and their pedagogical rationale; (b) evaluate changes in academic performance through group comparison; and (c) identify the qualitative factors associated with improved motivation and conceptual understanding. It should be noted that this study was conducted at the 'Oswaldo Lombeyda' Municipal School, located in Quito, Ecuador. Consequently, the relevance of this case lies in its potential for transfer to other schools within the Ecuadorian municipal system with similar socio-educational characteristics.

Consequently, the aim of the research was to analyse strategies for improving the understanding of chemical concepts among secondary school students through a case study in Ecuador.

Theoretical framework

Conceptual difficulties in learning chemistry

Learning chemistry involves mastering three levels of representation simultaneously: the macroscopic, the submicroscopic and the symbolic, as proposed by Garritz and Trinidad-Velasco (2003); the difficulty in integrating these levels is recognised as one of the main causes of poor performance in the subject, as secondary school students often resort to rote learning strategies when they fail to establish meaningful connections between the symbolic representation of equations and observable phenomena, as documented by Miranda-González (2024); this situation is exacerbated when teaching prioritises the verbal transmission of abstract concepts without tactile or visual mediation, in line with the views of López-Valentín (2020).

Studies conducted in Colombia, Mexico and Ecuador confirm that over 60% of sixth-form students perceive chemistry as a difficult or very difficult subject, and

that the absence of laboratory work and contextualised strategies constitutes a determining factor in this perception, according to Chonillo-Sislema et al. (2024) and Saavedra-Mera et al. (2024); this negative perception creates a cycle of demotivation that feeds back into poor performance, which is why pedagogical interventions must address both the cognitive and affective dimensions of the learning process, as argued by Urtecho-Arancibia (2025).

Learning based on concrete models

The use of three-dimensional models in chemistry teaching has proven particularly effective in reducing the abstraction inherent in molecular concepts; the tactile manipulation of structures such as the water molecule or sodium chloride allows students to construct more accurate and lasting mental representations than those derived from exclusively verbal instruction, as confirmed by Espinosa-Ríos et al. (2016). Alcarraz-Carbajal (2025) reports that the use of innovative teaching materials, such as chemical cubes made from readily available materials, generates meaningful learning about the periodic table among secondary school students; their results indicate performance gains of over 40% compared to control groups receiving traditional instruction.

In contexts with partially equipped laboratories, the DIY construction of molecular kits using recycled materials emerges as a pedagogically valid alternative, in line with the proposal by Del-Valle-Calderón and Jiménez-Alonzo (2024); this option not only compensates for the lack of infrastructure but also facilitates active learning processes in which students construct their own representational materials, thereby promoting conceptual understanding from a constructivist perspective.

Contextualised problem-solving and cooperative learning

Curricular contextualisation is one of the principles most consistently supported by educational research in science; when chemistry content is linked to

phenomena in the student's immediate environment, mechanisms of meaningful learning are activated, leading to greater retention and transfer of knowledge, as proposed by Rutto-Martínez et al. (2025). The use of problem situations drawn from the students' cultural and geographical environment, such as water purification processes or traditional fermentation methods, facilitates the understanding of abstract concepts by providing them with observable and culturally relevant references, according to Colomer et al. (2016).

Cooperative learning similarly represents a methodological approach that enhances chemical understanding by promoting the verbalisation of cognitive processes among peers. Valero-Alemán and Mayora (2009) demonstrated that Year 9 groups working in cooperative teams with assigned roles achieved significantly higher marks than those in groups receiving individual instruction. Peña-Martínez et al. (2021) reaffirmed this finding in the specific field of chemical reactions, emphasising that the assignment of roles such as reader, calculator and verifier increases individual responsibility within the group and reduces dependence on the teacher.

Digital simulations in chemistry teaching

Learning and knowledge technologies (LKT) have gained increasing prominence in science education; within this conceptual framework, the cognitive theory of multimedia learning posits that the combination of dynamic visual representations with verbal information promotes the construction of more robust mental models than those derived from monomodal instruction, as argued by González-Oviedo and Naranjo-Lugo (2023); hence, the simulations on the University of Colorado's PhET Interactive Simulations platform have been widely evaluated as low-cost, highly effective resources.

METHOD

The research adopted a quasi-experimental design with a comparison group and pre-test/post-test measurements, within a mixed-methods research approach; the quantitative component enabled the assessment of the intervention's effect on academic performance, whilst the qualitative component facilitated an understanding of the underlying motivational and conceptual processes. In epistemological terms, the study was configured as an instrumental case study (Stake, 1999), in that the case of the 'Oswaldo Lombeyda' Municipal Educational Unit served as a unit of analysis that enabled the generation of transferable insights into science teaching within the Ecuadorian municipal education system.

Context and participants

The study was conducted at the "Oswaldo Lombeyda" Municipal Educational Unit (AMIE code: 17H01275), located in the parish of Guamaní, Calle OE6.22, Quitumbe zone administration, in the south of the Metropolitan District of Quito, province of Pichincha. The institution served a population from the lower-middle socioeconomic stratum, predominantly comprising families from working-class neighbourhoods in the south of the capital; it offered primary and secondary education in morning and afternoon sessions, with 55 teachers and an enrolment of approximately 1,238 students. In the 2023–2024 academic year, the natural sciences department recorded a failure rate of 36.4% in chemistry for the first and second years of the BGU programme.

The study participants were the 70 first-year BGU students, divided into two classes of 35 students each. Class A constituted the experimental group, in which the intervention plan was fully implemented; Class B served as the comparison group, using traditional lecture-based methodology. The allocation of groups was not random, as it followed the pre-existing institutional distribution, which represented a limitation in terms of experimental control. Two teachers participated: one with fifteen years' experience and training in biology and

chemistry, and another with five years' teaching experience and a degree in applied chemistry from the Central University of Ecuador.

Instruments

The following instruments were used: (a) a twenty-item multiple-choice diagnostic test on inorganic nomenclature and chemical bonds, with content validity verified by the subject's teaching team; (b) an exit test equivalent in structure and level of difficulty to the diagnostic test, administered at the end of the intervention; (c) a perception survey using a five-point Likert scale to assess students' attitudes towards the subject; (d) systematic classroom observation records drawn up on the basis of formative assessment criteria aligned with the national curriculum; and (e) five closing focus groups conducted with subgroups of six to eight students from Class A, with the aim of exploring perceptions of the strategies implemented.

Procedure and intervention

The intervention was structured in three phases, each lasting four weeks:

The first phase (weeks 1–4) focused on learning based on concrete molecular models. The students constructed handmade molecular model kits using recycled materials, namely flex foam spheres, wooden sticks and coloured paint, used to represent H_2O, CO_2, CH_4 and NaCl molecules. Each group of four students created their own models following structured guidelines, with the aim of reducing symbolic abstraction through the tactile manipulation of three-dimensional structures.

The second phase (weeks 5–8) focused on solving contextualised problems through cooperative learning. The decontextualised exercises from the textbook were replaced by problem situations drawn from the everyday environment of the students in Guamaní: the process of purifying water distributed by the Metropolitan Public Water and Sanitation Company (EPMAPS), which included

chlorination as an example of a chemical reaction with an impact on public health; the fermentation of chicha de morocho as a biochemical reaction present in the culinary traditions of southern Quito; and the artisanal production of soap as an illustration of the saponification reaction. The 45-minute sessions were organised with assigned roles: reader, calculator, reporter and verifier.

The third phase (weeks 9–12) incorporated digital simulations using the University of Colorado's PhET Interactive Simulations platform, available in Spanish and freely accessible. We worked with the modules 'States of Matter', 'pH: Scale' and 'Reactions and Rates' in the institution's computer lab, equipped with 28 computers with internet access, using observation guides previously prepared by the teaching team.

Data analysis

The quantitative data were analysed using descriptive statistics (mean, standard deviation) and inferential statistics. For comparisons between groups, Student's t-test for independent samples was used, with a significance level of $\alpha = 0.05$. Effect size was calculated using Cohen's d (1988), following conventional criteria that define values of 0.2 as a small effect, 0.5 as a medium effect and 0.8 as a large effect. Qualitative data obtained from the focus groups and observation records were analysed using inductive thematic coding.

RESULTS

In light of the achievement of the stated research objective, the following is presented:

Initial assessment

The diagnostic test administered at the start of the term revealed that 62.9% of the 70 first-year BGU students failed to achieve the minimum pass mark (7/10); the overall mean was 4.2 points (SD = 1.3), and incorrect answers were concentrated on items requiring symbolic representation of molecules and

understanding of the concept of electronegativity, which highlighted the gap between rote learning and conceptual understanding reported in the literature, in line with the findings of Garritz and Trinidad-Velasco (2003) and Chonillo-Sislema et al. (2024).

The perception survey revealed that 76.1% of students considered chemistry to be 'difficult or very difficult'; 60.0% stated that lectures did not allow them to visualise the phenomena described in the texts, and only 10.0% indicated that they had undertaken laboratory practicals during the previous basic education cycle. These figures were consistent with the records of the Student Counselling Department (DECE), which identified a lack of motivation towards the exact sciences as one of the main factors contributing to poor performance.

Quantitative results of the intervention

At the end of the twelve-week intervention, the final test yielded the following results: the experimental group (parallel A) achieved an average of 7.9 points (SD = 0.8), compared to the initial 4.2 points, with a pass rate rising from 37.1% to 85.7%. The comparison group (parallel B), which continued with traditional lecture-based methodology, recorded an average of 5.0 points (SD = 1.1) at the end of the term, with a 45.7% pass rate.

The Student's t-test for independent samples yielded a t-value of 8.61 ($p < 0.001$), reflecting statistically significant differences between the two groups; the effect size calculated using Cohen's d was 1.21, classified as a large effect according to Cohen's conventional criteria (1988), indicating that the intervention produced an educationally relevant improvement, not merely a statistically significant one. In practical terms, 85.7% of students in the experimental group achieved the minimum pass mark, compared with 45.7% in the comparison group, representing a difference of forty percentage points.

Progress across the phases was also noticeable; by the end of the first phase, formative assessments showed that students in parallel A were able to describe the bonding properties of the molecules studied using concrete models with greater precision. By the end of the second phase, oral participation in collaborative sessions had increased progressively; several groups correctly completed the stoichiometric calculations associated with the chlorination and saponification reactions presented in the contextualised problems. In the third phase, the use of PhET simulations enabled students to dynamically visualise the behaviour of states of matter and pH variations, concepts that had proved particularly difficult to grasp in the diagnostic test.

Qualitative findings

Class observation records documented a progressive and sustained increase in oral participation during the sessions of the second phase, particularly in the groups that worked on the problem-based scenarios concerning morocho chicha and water purification. In four of the five closing focus groups, students spontaneously used the expression "understanding what chemistry is for" when referring to the impact of the second phase; this recurring expression suggests that curricular contextualisation acted as a key motivational factor.

The focus groups also revealed that the hands-on construction of molecular models in the first phase generated a sense of ownership of learning, expressed by the students in terms such as "you build it yourself and understand it better". This perception is consistent with the premises of active learning and constructivism, widely referenced in educational research (Espinosa-Ríos et al., 2016). In contrast, the third phase involving digital simulations was rated positively by most students in terms of visualisation, although some reported difficulties arising from unstable internet connectivity during three sessions, which forced the teaching team to make didactic adjustments in real time.

DISCUSSION

The results obtained are consistent with the accumulated evidence from educational research on the teaching of chemistry in secondary education; the significant improvement in the experimental group, expressed as a Cohen's d of 1.21, places the effects of the intervention in the high range of magnitudes reported for active pedagogical interventions in science, according to Peña-Martínez et al. (2021) and García-Gruezo et al. (2025); this consistency suggests that the combination of three complementary strategies—namely, concrete models, curricular contextualisation and digital simulations—produces a synergistic effect that exceeds what each strategy could generate in isolation.

The first phase, based on the manual construction of molecular models, directly addressed the problem of symbolic representation disconnected from sensory experience, identified as a central source of difficulty by Garritz and Trinidad-Velasco (2003); the ability to manipulate three-dimensional molecular structures created by the students themselves bridged the gap between the macroscopic and submicroscopic levels of chemistry, in line with the principles of meaningful learning outlined by López-Valentín (2020); Similarly, Del-Valle-Calderón and Jiménez-Alonzo (2024) found results consistent with their QUIMIOKIT proposal in a hybrid format, confirming that portable chemistry kits, regardless of their level of technological sophistication, are effective when integrated into structured teaching sequences.

The second phase of curricular contextualisation provided the motivational element that the research identifies as a necessary condition for in-depth learning in chemistry, in line with the views of Urtecho-Arancibia (2025) and Saavedra-Mera et al. (2024); the selection of problem situations linked to the reality of Guamaní—specifically EPMAPS drinking water, morocho chicha and handmade soap—demonstrated that the cultural relevance of the content can function as a cognitive and affective anchor that transforms perceptions of the subject. This

finding is consistent with the findings of Rutto-Martínez et al. (2025), who conceptualise the classroom as a scientific microsociety in which chemistry is practised as a tool for understanding the environment, and with the arguments of Colomer et al. (2016) regarding the pedagogical value of contextualised learning pathways in earth sciences. The assignment of cooperative roles—reader, calculator, narrator and verifier—reinforced the positive interdependence described by Valero-Alemán and Mayora (2009), by distributing cognitive responsibility amongst the group members.

The third phase, mediated by PhET simulations, offered students a dynamic representation of chemical phenomena that complemented the tactile and contextualised experiences of the previous phases; Pacheco et al. (2021) documented convergent effects with the use of PhET for learning the concept of solutions, whilst González-Oviedo and Naranjo-Lugo (2023) theoretically grounded this effectiveness in the principles of the cognitive theory of multimedia learning. The usefulness of digital simulations for highly complex concepts, such as acid-base equilibrium and states of matter, has also been highlighted by Nicolalde-Guanoluisa et al. (2025), whose proposal for titration curves produced comparable results. However, the connectivity issues reported in three sessions during this phase serve as a reminder of the digital divide that still affects public institutions in southern Quito, a limitation already highlighted in Parra-Hernández's (2024) report on the use of TAC in Ecuador.

The comparison with the control group is equally important for interpreting the results. Parallel group B, which continued with the expository methodology, showed a slight improvement compared to the initial assessment (from 4.2 to 5.0 points on average), which could be attributed to maturation effects or the impact of regular formative assessment; however, its pass rates, at 45.7%, remained consistent with the previous institutional failure rate. This contrast reinforces the conclusion that the improvement in the experimental group cannot be attributed

exclusively to factors external to the intervention, although the absence of randomisation limits the possibility of establishing definitive causal relationships.

It should be noted that the intervention was carried out in a context with limited material resources: without an equipped laboratory, with unstable connectivity and with a timetable comprising only three weekly periods per class; this context makes the magnitude of the effect obtained all the more significant and underscores that pedagogical innovation does not necessarily require major technological investments, but rather a coherent instructional design that integrates diverse strategies based on the principles of active and contextualised learning (Ojeda-Salvatierra et al., 2025; Bastidas et al., 2025). Thus, gamification and augmented reality, explored in other studies as complementary approaches, could be integrated into future versions of the intervention provided that the appropriate technological infrastructure is available (López-Hernández et al., 2024).

CONCLUSION

With regard to the research objective set out, it was found that the coordinated implementation of concrete models, contextualised problem-solving and digital simulations significantly improved secondary school students' understanding of chemical concepts, whilst this methodological combination promoted integration between levels of representation and reduced the tendency towards rote learning.

In this regard, the results showed a substantial increase in the academic performance of the experimental group, accompanied by statistically significant differences compared to the control group, confirming that methodological diversification had a direct impact on the quality of learning, not only in quantitative terms but also in terms of conceptual understanding.

Furthermore, it was observed that linking content to the students' everyday context, together with the manipulation of models and the dynamic visualisation of phenomena, promoted both motivation and understanding, highlighting the role

of pedagogical mediation as the central axis of the chemistry teaching-learning process.

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CONFLICT OF INTEREST

There is no conflict of interest with any individuals or institutions associated with the research.

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