Revista Multidisciplinaria Perspectivas Investigativas
Multidisciplinary Journal Investigative Perspectives
Vol. 6(2), 20-29, 2026
https://doi.org/10.62574/rmpi.v6i2.517

Experimental inquiry-based teaching for the instruction of stoichiometry and academic achievement in Ecuadorian upper secondary schools

Didáctica experimental en indagación para la enseñanza de estequiometría y rendimiento académico en bachillerato ecuatoriano

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ABSTRACT

The research objective of this article is to design strategies for inquiry-based experimental teaching in the teaching of stoichiometry and academic achievement in Ecuadorian upper secondary schools. Using a descriptive documentary design based on the 'feasible project' approach, fifteen academic sources on inquiry-based teaching applied to the teaching of chemistry were analysed. The results show that inquiry-based learning improves conceptual understanding of stoichiometry when it is structured in phases, integrated with submicroscopic models and supported by progressive teaching scaffolding, although gaps in teacher training remain. On this basis, a four-component proposal is formulated a structured inquiry cycle, particle-level models, progressive scaffolding and a two-tiered integrated assessment which is feasible using basic laboratory resources available in Ecuadorian secondary education.
Descriptors: chemistry teaching; experimental method; academic achievement. (Source: UNESCO Thesaurus).

RESUMEN

El presente artículo tiene como objetivo de investigación diseñar estrategias para la didáctica experimental en indagación para la enseñanza de estequiometría y rendimiento académico en bachillerato ecuatoriano. Mediante un diseño documental descriptivo apoyado en la modalidad de proyecto factible, se analizaron quince fuentes académicas sobre didáctica de la indagación aplicada a la enseñanza de la química. Los resultados evidencian que la indagación mejora la comprensión conceptual de la estequiometría cuando se estructura en fases, se articula con modelos submicroscópicos y se acompaña de un andamiaje docente progresivo, aunque persisten vacíos en la formación del profesorado. A partir de ello se formula una propuesta de cuatro componentes: ciclo de indagación estructurado, modelos a nivel de partículas, andamiaje progresivo y evaluación integrada de dos niveles, viable con recursos de laboratorio básicos disponibles en la educación secundaria ecuatoriana.
Descriptores: enseñanza de la química; método experimental; rendimiento académico. (Fuente: Tesauro UNESCO).

Received: 06/02/2026. Reviewed: 17/02/2026. Approved: 18/03/2026. Published: 01/04/2026.
Research articles section

INTRODUCTION

Stoichiometry is one of the content areas where students' difficulties most often concentrate within the secondary school Chemistry curriculum, since it combines mathematical reasoning, conceptual understanding of the chemical reaction and the capacity to represent that reaction at different levels of abstraction. It is no coincidence that stoichiometry has become, in the specialised literature on science education, a paradigmatic content for testing different experimental teaching strategies: Talanquer (2011) systematised that expert chemical understanding requires a fluid articulation among three levels of representation (macroscopic, submicroscopic and symbolic), an articulation that is precisely where a large part of students' problems in stoichiometry are concentrated.

Inquiry-based teaching (that is, the pedagogy that places the student in the role of a researcher confronting scientific questions and phenomena) has repeatedly been proposed as an alternative to the expository and algorithmic instruction that has traditionally dominated the solving of stoichiometric problems. In this regard, Minner et al. (2010) systematised this result through a research synthesis spanning almost two decades of studies: inquiry-based science instruction produces positive and consistent effects on students' conceptual understanding compared with purely expository instruction; consequently, Furtak et al. (2012) confirmed this result through a meta-analysis of experimental and quasi-experimental studies, showing that moderate-magnitude effects favour inquiry-based science teaching over conventional methods.

Given that inquiry is neither uniform nor automatic, it is necessary to specify under which conditions this strategy works best; in this regard, Lazonder and Harmsen (2016) showed in a meta-analysis on the amount of teacher guidance during inquiry that guided inquiry systematically outperforms both fully open inquiry and traditional instruction (especially when students have no experience with investigative processes). Along these lines, the question arises of whether the issue is not so much inquiring as such, but rather how much structured guidance is needed for inquiry to work.

However, applying inquiry to chemistry as a specific field presents characteristics that the general literature on science teaching does not address in sufficient detail; in this context, Jegstad (2024) systematised, through a systematic review focused solely on inquiry-based chemistry education, that this field exhibits considerable conceptual heterogeneity regarding what is understood by inquiry in the chemistry laboratory, which makes it difficult to compare studies directly. Therefore, Strippel and Sommer (2015) showed that even among teachers specifically trained in science, different conceptions still exist of what scientific inquiry applied to laboratory work actually is, which directly conditions the way in which such inquiry can be translated into classroom practice.

Likewise, the specific representational dimension of stoichiometry as chemical content must be taken into account; for this reason, Chandrasegaran et al. (2007) developed a two-tier diagnostic instrument capable of distinguishing between students' ability to describe a chemical reaction and their ability to explain it using multiple levels of representation, showing that both abilities do not progress together. Similarly, Jaber and BouJaoude (2012) demonstrated that teaching which deliberately articulates the macroscopic, microscopic and symbolic levels leads to a relational understanding of chemical reactions superior to that achieved with approaches favouring a single level of representation.

Put differently, this study does not aim to close the epistemological debate on what scientific research is, but rather to provide an operational bridge between international evidence and the curricular conditions of Ecuadorian secondary education, where the teaching of stoichiometry still depends largely on the algorithmic solving of problems with no experimental anchoring. From this standpoint, the relevance of the study lies in the fact that the chosen teaching strategy directly affects the quality of the conceptual learning achieved (Kimberlin & Yezierski, 2016),

since inquiry lessons supported by particle-level models improve conceptual understanding of stoichiometry better than traditional algorithmic instruction.

Based on the foregoing, the present article aims to design strategies for experimental inquiry-based teaching for the instruction of stoichiometry and academic achievement in Ecuadorian upper secondary schools.

METHOD

In accordance with the stated objective, the present study is designed as descriptive documentary research and is supported by the 'feasible project' modality. In the descriptive documentary component, the systematisation, description and comparison of published scientific evidence on inquiry-based teaching applied to chemistry education (specifically stoichiometry) was carried out, while in the feasible-project component an experimental teaching proposal was constructed for secondary school classrooms in Ecuador.

To this end, academic sources indexed in databases related to science education and chemistry education were reviewed (systematic reviews, meta-analyses and intervention studies teaching stoichiometry through inquiry). Fifteen sources were thus included because they were thematically relevant, reported methodological rigour and corresponded to the educational level under study.

The documentary analysis method was used as the analytical technique. The following was extracted from each source: the theoretical research model used, the level of teacher guidance employed, the population and educational context studied, and the main results reported on conceptual understanding or academic achievement. This information was then organised into comparative matrices to identify common patterns among the different studies reviewed.

The feasible-project phase, in turn, was developed in three interrelated stages: first, the diagnosis of the didactic conditions that the evidence identifies as determinants of the effectiveness of inquiry in chemistry; second, the design of the proposal of experimental strategies based on such evidence; and third, the definition of feasibility criteria (laboratory materials usually available in Ecuadorian secondary education institutions).

RESULTS

From the documentary analysis carried out, three main categories of results were identified: those related to theoretical models of scientific inquiry, those related to its specific application to the teaching of stoichiometry, and those related to the conditions of teacher guidance that maximise its effectiveness. Table 1 systematises the reviewed studies with the greatest empirical weight for the design of the proposal.

Table 1. *Studies reviewed under documentary analysis.*

Author(s) and year	Study type	Context	Main contribution
Furtak et al. (2012)	Meta-analysis	International	Inquiry-based science teaching produces moderate-magnitude effects on learning compared with conventional instruction.
Kimberlin & Yezierski (2016)	Quasi-experimental study	United States	Inquiry lessons using particle-level models strengthen conceptual understanding of stoichiometry.
Lazonder & Harmsen (2016)	Meta-analysis	International	Guided inquiry systematically outperforms open inquiry and traditional instruction.
Minner et al. (2010)	Research synthesis	United States	Inquiry-based science instruction improves students' conceptual understanding.
Panggabean et al. (2023)	Development study	Indonesia	Inquiry-based STEM materials improve students' stoichiometric thinking skills.
Pedaste et al. (2015)	Systematic review	International	Proposes a five-phase inquiry cycle: orientation, conceptualisation, investigation, conclusion and discussion.
Pratiwi et al. (2021)	Development study	Indonesia	Inquiry-based stoichiometry teaching material strengthens conceptual understanding, science process skills and attitudes.
Strat et al. (2024)	Systematic review	International	Teacher training in inquiry-based science teaching shows significant implementation gaps.
Strippel & Sommer (2015)	Qualitative study	Germany	Disparate conceptions persist among teachers regarding the nature of scientific inquiry applied to laboratory work.
Sudchanham & Cojorn (2025)	Intervention study	Thailand	The 5E model combined with the FOPS strategy improves stoichiometric problem-solving skills.

Source: Own elaboration (2026).

As can be seen in Table 1, the evidence shows that scientific inquiry has positive effects on chemistry learning in general, but these effects are maximised when inquiry is organised through a cycle of phases (rather than a random sequence) and when it is applied to specific content, such as stoichiometry. Along these lines, Pedaste et al. (2015) systematised, on the basis of a systematic literature review, a theoretical model of the inquiry cycle comprising five articulated phases: orientation (posing the problem or phenomenon to be investigated), conceptualisation (formulating questions or hypotheses), investigation (collecting data through experimentation), conclusion (comparing the data obtained with the initial hypotheses) and discussion (communicating and reflecting on the results obtained). It should be noted that this cycle does not operate as a rigid sequence, but rather as a flexible framework that allows for iterations and returns between phases, especially for conceptually demanding content such as stoichiometry.

When inquiry is applied specifically to the teaching of stoichiometry, Panggabean et al. (2023) developed STEM-oriented inquiry-based teaching materials and demonstrated that secondary school students' stoichiometric thinking skills improved significantly; similarly, Pratiwi et al. (2021) developed stoichiometry-specific teaching material under the same approach and showed a simultaneous strengthening in three dimensions: conceptual understanding, science process skills and attitudes towards the discipline.

With regard to inquiry models combined with complementary problem-solving strategies, Sudchanham and Cojorn (2025) demonstrated that, when the five-phase model is combined with the FOPS strategy (of a systematic nature), stoichiometric problem-solving skills improve more than when either strategy is applied separately. In this respect, Kimberlin and Yezierski (2016) also found that the particle-level models used in inquiry lessons specifically improve

conceptual understanding of stoichiometry, since algorithmic strategies tend to ignore this dimension.

In addition, Lazonder and Harmsen (2016) demonstrated that guided inquiry systematically outperforms both fully open inquiry and traditional instruction; consequently, Arifin et al. (2025) also confirmed, through a systematic review with meta-analysis, that inquiry-based learning significantly strengthens students' critical thinking skills in science, and the effects are greater when inquiry includes explicit teacher scaffolding in the early phases of the process. Regarding the teacher training required to implement these strategies, Strat et al. (2024) demonstrated, through a systematic review of science teacher education, that gaps still exist in teacher preparation for inquiry-based teaching. Strippel and Sommer (2015) further show that even among teachers specifically trained in chemistry, different ideas still exist about what scientific inquiry in the laboratory actually constitutes; the conceptual and practical categories found in the literature are therefore summarised, together with their basis, in Table 2.

Table 2. *Emerging documentary categories.*

Category	Teaching element	Basis
Structured inquiry cycle	Sequence of orientation, conceptualisation, investigation, conclusion and discussion phases	Pedaste et al. (2015)
Particle-level models	Submicroscopic representations linking the observed reaction to its molecular explanation	Kimberlin & Yezierski (2016); Talanquer (2011)
Guided inquiry with teacher scaffolding	Degree of teacher guidance adjusted to students' prior experience	Lazonder & Harmsen (2016); Arifin et al. (2025)
Integration with problem-solving strategies	Combination of the 5E cycle with systematic problem-solving strategies, such as FOPS	Sudchanham & Cojorn (2025)
Articulation of representation levels	Teaching that deliberately connects the macroscopic, submicroscopic and symbolic levels	Jaber & BouJaoude (2012); Chandrasegaran et al. (2007)
Teacher training in inquiry	Specific training of teaching staff in the nature and conduct of scientific inquiry	Strat et al. (2024); Strippel & Sommer (2015)

Source: Own elaboration (2026).

As Table 2 shows, the categories identified demonstrate that research on the teaching of stoichiometry is not sustained by a single component. Rather, it is articulated among a structured teaching cycle, explicit submicroscopic representations, a properly calibrated degree of teacher guidance and specific teacher training capable of sustaining this articulation in classroom practice. In sum, the systematised results show that experimental inquiry-based teaching has international empirical support for strengthening conceptual understanding in stoichiometry, but only under certain conditions of didactic structuring and teacher training, conditions that the proposal formulated in the following section seeks to operationalise.

PROPOSED EXPERIMENTAL TEACHING STRATEGIES

Therefore, on the basis of the documentary diagnosis described above, a proposal of experimental inquiry-based teaching strategies is formulated below for the teaching of stoichiometry in Ecuadorian secondary schools under the feasible-project approach. It consists of four interrelated components: structuring of the inquiry cycle, submicroscopic models, progressive teacher scaffolding and integrated assessment of academic achievement. It should be noted that these components do not function separately, but rather reinforce one another throughout the same teaching sequence.

The first component (structuring of the inquiry cycle) starts from the fact that effective inquiry requires an explicit teaching sequence rather than unstructured experimentation. For this reason, it is proposed that each stoichiometry unit be organised according to the five phases reported by Pedaste et al. (2015): an orientation phase, in which students are confronted with a specific experimental problem (for example, the limiting reagent in a precipitation reaction); a

conceptualisation phase, in which hypotheses are formulated about the expected amounts of product; an investigation phase, in which the experimental procedure is carried out and mass or volume data are collected; a conclusion phase, in which the results obtained are compared with the expected stoichiometric calculations; and a discussion phase, in which students communicate and argue their results before the group. This measure responds directly to the theoretical framework systematised by Pedaste et al. (2015), who demonstrated that this cycle constitutes the common structure of inquiry processes with the strongest empirical evidence.

The second component is the systematic inclusion of particle-level models in every laboratory activity. In other words, each stoichiometry experimental activity must be accompanied by explicit submicroscopic representations (particle diagrams or manipulable molecular models) so that students link the macroscopic observation of the chemical change with its explanation at the atomic and molecular level (Kimberlin & Yezierski, 2016; Talanquer, 2011). This strategy is based on the work of Kimberlin and Yezierski (2016) and Talanquer (2011), who demonstrated that the explicit articulation among the macroscopic, submicroscopic and symbolic levels is the cognitive condition that determines conceptual understanding of stoichiometry. Jaber and BouJaoude (2012) also demonstrated that this articulation is more effective when practised systematically rather than sporadically throughout the teaching unit.

The third component is progressive teacher scaffolding according to students' prior experience with investigative processes. For this reason, secondary schools should begin with structured inquiry activities (the teacher provides the research question and the experimental procedure) and then move towards guided inquiry activities (students design part of the procedure based on the teacher's question). Lazonder and Harmsen (2016) demonstrated that guided inquiry systematically outperforms both fully open inquiry and traditional instruction, especially for students with no prior experience in investigative work.

The fourth component is the integrated assessment of academic achievement, which entails more than merely correcting numerical stoichiometric calculations. Two-tier assessment instruments are therefore proposed (such as those developed by Chandrasegaran et al., 2007), capable of distinguishing between students' ability to carry out algorithmic procedures and their ability to conceptually explain these procedures using the three levels of chemical representation. This line of action was also documented by Panggabean et al. (2023) and Pratiwi et al. (2021), who demonstrated that inquiry-based stoichiometry teaching materials simultaneously improve conceptual understanding, science process skills and students' attitudes towards chemistry.

By way of example, the specific experimental activities that could be included in the proposal are: limiting reagent in the laboratory (a practical activity in which students experimentally determine, through a simple precipitation reaction, which of two reagents limits the amount of product obtained); actual versus theoretical yield (an activity in which students calculate the percentage yield of a reaction and discuss the sources of error in the experiment); and particle gallery (an exercise in which students produce submicroscopic representations of a reaction before and after carrying it out experimentally). This type of activity is consistent with the work of Sudchanham and Cojorn (2025), who demonstrated that combining the inquiry cycle with systematic problem-solving strategies significantly improves students' performance in stoichiometry. To show its feasibility, Table 3 groups the proposal into phases, with their activities, those responsible and the estimated time.

Table 3. *Phases of the proposal.*

Phase	Main activity	Responsible party	Estimated duration
Diagnosis	Two-tier diagnostic assessment of students' prior understanding of stoichiometry	Chemistry teacher	1 week
Teacher awareness-raising	Workshop on the five-phase inquiry cycle and its application to the stoichiometry laboratory	Subject-area coordination	1 week
Structured implementation	Development of stoichiometry units through structured inquiry with particle models	Chemistry teacher	4 weeks
Transition to guided inquiry	Experimental activities with increasing student autonomy in designing the procedure	Chemistry teacher	4 weeks
Integrated assessment	Application of two-tier instruments and analysis of the academic achievement attained	Chemistry teacher	At the close of the unit
Monitoring and adjustment	Analysis of results and adjustment of the teaching sequence for the following period	Subject-area coordination	At the close of the term

Source: Own elaboration (2026).

The proposal can be implemented with basic laboratory materials, available in most Ecuadorian secondary schools, because the practical activities are based on low-risk, low-cost reagents and procedures; consequently, the feasibility of the proposal is conditioned mainly by the didactic reorganisation of existing practices and by teacher training in the inquiry cycle, rather than by the acquisition of additional specialised equipment. The evaluation of the proposal should therefore include quantitative and qualitative indicators: student performance on two-tier assessment instruments, the quality of the submicroscopic representations developed by students, and teachers' perceptions of the changes observed in the group's conceptual understanding. This monitoring system allows for the progressive adjustment of strategies, a flexible principle inherent to the feasible-project approach.

DISCUSSION

The systematised results of this study make it possible to discuss, first, the centrality of the structured inquiry cycle as a condition for didactic effectiveness. Although the general literature on science teaching supports the benefits of inquiry, it does not work automatically or indiscriminately (Pedaste et al., 2015), as evidenced by the fact that Pedaste et al. (2015) systematised a five-phase cycle that clearly distinguishes structured inquiry from mere disorderly experimentation; it is therefore necessary to differentiate between manipulating laboratory materials and carrying out a genuine investigative process.

In this connection, it is necessary to observe the relationship between the amount of teacher guidance and the functioning of inquiry in contexts with little prior investigative experience, as is usually the case in Ecuadorian secondary schools. Lazonder and Harmsen (2016) demonstrated that guided inquiry systematically outperforms both fully open inquiry and traditional instruction. This is important for Ecuador because stoichiometry has traditionally been taught algorithmically, so that an abrupt shift towards fully open inquiry, without progressive scaffolding, could prove counterproductive. In addition, the evidence reviewed allows for a discussion of the representational aspect of stoichiometry as a particularly challenging content from a cognitive standpoint. Talanquer (2011) systematised that expert chemical understanding involves a fluid articulation among the macroscopic, submicroscopic and symbolic levels; the proposal formulated in this study therefore intentionally includes explicit submicroscopic representations in each experimental activity, so that inquiry is not reduced to the mechanical manipulation of reagents with no conceptual anchoring.

It is also necessary to mention gaps in teacher training as a limiting condition for the effectiveness of any inquiry-based teaching proposal. Strat et al. (2024) showed that science teachers' training in inquiry-based teaching is still deficient; this means that having a good teaching proposal does not guarantee its success in the classroom, which is why the proposal formulated here includes a teacher-awareness phase prior to carrying out the experimental activities. Thus, the proposal put forward constitutes precisely a progressive sequence of teacher scaffolding, as found by Lazonder and Harmsen (2016): inquiry works best when teachers adjust the amount of guidance to students' experience, rather than applying the method uniformly and disregarding prior level; otherwise, inquiry that is too open from the outset will frustrate rather than foster understanding.

It is also necessary to refer to the combination of inquiry models and systematic problem-solving strategies. Sudchanham and Cojorn (2025) showed that, when the 5E cycle is combined with the FOPS strategy, stoichiometric problem-solving skills improve significantly. This convergence gives the proposal formulated here a particular empirical basis, since conceptual inquiry without a systematic problem-solving strategy could leave unattended the procedural dimension that stoichiometry, as mathematically demanding content, also requires. In contrast to a view that sharply opposes conceptual inquiry and algorithmic problem-solving, the evidence reviewed shows an approach that combines both dimensions. Panggabean et al. (2023) and Pratiwi et al. (2021) demonstrated that inquiry-based stoichiometry teaching materials simultaneously develop conceptual understanding and science process skills, without compromising the development of the procedural competence needed for stoichiometric calculations; as for academic achievement, the central variable of interest in this study, it should not be reduced to the correction of numerical results. Chandrasegaran et al. (2007) developed a diagnostic instrument capable of differentiating between the ability to describe and the ability to explain a chemical reaction; two-tier assessment instruments, such as those included in the proposal, are therefore required to capture both procedural performance and conceptual understanding.

CONCLUSION

The objective of this study was to design strategies for inquiry-based experimental teaching for the instruction of stoichiometry and academic achievement in Ecuadorian secondary schools. The results support the conclusion that this is achieved through a proposal that articulates four interdependent components: a five-phase structured inquiry cycle, the systematic inclusion of submicroscopic models, progressive teaching scaffolding adapted to students' prior experience, and an integrated assessment capable of differentiating algorithmic performance from conceptual understanding. The analysis shows that inquiry does not, by itself, guarantee better learning outcomes, but rather depends on the didactic structuring of the process, the explicit articulation among the macroscopic, submicroscopic and symbolic levels, and teacher training that is currently very weak in this respect. In this way, the proposed approach does not replace the algorithmic solving of stoichiometric problems, but rather integrates it with the conceptual and experimental dimension, a deficit documented in Ecuadorian secondary education. It is thus concluded that designing experimental inquiry strategies is feasible with the laboratory resources generally available in the country's schools, and that their feasibility depends mainly on the didactic reorganisation of practices and on teacher training, rather than on investment in additional equipment.

FUNDING

Non-monetary.

CONFLICT OF INTEREST

There is no conflict of interest with individuals or institutions linked to the research.

ACKNOWLEDGEMENTS

To the Universidad Central del Ecuador and the Unidad Educativa Mejía, Quito, Ecuador, for the institutional support provided for the development of this research.

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