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Experimentation in secondary education: how to develop higher-order scientific skills?

La experimentación en secundaria: ¿cómo formar habilidades científicas de orden superior?

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Abstract

This article analyzes how experimentation in secondary education contributes to the development of higher-order scientific skills (HOSS): critical thinking, problem solving, argumentation, and hypothesis formulation. Through a systematic review using PRISMA methodology (2016-2026) in databases such as *Scopus, WoS, ERIC, SciELO and Redalyc*, seven thematic categories were identified: scaffolding, teaching based on international studies, collaborative problem solving, design-build-test (maker culture), STEM/STEAM education, contextualization of learning, and reflective exchange spaces. Findings reveal that experimentation alone does not automatically develop HOSS; explicit teacher scaffolding, pedagogical guidance, meaningful contextualization, and argumentation opportunities are required. Lack of teacher training and infrastructure in Latin America limits this potential.

Keywords: experimentation, higher-order scientific skills, secondary education, scaffolding, systematic review.

Resumen

Este artículo analiza cómo la experimentación en educación secundaria contribuye a la formación de habilidades científicas de orden superior (HCOS): pensamiento crítico, resolución de problemas, argumentación y formulación de hipótesis. Mediante una revisión sistemática con metodología PRISMA (2016-2026) en bases como *Scopus, WoS, ERIC, SciELO y Redalyc y*, se identificaron siete categorías temáticas: andamiaje, enseñanza basada en estudios internacionales, resolución de problemas colaborativa, diseño-construcción-prueba (cultura maker), formación STEM/STEAM, contextualización del aprendizaje, y espacios de intercambio reflexivo. Los hallazgos revelan que la experimentación por sí sola no desarrolla automáticamente HCOS; se requiere un andamiaje docente explícito, orientación pedagógica, contextualización significativa y oportunidades de argumentación. La falta de formación docente y de infraestructura en América Latina limita este potencial.

Palabras claves: experimentación, habilidades científicas de orden superior, educación secundaria, andamiaje, revisión sistemática.

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Introduction

When teaching science in secondary education, the aim is to educate citizens capable of understanding the world from a scientific perspective, developing critical thinking and problem-solving skills (Jiang et al. 2023). Undoubtedly, such consideration implies that education must correspond to the demands of today's world, as UNESCO (2017) affirms, along with the challenges and aspirations of the 21st century through relevant learning objectives and content. In this perspective, how can we achieve what Furman (2016, p. 32) calls "the possibility of experiencing first-hand the very process of investigating the world"? The answer is none other than through experimentation. Laboratory practices in natural sciences have long been considered a backbone connecting theoretical knowledge with empirical reality. But what role does the teacher play in this epistemic shift in the classroom? García and Moreno (2019, p. 157) respond:

> The teacher can foster the learning process through experimental work that involves active observation, questions and hypotheses, the artificialization of natural phenomena, and the search for solutions to everyday situations, and simultaneously, the development of scientific skills such as description, argumentation, analysis, appropriation, and application of scientific knowledge to question reality and transform it; finally, to understand science as knowledge that is built from everyday situations with no apparent answers, where students are the protagonists in the construction of their own new explanations.

A review of the published scientific literature shows that laboratory practices contribute to the development of experimental skills in secondary school students. Osorio (2022) and Jiang et al. (2023) mention that at this age, young people learn to handle chemical reagents, laboratory equipment and instruments, formulate hypotheses, conduct experiments to confirm them, and measure variables related to the phenomena under study.

Similarly, voices from the scientific community argue the benefits that experimentation brings to secondary education and how learning is generated across multiple dimensions. Along these lines, Bretz et al. (2013) and Hakim et al. (2013, 2016) have found that conducting scientific experiments allows for conceptual understanding and helps correct erroneous ideas. Furthermore, they affirm that laboratory practices help achieve meaningful learning by creating a motivating environment that awakens students' interest and curiosity to learn, while also favoring a deep understanding of complex concepts such as mediating space (Escobar, 2016; Pillajo et al., 2025).

However, if considered from a procedural perspective, it is worth mentioning that laboratories contribute to the development of specific skills. Thus, the study by Hernández et al. (2018) argues that experiments in secondary education are a source of knowledge and a means to confirm hypotheses, contributing to the development of experimental skills and habits.

Similarly, the University of San Pedro Sula (2017) states that laboratories contain measuring instruments, reagents, and other elements that facilitate the achievement of objectives in the search for concrete scientific knowledge through discovery learning. Palacios (2016), for his part, affirms that these practices increase experimentation skills and foster respect for the environment.

From a reflective perspective on the attitudinal and epistemic level, it can be argued, as González et al.

(2004) indicate, that experimentation in science teaching goes beyond facilitating hypothesis verification. In this sense, experiments are actually a key means to promote content learning, solve problems, and reach solid conclusions, adding greater scientific rigor to secondary education teaching. This aligns with what the National Research Council (2013, cited in Murphy et al., 2018, p. 1239) states: "it requires a fundamental shift in scientific pedagogy to foster knowledge and practices such as deep conceptual knowledge, model-based reasoning, and oral and written argumentation where scientific evidence is evaluated."

In this line of thought, López and Tamayo (2012) insist on considering that laboratories strengthen both conceptual and procedural knowledge, allowing for deeper exploration of essential aspects of scientific methodology and fostering reasoning skills such as critical and creative thinking, as well as attitudes like open-mindedness, objectivity, and a healthy distrust of judgments not supported by sufficient evidence.

Now, one might ask: What are the conditions for experimentation to take place? Today, both physical and virtual laboratories are essential. De Jong et al. (2013) have stated that at the pre-university and university levels, attractive and stimulating scientific experiences are often offered. In this same vein, Satterthwait (2010) affirms that hands-on experiences in science laboratories play a fundamental role in enabling students to learn. Ambusaidi et al. (2018) add that by incorporating technology into these spaces, the way students learn science changes notably. Bazán and Díaz (2021, p. 18) synthesize this idea by stating that laboratories make possible "problem-solving based on their real experiences, and enable the improvement of school scientific skills."

However, despite theoretical consensus among researchers, it is undeniable that in Venezuela and some countries, many institutions face significant obstacles to implementation. For example, there are educational centers where experiments cannot be carried out because they lack equipped laboratories. Studies such as those by Torres and Ayuso (2025, p. 22), conducted in the Dominican Republic, indicate that:

> 50% of students in public schools and 52% in subsidized schools state that they have low or very low levels of proficiency in evaluating and designing experiments. Likewise, 73% of students in public schools and 70% in subsidized schools indicate that experiments are only sometimes or never carried out in the classroom. Also, 53% of students in public schools and 44% in subsidized schools state that the scientific method is only sometimes or never used in class.

The same situation has been found in Colombia, where, despite investment, a lack of clear guidelines persists. Ortiz and Cervantes (2015, p. 16) hold the State responsible: "there are no policies that define, regulate, support, and ensure the general development of scientific skills in the child population from their entry into the formal education system." This has prevented the widespread implementation of programs and proposals that have been presented, even though investment in resources has been made.

In the case of Ecuador, there is also a stated "need for training programs that promote the participation of the Natural Sciences teacher as a guide in preparing the student to become more independent in the search for and assimilation of scientific knowledge through experimentation" (Ramírez, 2023, p. 637).

Paradoxically, the opposite occurs: facilities exist, but teachers do not conduct laboratory practices, thereby depriving students of the opportunity to validate their hypotheses, refine their observation and analysis skills, and learn from their own mistakes—all of which are relevant aspects for the development of scientific competencies (Osorio, 2022).

Nevertheless, the problem is not only one of infrastructure and laboratory equipment. There are teachers who adopt teaching practices that undermine meaningful learning, giving greater importance to reading books or didactic materials than to situations where students acquire knowledge through experimentation. In this regard, Ramírez (2023, p. 634) states that these teachers show "a predominance of content development, knowledge, and terms over experiential activities." Coinciding with this, other researchers have mentioned that teachers implement few classroom activities where students engage in authentic argumentation within the science classroom (Sampson & Blanchard, 2012; Knight-Bardsley & McNeill, 2016).

This behavior is based on a traditional role and rote learning focused on repetition without the possibility of knowledge reconstruction and without favoring the learning of natural sciences (Muñoz & Charro, 2023). As a consequence, classes often fall into boredom, with students assuming a passive role, neither awakening student interest nor promoting the everyday usefulness of what is learned (Sanmartí & Márquez, 2017).

These teacher behaviors set aside higher-order scientific reasoning such as transfer, heuristics, and argumentation—cognitive dimensions of learning according to the taxonomy proposed by Bloom et al. (1956) and revised by Anderson and Krathwohl (2001) and Gallardo et al. (2010).

It also often happens that some teachers ask questions to students instead of letting students ask questions to the teacher. This situation is contrary to what experts suggest (Martin-Hansen, 2002). Moreover, this classroom inquiry is often of a low level (Fay et al., 2007; Tamir & García, 1992). Furthermore, the teacher ends up providing answers based on content, which is why the question is not investigable because it is structured inquiry and not true inquiry (Ferrés, 2017). This is the case even though constructivist curricula suggest that content should be an instrument to formulate a hypothesis that guides the research process (Domènech, 2014). This is by no means easy for the teacher to achieve. Lombard and Schneider (2013) state that question formulation is an interactive and iterative process between student and teacher, leading from vagueness to complexity and appropriateness, and that it takes time.

Based on the above, experimentation is an unavoidable component in the scientific training of secondary school students. However, upon a deeper observation of the nature of the learning that typically derives from the development of experimental activities in laboratory practices, a fundamental distinction emerges. While the acquisition of basic skills—such as following a protocol or a set of steps to conduct an experiment in biology, physics, or chemistry and measuring a variable or handling a reagent—appears automatically during laboratory practice, the development of so-called Higher-Order Scientific Skills (HOSS) presents a less clear picture from an epistemological point of view.

While some studies focus their attention on basic skills, other higher-order aspects are neglected. In this regard, it is worth mentioning that Coronado (2024) and Hernández et al. (2018) describe experiments as spaces where students confirm hypotheses and develop habits. However, such a characterization may be omitting the deep cognitive process.

When students conduct experiments in the natural sciences laboratory, they carefully follow the steps corresponding to that analytical procedure of the experience, which implies prior planning of the experiment, design, selection of necessary materials and equipment, as well as safety rules to follow. This demonstrates the student's ability to solve problems and learn scientific concepts validated in their context (Coronado, 2024).

Despite the above, conducting a laboratory experience is, as Silva and Cáceres (2024) argue, a way of approaching scientific knowledge, but one might ask: Is confirming a hypothesis a mechanical act of verification, or does it imply a genuine exercise of contrast and reflection? Likewise, does the design of an experiment emerge from the student's initiative and reasoning, or is it guided step by step by the teacher only to confirm what is already known rather than posing new perspectives and scientific hypotheses according to the student's interest?

Undoubtedly, these questions become more important if one considers what is meant by complex scientific skills. Researchers such as Faicán and Manzano (2024, p. 100) state that "critical thinking, problem-solving, cognitive and communication skills, the ability to formulate hypotheses, experimentation, and interpretation" correspond to the core of authentic scientific competence, and that this is not usually developed automatically simply by conducting experimental activities.

Furthermore, it could be considered that, in many secondary education classrooms, the experiences carried out in natural sciences laboratories might be merely procedural activities without educational intentionality, rather than being motivating and useful for illustrating concepts that challenge students to think like scientists. As Ramírez (2023) has explained, when a traditional approach focused on repetition and content prevails, even laboratory practices can be used to follow a logic of memorization or simple verification, wasting their epistemic potential.

Although a large amount of published literature exists regarding the role of experimentation in the development of basic skills in students, there is still a significant gap in understanding the actual mechanisms that establish a link between experimental activities or laboratory practices and the development of HOSS in secondary school students. Without exaggeration, some studies aim to discern what is learned in the laboratory, but they do not direct their attention to how this complex learning occurs in students. It is worth mentioning that this distinction is of utmost importance when designing curricula, developing training and professional development programs for natural sciences teachers, and proposing didactic strategies that can be used in teaching natural sciences to young people in educational institutions.

In this sense, the present article has as its cardinal point the following scientific question: In what way does experimentation, when carried out in the context of secondary education, truly contribute to the formation of higher-order scientific skills? The logbook to follow has as its operations center a systematic review of the literature published between 2016–2026, seeking to analyze the pedagogical, contextual, and epistemological factors that determine whether a laboratory practice becomes a mere procedural exercise or an authentic inquiry experience that develops students' scientific thinking.

Methodology

In the research, a systematic review of the literature was conducted following the guidelines of the PRISMA 2020 statement (Page et al., 2021). The research question guiding the review was: In what way does experimentation in secondary education contribute to the formation of higher-order scientific skills (HOSS)?

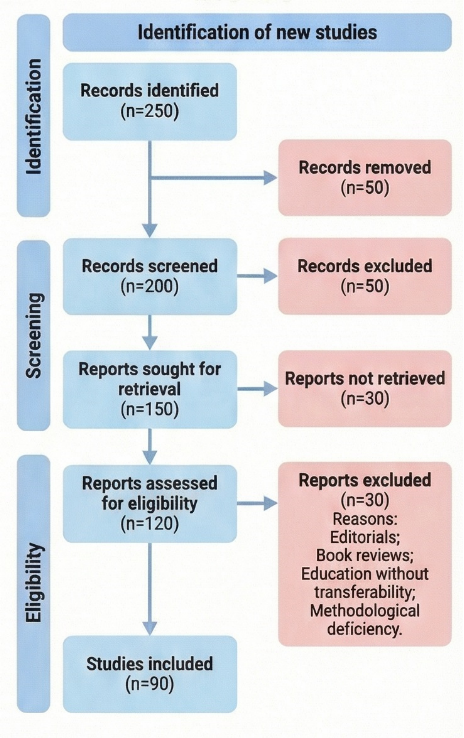
Search strategy. Search equations were developed in English and Spanish, combining key terms with Boolean operators (*AND, OR*) and wildcards (*). The main concepts were: **(a) population/context: secondary education; (b) intervention/phenomenon:** experimentation or laboratory practices; **(c) outcome:** higher-order scientific skills (critical thinking, problem-solving, hypothesis formulation, argumentation, inquiry). The equations were applied to the *Scopus, Web of Science, ERIC, SciELO, and Redalyc* databases, covering the period 2016–2026.

Inclusion and exclusion criteria. Empirical articles (qualitative, quantitative, or mixed), systematic reviews, and controlled trials, published in English or Spanish, that addressed experimentation in secondary education and its relationship with HOSS were included. Editorials, book reviews, studies focused exclusively on primary or university education without explicit transferability, and those that did not present original data or methodologically explicit syntheses were excluded.

Selection process and data extraction. Two reviewers independently examined titles and abstracts (phase 1), then full texts (phase 2). Disagreements were resolved by consensus. From each included study, the following were extracted: author(s), year, country, educational level, research design, type of experimentation (physical, virtual, mixed), HOSS evaluated, main findings, and limitations. Methodological quality was assessed using the MMAT (*Mixed Methods Appraisal Tool*) version 2018.

Synthesis of results. For the synthesis of results, a thematic analysis was performed following the phases of Braun and Clarke (2006). A total of 250 studies met the inclusion criteria and were subjected to thematic analysis. The emerging themes are presented in the results section.

PRISMA diagram: Study selection process



Results and discussion

Category 1: Scaffolding in learning how to research

In the research community, scaffolding is a construct of singular importance when posing scientific questions. It is not about offering immediate answers, but about providing the means for the autonomous construction of knowledge. From our perspective, we propose an illustrative example: in a biology experiment on photosynthesis, the teacher can model thinking and act as a mirror of reasoning, provoking doubt:

> "I observe that bubbles are coming out of the Elodea branch through the test tube that is in the water tank. What will happen if I bring the lamp closer to the glass tank?"
> The teacher can also encourage the student to connect variables: "If oxygen is a product of photosynthesis, then does the rate at which these bubbles are produced indicate the rate of production in the plant?"
> Likewise, the teacher can suggest measurement: "Kids, how do you think it is light, not the heat from the lamp, that controls the result? What do you think we can keep constant?"

Similarly, the teacher can use another common variant such as "do and then reflect on what happened" (Strat et al., 2023). In this type of experience, the student works collaboratively and actively. It has been found that under this methodology, students acquire both knowledge and key skills. However, the essential element is the motivational support provided by the teacher to the student to achieve the experience. Studies indicate that there is a positive correlation between teachers' motivational support and students' expressions of motivation (Adler et al., 2018). Although, Zhang and Cobern (2020) have also mentioned that it is important to make scientific content available to students. The reason is that it is not always easy for students to develop inquiry-based activities without them being linked to scientific concepts (Rönnebeck et al., 2016).

Category 2. Science teaching based on results from international studies

Various publications mention that in many educational systems, science instruction with an emphasis on inquiry is advocated, but studies based on large-scale international assessments often show that inquiry is negatively associated with achievement. Aditomo & Klieme (2020) show a positive association of inquiry with outcomes when teacher guidance is present. The study, with 151,721 students, indicates that multi-group confirmatory factor analyses further confirm that measurement invariance cannot be established, suggesting substantial regional variation in the pattern of inquiry-based instruction.

Likewise, Aditomo & Klieme (2020) point out that at the conceptual level, many regions exhibit a contrastable pattern between 'guided inquiry' and 'independent inquiry'. Inquiry is positively associated with outcomes when it incorporates teacher guidance and negatively when it does not. However, the strength of positive associations is stronger in regions where guided inquiry is measured with fewer items referring to student-centered activities. Such results correspond to what current theories propose regarding the role of scaffolding in learning how to research.

Other international research reveals that in experimental science teaching, a fundamental aspect to consider is the didactic training of teachers. In this perspective, Ríos (2021) raises the need to consider the onto-epistemological and gnoseological reality of the science to be taught without neglecting the articulation with the Philosophy of Science and Methodology from an ethical realism standpoint (Quijano et al., 2022). From the last two decades of the 20th century, an epistemological shift occurred in science didactics, moving from positivism to considering how teachers should take positions regarding phenomena of reality, that is, to see the repercussions of scientific research on them and make "socio-scientific" decisions in this regard (Adúriz & Ariza, 2012). These proposals represent a move from logical-positivist procedures to a civic humanism (De Hoyos, 2020).

This situation paves the way for the need (and at the same time the difficulty) for the philosophy of science and metasciences together with experimental sciences to set aside their mutual distrust because something fundamental is lost when one ignores the other. In this sense, collaboration between scientists from the metasciences and object sciences is necessary for disciplinary actions. However, such an approach is not easy to achieve. On the one hand, there are philosophers who disdain laboratory work. For them, it is not important to know what scientists study or how they do it. Hence, this scientific praxis is not relevant. Perhaps this is the reason why their eidetic process is merely mental, with a degree of abstraction whose basis is ideas, and the theories constructed are disconnected from empirical reality.

On the other side are experimental scientists who downplay the benefits of philosophy in a context dominated by hyper-specialization. From our point of view, the problem for experimental science teachers is taking sides with one of these extremes. Therefore, the challenge for secondary education natural science teachers is not only to choose between guided or independent inquiry methods, but also to overcome the false dichotomy between philosophy and scientific practice.

Logically, it is necessary to think about the development of higher-order scientific competencies such as critical thinking, modeling, or argumentation. This requires an integrative approach that combines experimental rigor with epistemological reflection. In other words, teachers must be capable of designing learning experiences where students not only manipulate variables but also question the nature of scientific knowledge, its methods, and its social implications. Only then can we advance toward a science education that forms citizens capable of participating in socio-scientific debates with a deep and contextualized understanding of science.

Category 3. Problem-solving through collaborative individual experiences

Different studies suggest that problem-solving competence is of great importance both academically and professionally. In fact, a recurring question in natural science classes, from our experience with secondary school children and even at university, is these two questions: "What use is this content in real life?" "What utility does it have in the things we do in our lives?" These two questions always destabilize teachers' lesson planning and in some cases generate unsatisfactory answers for the students, while for teachers they provoke a critical look at the curriculum provided by the ministries of education.

Young people always connect that knowledge with their lifeworld. However, contents are fragmented and explained from the perspective of disciplines. Teachers rarely contextualize and give little importance to the questioning and implications of the content. Although the epistemological foundations of curricular designs include aspects of meaningful learning and constructivism in the classroom, these aspects remain in the official document, and teachers assume the role of transmitting and reproducing knowledge as the central axis, leaving aside critical thinking and student participation, turning them into passive entities in their learning process.

This described scenario suggests the need for change. In the United States, it has been proposed that a program of excellence requires "effective teaching that engages students in meaningful learning through individual and collaborative experiences" (National Council of Teachers of Mathematics, 2014, cited by Koskinen & Pitkäniemi, 2022, p. 2). Isolating knowledge only to the realm of science means the student does not understand its relationship with their lifeworld, let alone develop reasoning competence. Cruz (2021, p. 55) states that "teachers must be capable of creating innovative teaching practices." Likewise, Cruz and Cabero (2020) suggest that one way to achieve this meaningful learning is through problem-solving. Through this, creativity is implemented in learning in an active, personalized, and dynamic way. But not only that, students also become active agents of learning, make decisions, and stop being mere reproducers of knowledge.

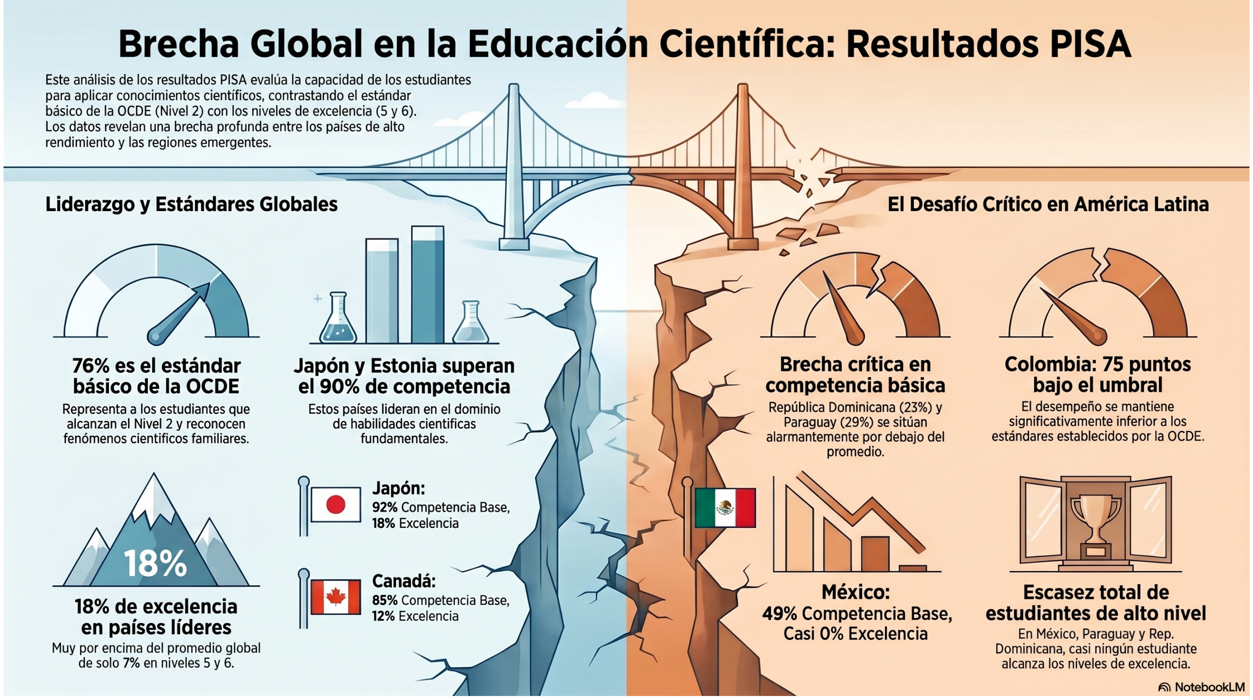
Now, what should be done to implement teaching based on problem-solving effectively in natural sciences? From our perspective, we believe that one way would be to pay attention to what certain documents, such as the Programme for International Student Assessment (PISA), suggest. A review of this document allows us to make some important considerations regarding science teaching.

At level 2, that is, where students are able to recognize the correct explanation of familiar scientific phenomena and can use that knowledge to identify, in simple cases, whether a conclusion is valid based on the data provided; we find that the situation is very concerning in countries such as Colombia, which is among the lowest performers, about 75 points below the threshold established by the OECD (2019); Argentina has only 46% of its students, Brazil 45%, Dominican Republic 23%, Mexico 49%, Peru 47%, Panama 38%, Paraguay 29%, compared to the OECD average of 76%. However, Turkey has 75%, United States 78%, Vietnam 79%, Canada 85%, Korea 86%, Estonia 90%, and Japan 92%.

Now, at levels 5 or 6, where students can creatively and autonomously apply their knowledge of and about science to a wide variety of situations, including unfamiliar ones; the OECD average is 7%. Brazil, Panama, and Peru reach only 1%; Colombia is not reflected; Chile 2%; Dominican Republic, Mexico, Paraguay, almost no students achieved the best results in science. The following infographic illustrates what we have stated.

Figure 1

PISA results



Brecha Global en la Educación Científica: Resultados PISA

Este análisis de los resultados PISA evalúa la capacidad de los estudiantes para aplicar conocimientos científicos, contrastando el estándar básico de la OCDE (Nivel 2) con los niveles de excelencia (5 y 6). Los datos revelan una brecha profunda entre los países de alto rendimiento y las regiones emergentes.

Liderazgo y Estándares Globales

76% es el estándar básico de la OCDE

Representa a los estudiantes que alcanzan el Nivel 2 y reconocen fenómenos cientificos familiares.

Japón y Estonia superan el 90% de competencia

Estos países lideran en el dominio de habilidades cientificas fundamentales.

18% de excelencia en países líderes

Muy por encima del promedio global de solo **7%** en niveles 5 y 6.

Japón:
92% Competencia Base,
18% Excelencia

Canadá:
85% Competencia Base,
12% Excelencia

El Desafío Crítico en América Latina

Brecha crítica en competencia básica

República Dominicana (23%) y Paraguay (29%) se sitúan alarmantemente por debajo del promedio.

Colombia: 75 puntos bajo el umbral

El desempeño se mantiene significativamente inferior a los estándares establecidos por la OCDE.

México:
49% Competencia Base,
Casi 0% Excelencia

Escasez total de estudiantes de alto nivel

En México, Paraguay y Rep. Dominicana, casi ningún estudiante alcanza los niveles de excelencia.

Note: Prepared in NotebookLM based on data from Lerma et al. (2023), OECD (2018, 2023), and PISA 2022. The data are universal and the infographic is in Spanish, but their understanding is immediate: 76% of global students reach Level 2 (basic proficiency); only 7% reach Levels 5 or 6 (excellence). Japan: 92% (Level 2+) and 18% (excellence); Canada: 85% and 12%; Mexico: 49% and 0%; Colombia: 75 points below the OCDE threshold; Dominican Republic: 23%; Paraguay: 29%.

Category 4. Designing, making, and testing as a shift toward active learning and the materialization of knowledge

One of the important aspects in teaching natural sciences is to provide the opportunity to design, make, and test. This implies going beyond observation or hypothesis verification and going through the process of knowledge construction. This principle has its roots in maker culture and active STEM methodologies. Lidueña and Alcocer (2025, p. 311) argue that maker culture focuses on creativity, "collaboration, and solving real problems, not only improving academic performance but also promoting educational equity and the development of essential competencies for the 21st century."

Logically, these scientific skills are higher-order, and among them we can mention creativity, complex problem-solving, and critical thinking because students are architects of their own experiment or design. Allowing teaching practice to unfold in this way means moving from a structured laboratory practice that often develops by following an analytical procedure and recording each experience in a manual or laboratory guide, i.e., simply following a predefined script. However, "designing, making, and testing" implies an iterative cycle of ideation, construction, error, reflection, and redesign.

Domínguez (2023) affirms that maker culture is based on the idea formalized as "do it yourself" and "do it with others." Epistemologically, knowledge is then seen as a construction, hence its connection to constructionism, a learning theory proposed by Seymour Papert. In this process of collective construction, real or virtual social networks intervene to share the created knowledge. Most people tend to access these networks where they find support or guidance. Interestingly, the knowledge created is subsequently left open so that it is accessible to others and better solutions can be found (Domínguez, 2021). Morales and Dutrénit (2017) synthesize this by saying that the Maker movement is involved in the processes of knowledge generation, transfer, and use.

Precisely, a study that materializes this philosophy of maker culture was conducted by Zulfa and Adam (2025) in Indonesia with secondary education students, where they implemented Project-Based Learning integrated with STEM (PjBL-STEM) through chemistry teaching on electrochemistry content. These researchers improved learning outcomes and developed Higher-Order Thinking Skills (analysis, synthesis, and evaluation, key cognitive steps that led them to a holistic understanding). Beyond experiments, they designed and completed authentic projects, where "making" was guided by a real question or problem that allowed the integration of engineering and technology into experimental design as a powerful vehicle for complex thinking. This project made it clear that an expensive, specialized laboratory is not needed; rather, when designing, one can reconfigure familiar objects for scientific purposes. This fact allows students to understand physical concepts and principles more deeply than a laboratory apparatus or equipment would allow.

In the same perspective, recently at the University of Malaya, they integrated design with action, but from social innovation and accessibility, in the project "Toying with Science." Through the experience, students participated in the co-creation of learning modules. Finally, the strategy employed awakened interest in STEM disciplines and facilitated the assimilation of essential transferable skills such as perseverance, critical thinking, creativity, and teamwork (Universiti Malaya, 2025).

In the line of discussion raised, the technological dimension also offers new possibilities in the cycle of "designing, making, and testing," especially if physical resources are limited. Research conducted in Nigeria mentions the impact of virtual laboratories in biology, chemistry, and physics on secondary school students. The results confirm significant differences in problem-solving skills between students who used virtual simulations and those who received traditional teaching (St. Clair et al., 2024). Likewise, students are able to modify variables, design new parameters, and test hypotheses iteratively in simulated environments, developing scientific reasoning ability without the barrier of physical input availability. However, tactile experience should not be completely replaced; rather, it is complementary. Similarly, scaffolding is needed to guide students' thinking.

Category 5. STEM or STEAM education

In this category, according to the research found, we focus on didactic strategies and technological environments for the development of HOSS. These strategies serve as scaffolding and technological mediation, allowing for higher-order reflective experimentation, that is, going beyond procedural experimentation or recipe-based manipulation of instruments (St. Clair et al., 2024).

In the case of countries with limited physical infrastructure, as mentioned in previous paragraphs, and also in cases where there are gaps in teacher training, as in Colombia and Ecuador, an epistemological shift in natural sciences teaching is necessary. Similarly, in situations such as the COVID-19 pandemic, where students could not attend classes and virtual laboratories were implemented (Gamage et al., 2020), these should not be seen as substitutes but rather as a valuable environment for scientific modeling and evidence-based reasoning (Solbes et al., 2025).

Meronda et al. (2025, p. 2020) argue that: "Virtual laboratories have emerged as a significant innovation in science education, enriching learning experiences, deepening conceptual understanding, and providing more flexible and safer access to experiments." It is important to mention that these technological tools allow students to focus on scientific argumentation and critical decision-making in the case of unexpected data—skills that define the scientifically literate citizen of the 21st century.

Raman et al. (2022) and Zhang et al. (2024) mention that these laboratories are effective solutions for the challenges of modern learning. Meanwhile, Chen and Wang (2023) argue that they foster motivation, enthusiasm, and creativity among students. Bazie et al. (2024), referring to virtual laboratories, state that in practical chemistry courses, they offer electronic simulations that replicate real laboratory experiences.

Recent studies confirm that there is currently a transition from traditional modes to online modes, facilitated by interactive simulations (Vo & Simmie, 2025). Thus, the challenge for teachers lies in transforming the laboratory into a space of explicit inquiry, where error and material resistance become the engine of critical thinking rather than an obstacle to learning.

From our perspective, we consider it necessary to train students to evaluate the validity of claims. The secondary school laboratory is the ideal place to practice this media scientific literacy. By designing their own experiments, students learn to identify biases, control variables, and understand that science does not offer absolute truths, but rather conclusions supported by evidence. This process elevates the activity from a low-order skill (memorizing steps) to a higher-order one (evaluation and synthesis). The major epistemological obstacle often encountered in secondary education is that some teachers are very comfortable with confirmation laboratories (where the outcome is already known), but they fear the uncertainty of an open, problem-based laboratory.

Category 6. Contextualization of learning

A few years ago in Hong Kong, despite being a pioneer in PISA results, several curricular reforms were undertaken because, as Kwok (2018, p. 533) expressed, "Our students succeed in exams, but they do not know to what extent science and mathematics are relevant to their lives." This statement leads to a highly valuable reflection: how to achieve meaningful learning that is accessible to all students, especially in secondary education. The answer lies in the contextualization of learning.

In this regard, Hüfner et al. (2025, p. 1) argue that "Context-based science education (CBSE) has played a central role in reorienting scientific literacy for all students." The idea of using context as a support for pedagogical purposes considers that content is connected to everyday phenomena, social issues, and students' prior experiences.

Along these lines, Fayzullina et al. (2023, p. 2) affirm that "context-based learning has become a cutting-edge educational strategy that seeks to bridge the gap between theoretical scientific concepts and their real-world applications." Moreover, context-based learning is widely valued for education within the scientific community (Sevian et al., 2018). Studies also indicate that context as a learning environment and social construction is sustained by continuous interactions (AlabdulRazzak et al., 2018).

In science teaching, context-based learning is recognized as a promising method (Nagarajan & Overton, 2019). But beyond that, there is talk of context-based science curricula (Fensham, 2009). In this sense, contextualization makes it possible for content to cease being complex and become a bridge between school learning and real life, logically awakening students' interest and facilitating their understanding of science (Aydın-Ceran, 2021).

In this system, one starts with a sociocultural context that is familiar to the student; each concept is taught from that starting point, but the effectiveness of the process is truly reflected when the student is able to associate the taught concepts with other, more complex contexts (Aydin-Ceran, 2018; De-Girolamo et al., 2024). This situation gives rise to a "need to know" in order to explain the scientific phenomena being studied. For this reason, it is necessary to understand the underlying concepts and principles to clarify the questions triggered by the context. This fact generates student engagement in their own learning process (Vogelzang & Admiraal, 2017). Studies show that students connect academic knowledge with everyday life through practical applications (Demelash et al., 2024).

In the case of secondary education students, from our disciplinary perspective, biology, physics, and chemistry present themselves as fertile domains for context-based learning because there are many real-world phenomena connected to the content included in curricular designs. For example, in biology, laboratory experiments can be contextualized with issues such as antibiotic resistance, the biodiversity of the students' nearby environment. Changes occurring in local ecosystems could also be considered; this would help students formulate hypotheses based on authentic observations, design small samplings, and argue using ecological and physiological evidence. Regarding physics, contexts such as home energy efficiency and road safety can be used. Likewise, designing simple technological devices transforms the measurement of variables and the application of physical laws into an exercise in modeling and informed decision-making.

Similarly, in chemistry, contextualization is possible through water quality analysis, food composition, or recycling processes. This prompts students to connect abstract concepts with inquiry practices that demand critical thinking and creativity. In all cases, contextualization is not exhausted in an initial anecdote; its formative potential unfolds when it becomes the structuring axis of the entire didactic sequence, promoting inquiry processes that require not only the application of procedures but also the formulation of relevant questions, the evaluation of evidence, and the construction of scientifically based arguments.

Precisely, these latter elements constitute the core of HOSS. Therefore, contextualization is not a pedagogical ornament; rather, it is an epistemic scaffold that gives meaning to experimental practice and mobilizes complex cognitive processes, essential for forming citizens capable of critically intervening in their reality. Thus, from a theoretical perspective, situated learning is one of the frameworks that underpins contextualization. Ojo (2025), when investigating the teaching of genetics concepts in secondary education in Nigeria, used this theory to demonstrate that when scientific content is addressed in authentic contexts linked to socio-scientific controversies (such as reproductive cloning or genetic modification), students develop more positive attitudes toward concepts that are traditionally abstract or distant.

Category 7. The need to offer spaces for exchange and reflection to make thinking visible

The need to offer spaces for exchange and reflection to make thinking visible constitutes a fundamental category in the formation of HOSS in secondary education. As García and Moreno (2019, p. 149) point out, it is a priority "to implement experimental practices in the classroom, especially at the basic education level, where curiosity and observation skills are configured as a key element in the articulation of the biological and the social." These practices to be developed, according to Harvard University's Project Zero, are based on "a thinking routine called I think–I wonder–I explore, which makes students share what they think about a topic, identify questions that intrigue them, and point out directions for exploration" (Ritchhart & Perkins, 2008, p. 57).

Although this thinking develops in the person's mind and is invisible to oneself and others, it becomes externalized when the thinker expresses their ideas through speech, writing, drawing, or other means, thus allowing them to direct and improve their own cognitive processes. However, this externalization is not a mere communication exercise, but an epistemic condition for the development of critical thinking and metacognition.

Recent research has confirmed that the deliberate creation of dialogic spaces in the science classroom significantly enhances higher-order skills. Wijesekera & Hameed (2025), in an intervention study in science classrooms and English Medium Instruction in Sri Lanka, where traditionally exam-oriented rote learning predominates, limiting critical thinking and meaningful cognitive engagement, implemented two specific strategies: "What if?" questioning and "Notice and Wonder" observation within collaborative groups. The results showed substantial improvement in higher-order thinking: students' critical thinking, problem-solving ability, and deep cognitive engagement. Furthermore, greater curiosity and willingness to approach complex scientific concepts were observed, even in contexts where the language of instruction (English) represented an additional barrier.

In this analytical category under discussion, an important element that emerged from the reviewed literature is that discursive scaffolding is essential for these exchange spaces to be effective. A study on the effects of the argumentation-based teaching approach on students' critical thinking disposition and argumentation skills, as well as the relationship between argumentation skills and critical thinking disposition in secondary school students in Turkey (Meral et al., 2021).

The cited work demonstrated that: *(a) Argumentation-based teaching improves critical thinking disposition*. This fact is fundamental from our perspective because it is not only necessary for students to have skills, but also to have the disposition to use them. Critical thinking disposition is a prerequisite for activating HOSS. "The argumentation-based teaching approach had a positive effect on students' critical thinking disposition" (Meral et al., 2021, p. 17). *(b) Argumentation is not spontaneous:* it requires explicit and sustained practice. We have already indicated in this article that many teachers assume that experimentation automatically develops HOSS. This study demonstrates that without deliberate scaffolding (such as argumentation routines), students remain at low levels. *(c) Argumentation predicts critical thinking*. We consider that if experimentation is accompanied by argumentative activities such as designing, making, testing, STEM, HOSS can be enhanced. Furthermore, as evidenced, "Argumentation skills explained 34% of the variation in critical thinking disposition" (Meral et al., 2021, p. 17). This means that working on argumentation has a direct and measurable impact on critical thinking.

Conclusions

Throughout this systematic review, it has been shown that experimentation in secondary education, while constituting an unavoidable component in the scientific training of students, is not sufficient on its own to develop the so-called HOSS. Traditional laboratory practices, often focused on hypothesis verification and strict adherence to protocols, tend to foster basic skills such as instrument manipulation or variable measurement, but leave complex cognitive processes such as critical thinking, evidence-based argumentation, or creative problem-solving in the background. This finding invites us to move beyond the idea that simply conducting experiments automatically guarantees deep and meaningful learning.

It is also concluded that the teacher's role in this context is a determining factor for experimentation to achieve its true epistemic potential. It is not enough for students to follow instructions or confirm expected results; explicit scaffolding by the teacher is required, including modeling scientific thinking, formulating researchable questions, connecting variables, and sustained motivational support. The reviewed findings agree that deliberate pedagogical guidance turns a merely procedural activity into an authentic inquiry experience, where error becomes a learning opportunity and curiosity becomes the engine of knowledge.

Likewise, it has been identified that contextualization of learning and the adoption of approaches such as maker culture or STEM and STEAM methodologies significantly enhance the development of HOSS. When experiments are linked to real problems in students' environments, everyday situations, or authentic social challenges, science ceases to be a set of abstract concepts and becomes a living tool for interpreting and transforming reality. The design-build-test cycle, characteristic of the maker movement, promotes iterative, creative, and collaborative thinking that is difficult to achieve with conventional laboratory practices.

It is also concluded that there is a close relationship between argumentation and critical thinking. The studies analyzed demonstrate that explicit teaching of scientific argumentation not only improves students' ability to support their claims with evidence but also explains a substantial part of the variation in critical thinking disposition. This means that fostering dialogic exchange spaces, question routines such as "what if...?" or reflective observation strategies are not complementary activities but central components of any didactic proposal that aims to form scientifically literate citizens.

Finally, it becomes evident that, despite the theoretical consensus on the benefits of experimentation, significant structural and training gaps persist in Latin America that limit its impact. The lack of equipped laboratories, connectivity difficulties, and, above all, insufficient teacher training in inquiry and argumentation approaches keep many classrooms anchored in traditional practices focused on repetition and content. Overcoming these limitations requires not only investment in infrastructure but also a profound change in the initial and continuing training of natural science teachers, so that experimentation truly becomes a vehicle for the development of higher-order scientific skills rather than a mere verification exercise.

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CRediT Authorship Contribution Statement

Autor	Rol desempeñado
OEV	Writing – review & editing, Writing – original draft, Supervision, Conceptualization..
VBG	Resources, Project administration, Investigation, Data curation..

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