ORIGINAL ARTICLE

Learning Science or Learning to Become a Scientist? Effects of Inquiry-based Laboratory Work on Secondary Students' *Scientific Learning*

Fernando Morcillo de Amuedo*, Ainhoa Arana-Cuenca, Guiomar Garrido Álvarez-Coto

Department of Didactics of Mathematics and Experimental Sciences, Universidad Internacional de La Rioja, Logroño, Spain

***Corresponding Author:** fernando.morcillo@unir.net

ABSTRACT

Practical work in secondary science education is often organized through closed "cookbook" protocols that constrain students' autonomy and limit the development of scientific thinking. This study examines the impact of two instructional approaches to a DNA extraction activity in Biology and Geology: A cookbook-style laboratory practice and an inquiry-based science education (IBSE) activity. A mixed-methods design was implemented, combining a pre–post-test component within each group with a comparison between two non-randomized cohorts of students in the 4th year of compulsory secondary education in Spain (n = 45). Academic performance was assessed through a multiple-choice test, self-perceived critical thinking and satisfaction were measured using validated questionnaires, and meaningful learning was explored through qualitative analysis of delayed open-ended responses. Both approaches led to improvements in immediate academic performance. However, only students in the inquiry-based condition showed evidence of deeper conceptual understanding, explicit references to the scientific method and a sustained perception of meaningful learning. These findings highlight the potential of IBSE-oriented laboratory work to foster not only scientific literacy and deep learning, but also transferable competences relevant for science-related vocational pathways.

KEY WORDS: Deep learning, inquiry-based science education, laboratory work, secondary biology education

INTRODUCTION

In secondary science education, practical activities are widely valued for their potential to motivate students and promote understanding of complex phenomena. However, many of them follow a prescriptive approach, known as the "cookbook" approach, in which closed protocols are reproduced without the need to understand rationale or make decisions (Abrahams and Reiss, 2012; McComas, 2005). Although logistically simple, this model limits autonomy and conveys a passive view of scientific knowledge (Herron, 2009; Roehrig and Luft, 2004).

Alternatively, Inquiry-based science education (IBSE) places students at the center of learning, engaging them in question formulation, experimental design and the interpretation of results (Furtak et al., 2012; García-Carmona, 2020). This approach favors conceptual understanding, critical thinking, and intrinsic motivation (Chen et al., 2020; Wallace et al., 2003), although its implementation is constrained by curricular pressure, limited time and resources, and limited specific teacher training (Özel and Luft, 2013).

Within secondary science education, instructional approaches to laboratory work are expected not only to support conceptual understanding of natural science content but also to foster transferable competences such as autonomy, problem-solving, and a disposition towards lifelong learning, which are highly relevant to students' emerging vocational trajectories. Building on this framework, the present study compares two ways of organizing a DNA extraction activity with 4th-grade secondary students in Spain: an inquiry-based laboratory practice, grounded in IBSE, and a traditional cookbook-style practice. The effects of these approaches are examined in terms of academic performance, self-perceived critical thinking, student satisfaction and meaningful learning, understood as a deep, transferable, and epistemically aware understanding of the activity and its underlying concepts.

IBSE

IBSE has established itself as a key approach to science teaching, especially at the secondary education level. Based on constructivist principles, IBSE encourages students to actively construct their knowledge through exploration, questioning and solving real-world problems (Duschl and Bybee, 2014; Windschitl, 2003), adopting a role similar to that of a scientist, which can foster an early identification with the thinking and practices characteristic of professional scientific work. In this model, the teacher serves as a facilitator of meaningful learning rather than a direct transmitter of content (Constantinou et al., 2018; Louca et al., 2018).

IBSE extends beyond a mere teaching methodology, serving as an epistemological framework that seeks to connect school practices with authentic scientific practices. This approach encourages a view of science as an interpretative, collaborative and dynamic activity, moving away from the idea of science as a definitive body of knowledge (García-Carmona, 2020; Petersen, 2022). In this way, IBSE aligns with the current goals of scientific literacy, which involve the ability to participate critically and knowledgeably in decision-making related to science and society, using evidence-based argumentation, understanding the provisional nature of scientific knowledge (Chen et al., 2020; García-Carmona, 2020; Osborne, 2014).

Numerous studies have documented the positive impact of IBSE on the development of critical thinking, deep conceptual understanding and student motivation, especially when implemented in real classroom contexts rather than as decontextualized or overly guided activities (Furtak et al., 2012; Herron, 2009; Minner et al., 2010).

Cookbook Practices and Their Contrast to the Research Approach

Despite the widespread presence of practical activities in science programs of study, a significant proportion of them follow a traditional instructional model based on closed "cookbook" procedures. These cookbook practices are characterized by the meticulous execution of a set of steps prescribed by the teacher or learning material, resulting in a predictable, known outcome. Although this approach facilitates logistical organization, the control of variables and safety in the laboratory, multiple studies have pointed out that it severely limits the development of real scientific and critical thinking skills (McComas, 2005).

From a cognitive point of view, the cookbook model is associated with superficial learning, since it focuses on memorizing procedures and mechanically reproducing results. As a consequence, students are rarely faced with decision-making processes, reformulation of hypotheses or critical validation of the results obtained, all essential elements of real scientific work and potentially formative for the development of a professional identity related to science (Julien and Lexis, 2015; Wallace et al., 2003), which has proved inefficient for developing higher-order skills (Putri and Malik, 2024; Windschitl, 2003).

In contrast, activities based on scientific inquiry break this transmissive logic by placing students in scenarios involving genuine exploration, where they must design procedures, make methodological decisions, manage uncertainties and justify their interpretations based on empirical evidence. Recent research shows that such experiences not only improve academic performance and conceptual understanding but also increase intrinsic motivation, foster intellectual autonomy, and develop essential skills for collaborative work (Goodey and Talgar, 2016; Seyed Fadaei, 2022; Van Wyk et al., 2024).

Although operationally simple, cookbook-style experimental activities miss the opportunity for genuine scientific literacy, whereas inquiry-based experimental activities foster both conceptual understanding and the critical skills essential for 21st-century citizens (Osborne, 2014) and guide early vocational orientation toward science-related fields.

Key Dimensions of Science Education: Critical Thinking, Satisfaction, and Deep Learning

The assessment of the impact of scientific practices in the classroom cannot be limited to immediate academic outcomes. Numerous studies have highlighted the need to consider additional dimensions, such as critical thinking, satisfaction with the experience, and, as a priority, depth of learning, as key indicators of quality in science education (Albertos and De la Herrán, 2018; Guerrero and Bautista, 2023).

The practice of scientific inquiry not only promotes long-term conceptual understanding, but also stimulates the development of critical thinking, understood as the ability to evaluate information, make informed decisions and formulate reasoned judgments. This type of competence is essential for developing citizens capable of taking action in a science- and technology-driven society (Furtak et al., 2012; Wallace et al., 2003).

Student satisfaction, in turn, acts as a key mediating factor between the learning experience and its effectiveness. Pedagogical environments that encourage autonomy, exploration, and cognitive challenges tend to elicit higher levels of enjoyment, interest, and emotional engagement, thereby facilitating knowledge retention and transfer (Feriyanto and Anjariyah, 2024; Sung et al., 2018). Thus, intrinsic motivation is not a marginal by-product, but an enabling condition for deep and lasting learning.

Deep learning, as opposed to surface learning, is defined as a process in which the learner actively constructs meaning, connects new knowledge with prior knowledge, and transfers learning to diverse real contexts (Fullan et al., 2017). This type of learning involves the development of higher-order thinking (analysis, evaluation, synthesis) and a high degree of metacognitive and emotional engagement (Feriyanto and Anjariyah, 2024; Winje and Løndal, 2020). In science education, such learning is particularly enhanced in environments where genuine inquiry, open-ended problem-solving and the development of evidence-based explanations are systematically encouraged (Archer-Kuhn et al., 2020; Ridlo et al, 2025).

Nonetheless, several studies have warned that the use of innovative methodologies, such as IBSE, does not, in itself, guarantee meaningful educational outcomes. For deep learning to occur, an intentional instructional design is essential one that integrates clear cognitive, affective, and metacognitive objectives and coherently articulates the what, how, and why of learning (Chen et al., 2020; García-Carmona, 2020).

Research Problem and Hypotheses

Based on this conceptual framework, the present study aims to compare academic performance, self-perceived critical thinking, satisfaction and meaningful learning among secondary education students who conduct a DNA extraction activity using an inquiry-based approach and those who use a cookbook approach. The comparison involves two intact cohorts in the same school, taught by the same teacher under comparable curricular conditions. Because the study was conducted in a real school context, students could not be randomly assigned to conditions; therefore, intact classroom cohorts were compared while keeping the teacher, curricular content, materials and time conditions as similar as possible.

To this end, the following working hypotheses are put forward:

- H_1. Students who engage in inquiry-based experimental activities improve their academic performance compared to those who conduct cookbook-style experiments
- H_2. Students who engage in inquiry-based experimental activities have higher self-perceived critical thinking than those who engage in cookbook-style experimental activities
- H_3. Both those who conduct inquiry-based and cookbook-style experimental activities are highly satisfied with the workshop
- H_4. Students who engage in inquiry-based experimental activities show meaningful learning, unlike those who conduct cookbook-style experiments.

RESEARCH METHODOLOGY

General Background

This study followed a mixed-methods design because it combined numerical data, obtained through tests and questionnaires, with qualitative data from students' delayed open-ended responses. The quantitative component included two complementary design elements. First, each group completed a pre-test and a post-test, which made it possible to examine whether students improved after the laboratory activity. This within-group comparison is considered pre-experimental because it observes change over time without randomly assigning students to conditions. Second, the study compared two intact classroom cohorts: One that carried out the inquiry-based activity and another that followed the cookbook-style protocol. This between-group comparison is considered quasi-experimental because the groups were naturally existing classes, and students were not randomly assigned. This design was selected because the intervention took place in a real secondary school setting, where random assignment was not feasible, while the same teacher, curriculum, materials and time conditions were maintained to increase comparability between groups.

The instructional experience was conducted following authorization from the school administration and in accordance with the ethical principles established by the scientific community and the Spanish Personal Data Protection Act (LOPD), ensuring the confidentiality of the information and the protection of participants' data. Approval from an ethics committee was not required, as no sensitive personal data was collected by the researchers and the implementation was developed within the students' regular academic process, following the annual programming established by the teacher.

Sample/Participants/Group

The intervention was carried out in a private secondary education school in Andalusia, Spain, in the subjects of Biology and Geology with students in their 4th year of Compulsory Secondary Education (ESO). The inquiry-based experimental activity was conducted in the school year 2023/2024 with a group of 25 students (11 women and 14 men). The cookbook-style experimental activity was conducted in the academic year 2024/2025 with another group of 20 students (13 women and 7 men). Both groups were taught by the same teacher, with an identical program of study, materials and time conditions. The only difference between them was the instructional approach to the experimental activity.

Although the two groups belonged to different academic years, they were treated as comparable cohorts because they followed the same subject program in the same school and were taught by the same teacher under equivalent curricular and time conditions. Nevertheless, the absence of random assignment is acknowledged as a limitation of the study.

Instrument and Procedures

In both groups, the core activity was a DNA extraction experiment, implemented in two different ways:

1. The IBSE approach (IBSE) was applied in the inquiry-based experimental activity. Based on the question "Can DNA be extracted?" students designed an experiment by manipulating variables, formulating hypotheses, carrying out procedures and producing a scientific article in which they interpreted and discussed the results. This intervention was previously validated by expert judgment (Arana-Cuenca et al., 2024)
2. In the cookbook-style experimental activity, the students followed a closed DNA extraction protocol outlined by Author 1 et al. (2024), without needing to ask questions or design the experimental procedure.

Before the intervention, students completed an initial form (pre-test) to assess their knowledge of the content covered and their self-perceived critical thinking. Once the experimental activity had finished, these same instruments were again applied (post-test), along with an additional questionnaire to measure satisfaction with the experience. Two months after the intervention, a new form was administered, which included an open-ended question aimed at exploring recall of the activity and students' perception of the learning achieved.

The same instruments were used in both groups to assess the following dimensions:

a. (Academic performance. An *ad hoc*, multiple-choice assessment test was designed, comprising 14 items focused on DNA content and cell structure. Each item had four response options, with only one correct answer, which scored 1 point. Incorrect answers did not count.
b. Self-perceived critical thinking. The Individual Generic Competences Questionnaire developed by Olivares and Lopez (2017) was also applied by Lara Quintero et al. (2017). The instrument consists of 10 items on a 5-point

Likert scale (1 = strongly disagree, 5 = strongly agree). It is structured into three dimensions: Interpretation and analysis of information, judgment based on objective and subjective data, and inference based on reflective self-regulation.

c. Satisfaction with the experience. The questionnaire designed by Romero-García et al. (2020) was administered, consisting of 22 items rated on a Likert scale (1-5). The items are grouped into three dimensions: presentation of content, planning of the activity and perception of learning.

d. Meaningful learning. Two months after the intervention, students were asked an open-ended question: "What do you remember from the DNA extraction activity?" The responses were analyzed qualitatively using a previously defined category system. Although the open-ended question focused on recall of the activity, qualitative analysis identified indicators of meaningful learning, such as a functional understanding of the procedure, references to the scientific method, and perceived usefulness or knowledge transfer.

Data Analysis

Quantitative analysis

The results of performance, self-perception, and satisfaction were analyzed using Statistical Package for the Social Sciences v.25.0 at a significance level of $\alpha = 0.05$. Normality was tested using the Shapiro–Wilk test, given the sample size ($n < 50$). As the normality assumption was not met, the Wilcoxon signed-rank test was applied to compare pre- and post-test results within each group. To compare the inquiry-based and cookbook-style groups, the Mann–Whitney U test was used. In cases with significant differences, effect sizes were calculated as r, following the guidelines proposed by Fritz et al. (2012).

Qualitative analysis

Meaningful learning was explored through a qualitative content analysis of the open-ended responses. A prompt specifically designed under the Role, Task, Context, and Statement model was used, with the support of the Gemini Advanced tool, to assist in the initial organization of responses into categories. The tool's output was then independently reviewed, corrected, and refined by the research team, who remained fully responsible for all analytical decisions. This limited, tool-assisted phase did not replace the researchers' judgment, and generative artificial intelligence was not credited as an author. Seven coding variables were defined (Table 1), and quantification was carried out to estimate relative frequencies. These categories allow differentiation among types of recall (procedure, visual result, functional understanding, reference to the scientific method), affective evaluations (positive or negative) and perceptions of deep learning.

RESEARCH RESULTS

Academic Performance and Conceptual Understanding

Academic performance was assessed by analyzing the level of knowledge acquired by the students participating in the instructional interventions. The results obtained from the comparison between pre-test and post-test scores reveal a significant increase in both groups (Table 2). Nevertheless, the effect size was comparable across both conditions, suggesting that both the inquiry-based and cookbook-style experimental activities contributed to improvements in immediate academic performance.

Therefore, the first hypothesis is rejected, as students in both the inquiry-based experimental activity and the cookbook-style activity increased their academic performance to a similar extent.

Self-perceived Critical Thinking

Self-perceived critical thinking, assessed using the Individual Generic Competences Questionnaire (Olivares and López, 2017), was measured at three different points in the process: Before the intervention (pre-test), immediately after (post-test) and 2 months later (follow-up). The means obtained in each phase for both intervention groups are shown in Table 3.

A comparison was carried out regarding the self-perceived critical thinking between students who participated in the inquiry-based experimental activity and those who participated in the cookbook-style experimental activity using the Mann–Whitney U test at each stage of the study (pre-test, post-test and follow-up), finding that in no case were the differences significant ($p > 0.05$). Thus, the second research hypothesis was rejected.

Student Satisfaction

After each educational experience (post-test), the satisfaction questionnaire designed by Romero-García et al. (2020) was administered to assess three dimensions: Presentation of content, Planning, and Learning. The results obtained are summarized in Table 4.

To compare the results, the Mann–Whitney U test was applied, finding only one case in which the difference was significant: The statement "the workshop was challenging," for which the students in the inquiry-based experimental activity rated it with a median of 4.0. In contrast, the students of the cookbook-style experimental activity rated it with a median of 3.0. The results of the analysis ($U = 132.500$; $z = -2.2485$; $p = 0.013$; $r = 0.784$) indicate a strong effect.

Thus, the third research hypothesis is accepted, as the participating students report a high level of satisfaction with the workshop, with those who carried out the inquiry-based experimental activity feeling they were more challenged.

Meaningful and Deep Learning

To explore the lasting impact of each intervention, an open-ended question was posed to the students two months after the experimental activity: "What do you remember from the DNA extraction activity?" The responses were subjected to a qualitative content analysis, structured into seven predefined variables (V1-V7), which are described below. Table 5 presents the categorical distribution and relative frequency for

Table 1: Variables selected for the qualitative analysis on meaningful learning

Variable	Description
V1: Recall of the specific procedure	Mention of concrete actions, sequence of steps, reagents or materials used, without elaborating on their purpose.
V2: Recall of visual result (Seeing DNA)	Explicit mention of the observable end-product of extraction
V3: Understanding the function of the Reagents/Steps	Explanation of the role of a reagent or step in the extraction process.
V4: Explicit mention of the scientific/Research Method	Direct reference to the process of inquiry, experimental design, hypothesis testing, analysis or scientific communication.
V5: Positive affective evaluation	Direct expressions of enjoyment, interest or positive evaluation of the activity
V6: Negative affective evaluation or difficulty	Comments expressing confusion, difficulty, problems or vague memories
V7: Perception of meaningful learning	Comments indicating that the student feels they have learned something relevant, profound or transferable, beyond following steps or seeing a result.

Table 2: Mean ranks for the pre- and post-test regarding knowledge acquisition. Wilcoxon signed-rank test

Methodology	n	Mean ranks	Sum of ranks	Z	Sig.	r
Inquiry-based experimental activity						
Negative ranks	4	4.38	17.50	−2.228	0.026	0.775
Positive ranks	10	8.75	87.50			
Ties	5					
Cookbook-style experimental activity						
Negative ranks	4	7.00	28.00	−2.317	0.020	0.787
Positive ranks	13	9.62	125.00			
Ties	3					

Table 3: Means of students' self-perceived critical thinking in both the inquiry-based experimental activity and the cookbook-style experimental activity at the three stages of assessment (pre-test, post-test and follow-up)

Dimensions	Inquiry-based experimental activity			Cookbook-style experimental activity		
	Pre-test (n=20)	Post-test (n=22)	Follow-up (n=23)	Pre-test (n=25)	Post-test (n=21)	Follow-up (n=21)
Interpretation and analysis of information	2.50	3.00	3.00	2.50	3.00	2.50
Judgment of a specific situation with objective and subjective data	3.67	3.92	3.75	3.67	4.00	4.00
Inference of decision consequences based on self-regulated judgment	2.50	3.00	3.00	2.50	2.88	3.00
Global	3.20	3.50	3.40	3.30	3.55	3.40

each, comparing the group that conducted the inquiry-based experimental activity with the group that participated in the cookbook-style experimental activity.

The result of variable V1 shows similar high percentages (89% vs. 86%), indicating that both activities, being practical and manual, create a lasting memory of having done something, of having followed certain steps using specific materials. However, this procedural recall does not necessarily imply understanding.

Example from the cookbook-style experimental activity: "Mixing different substances with saliva." or "I remember that we had to pour distilled water into something else and then we had to spit."

Example from the inquiry-based experimental activity: "I remember the components and the steps that had to be followed." or "we had to mix pieces of onion with different substances."

Variable V2 entails an explicit mention of the end product that was observed after extraction. The difference here is very high (56% for cookbook-style vs. 0% for inquiry-based). In the cookbook-style group, the visual appearance of DNA is a central memory for more than half of the students. This was not the case in the inquiry-based group, suggesting that the cookbook-style experimental activity led students to focus on the visual impact of the end product ("wow effect"), whereas the inquiry-based activity prompted them to prioritize understanding of the process over the spectacle.

Example from the cookbook-style experimental activity: "...little white things appear in the liquid" or "...we saw how the DNA separated".

Example from the inquiry-based experimental activity: No explicit mention.

Table 4: Median of the results obtained in the student satisfaction survey in relation to the inquiry-based experimental activity and the cookbook-style experimental activity

Dimension	Inquiry-based experimental activity (n=22)	Cookbook-style experimental activity (n=21)
Presentation of content	4.67	4.67
The objectives of the workshop are communicated	5.0	5.0
A challenge related to the main objective of the workshop is posed.	5.0	5.0
Students' preconceptions are taken into account.	5.0	5.0
Questions are asked to reflect on the content	4.5	4.0
Explanations were clear and concrete	5.0	5.0
Theoretical knowledge is linked to the activities	5.0	5.0
Planning	4.60	4.40
The activity was well planned	5.0	5.0
The workshop enables the application of concepts to real-life situations	5.0	5.0
The workshop was challenging	4.0	3.0
The time devoted to the workshop was appropriate	5.0	5.0
After the workshop, the proposed objectives were achieved	5.0	5.0
Learning	4.79	4.75
The workshop allowed me to work following the scientific method and to understand the process	5.0	5.0
It allowed me to apply theoretical content to solve the proposed challenge	4.0	4.0
It increased my creativity	4.5	5.0
It increased my autonomy for learning	5.0	5.0
It increased my interactions with the teacher	5.0	4.0
It increased my interactions with classmates	5.0	5.0
I was able to have fun while learning	5.0	5.0
It increased my interest in the subject	5.0	5.0
It increased my learning outcomes	5.0	5.0
It improved my understanding of the subject	5.0	5.0
It increased my motivation for the subject	5.0	5.0
Overall score	4.67	4.62

Variable V3 (understanding the function of reagents/steps), crucial for conceptual understanding, reveals a significant qualitative difference in learning: 64% of the inquiry-based group demonstrated understanding by recalling or explaining the function of the reagents, compared to a negligible 6% in the cookbook-style group.

Example from the cookbook-style experimental activity: "...mix water with detergent, saliva and alcohol to separate the DNA."

Table 5: Qualitative analysis of the meaningful learning of the students who participated in the inquiry-based experimental activity compared to those who carried out the cookbook-style experimental activity

Variable analyzed	Inquiry-based experimental activity (%)	Cookbook-style experimental activity (%)	Difference
V1: Recall of the Specific Procedure	19 (86)	16 (89)	Similar
V2: Recall of Visual Result (Seeing DNA)	0 (0)	10 (56)	Very high
V3: Understanding the Function of the Reagents/Steps	14 (64)	1 (6)	Very high
V4: Explicit mention of the Scientific/Research Method	17 (77)	0 (0)	Total
V5: Positive Affective Evaluation	5 (23)	3 (17)	Slight
V6: Negative Affective Evaluation or Difficulty	1 (5)	2 (11)	Low/ similar
V7: Perception of Meaningful Learning	14 (64)	1 (6)	Very high

Example from the inquiry-based experimental activity: "...pineapple juice broke down the proteins to release the DNA, the alcohol made it rise to the surface" or "...knowing what each element we used was for."

Variable V4 (references to the scientific method and inquiry processes), central to an IBSE approach, recorded 77% of mentions in the inquiry-based group compared to 0% in the cookbook-style group. This confirms that only the inquiry-based experimental activity succeeded in consciously involving students in the process of "doing science," fostering research skills, critical analysis, scientific communication and the understanding of the "how and why" of the study.

Example from the cookbook-style experimental activity: (No mentions found).

Example from the inquiry-based experimental activity: "Learning how to write an article" or "...examining the lack of ingredients" or "analyzing what would happen if we eliminated some components" or "...looking for a hypothesis and planning the whole task..." or "...we included both a positive and a negative control."

Regarding variable V5, both groups expressed enjoyment to a slightly higher level in the inquiry-based group (23% vs. 17%), indicating that the higher cognitive demand did not necessarily reduce enjoyment. The sources of motivation differed: In the cookbook-style group, they were more oriented towards novelty and the result; in the inquiry-based group, towards cognitive challenge and discovery.

Example from the cookbook-style experimental activity: "...it was a very cool activity" or "...it was a very fun group activity"

Example from the inquiry-based experimental activity: "...a very interesting and manageable project." or "...a fun and very educational experience..."

Regarding V6 (negative affective evaluation or difficulty), both groups demonstrated low percentages of negative comments. The slightly higher incidence in the cookbook-style group (11% vs. 5%) was attributed to recall problems. In contrast, the only mention of difficulty in the inquiry-based group was considered inherent to the normal research process and not indicative of a broadly negative experience.

Example from the cookbook-style experimental activity: "...not what ingredients were used..." or "...I don't remember much."

Example from the inquiry-based experimental activity: "...the problems we had, we had to repeat it..." (Interpreted as part of the research process, not necessarily as an overall negative evaluation).

Finally, variable V7 (perception of meaningful learning) showed a marked difference (64% in the inquiry-based group vs. 6% in the cookbook-style group). The inquiry-based group demonstrated awareness of valuable, transferable learning (understanding the "whys" and developing research skills). In contrast, in the cookbook-style group, only one isolated technical skill was mentioned. This suggests that the inquiry-based approach fosters metacognitive awareness of learning and generates a sense of competence and useful knowledge.

Example from the cookbook-style experimental activity: "...I learned to balance a scale." (Learning a specific skill).

Example from the inquiry-based experimental activity: "...understand the whys (the functions of each component)" or "we learned a lot".

The last working hypothesis can therefore be accepted, since the inquiry-based experimental activity shows meaningful learning, unlike the cookbook-style activity, whose recall is vaguer and more focused on the end product rather than the cognitive process.

DISCUSSION

The results of this study reveal important differences between the inquiry-based and cookbook-style experimental activities, both in their cognitive and affective dimensions of learning. This section discusses the findings in light of previous research, highlighting their contribution to the debate on the value of the IBSE approach in real Secondary Education contexts.

Academic Performance and Conceptual Understanding

Both instructional approaches improved students' academic performance. Nevertheless, the inquiry-based experimental activity showed signs of a deeper, more lasting understanding of the concepts of molecular genetics. Despite this, the quantitative results reveal no significant differences between the groups, and thus the first research hypothesis, which predicted a differential improvement for the inquiry-based approach, is rejected.

The fact that both approaches improved immediate academic performance may help explain why cookbook-style laboratory activities remain common in school science. From a teacher's perspective, these activities are easier to organize, require less classroom time, reduce uncertainty in the laboratory, and usually lead to visible outcomes that students perceive positively. In contexts marked by curricular pressure, limited resources and insufficient specific training in inquiry-based methodologies, the traditional approach may therefore appear to be a safe and efficient option. However, the present results suggest that this short-term effectiveness should not be confused with deeper learning.

These findings are consistent with previous studies that highlight how IBSE can foster a more meaningful organization of knowledge by enabling students to integrate facts into interpretative conceptual frameworks (Herron, 2009; Winje and Løndal, 2020). In contrast, cookbook-style experimental activities, although useful for consolidating procedures and obtaining immediate outcomes, tend to encourage superficial memorization and little transferability to new learning situations (McComas, 2005).

Critical Thinking and Scientific Skills

Self-perceived critical thinking was compared between the group that conducted the inquiry-based experimental activity and the group that conducted the cookbook-style experimental activity using the Mann–Whitney U test at three stages of the study (pre-test, post-test, and follow-up). Statistically significant differences were not found in either case ($p > 0.05$); thus, the second research hypothesis, which posited a differential improvement in this dimension attributable to the type of activity implemented, is rejected. This result may be explained by the brevity of the intervention, since modifying metacognitive skills, such as critical thinking, generally requires sustained processes over time. It is therefore unlikely that a single instructional experience, however significant, will generate stable changes in this dimension. In this regard, several studies have pointed out that sustained, repeated inquiry in the classroom, rather than isolated interventions, fosters the gradual development of complex scientific skills and reflective judgment (Julien and Lexis, 2015).

Satisfaction

The satisfaction questionnaire results showed high levels in both groups, with median scores above 4 for most items (Likert scale from 1 to 5). This high level of satisfaction can be attributed, at least in part, to the active, manipulative nature of the practical experience, which tends to elicit positive feedback from students, regardless of the methodological approach used.

However, important qualitative and quantitative differences between the two conditions were identified. The students who participated in the inquiry-based experimental activity reported higher levels of challenge, engagement and enjoyment. In contrast, the group who carried out the cookbook-style experimental activity scored significantly lower on the item

"The workshop was challenging", with a median of 3.0 compared to a median of 4.0 for the inquiry-based group.

Statistical comparison between the two groups using the Mann–Whitney U test revealed a significant difference ($U = 132.500$; $z = -2.2485$; $p = 0.013$), with a large effect size ($r = 0.784$). These data indicate that the perception of cognitive challenge was significantly higher in the group that carried out the inquiry-based experimental activity.

This pattern aligns with the available empirical evidence, which shows that inquiry-based learning environments tend to foster higher intrinsic motivation and academic satisfaction by actively engaging students in hypothesis formulation, experimental decision-making, and meaningful problem-solving (Seyed Fadaei, 2022; Sung et al., 2018).

Consequently, the third research hypothesis is accepted, confirming that, although overall satisfaction is high in both approaches, students who participated in the inquiry-based experimental activity perceived it as more challenging and cognitively stimulating.

This may also explain the persistence of cookbook-style activities: They are enjoyable, predictable and easy to complete, even if they provide fewer opportunities for students to engage in authentic scientific reasoning.

Meaningful and Deep Learning

Qualitative analysis conducted 2 months after the intervention revealed substantial differences in learning quality depending on the methodological approach. Although both groups clearly remembered the sequence of steps of the activity (V1: Recall of the specific procedure), with similar high percentages (89 % in the inquiry-based group and 86 % in the cookbook-style group), this type of procedural memory, common in manual experiences, does not necessarily lead to conceptual understanding or deep learning (Sung et al., 2018).

The most significant divergences emerged in variables associated with comprehension, transfer and self-regulation of learning. With regard to V2 (Recall of the visual result), the cookbook-style group recorded 56% explicit mentions of the observable end product, whereas in the inquiry-based group, this category was absent. This suggests that the cookbook-style experimental activity may have been mediated by a visual or 'show science' effect, in which attention is focused on the outcome rather than the process (Winje and Løndal, 2020), thereby limiting deeper cognitive elaboration.

Even more significant was the difference observed in V3 (Understanding functions), which measures students' ability to explain the purpose of each step or reagent. In this respect, 64% of students in the inquiry-based group constructed functional explanations, compared to only 6% in the cookbook-style group. This finding aligns with studies showing that inquiry-based approaches foster a richer, more coherent conceptual structure by inviting students to establish causal and functional connections among elements of the experimental process (Feriyanto and Anjariyah, 2024).

The most marked difference was observed in V4 (Mention of the scientific method), which was present in 77% of responses from the inquiry-based group and completely absent in the cookbook-style group. These mentions imply that students not only performed an activity, but also understood and internalized the epistemic nature of science, which is central to current models of scientific literacy (Herron, 2009; Maley et al., 2013). In other words, recalling is not limited to "what was done", but includes the "how" and the "why" of the research process.

In relation to the affective variables, both V5 (positive evaluation) and V6 (negative evaluation or difficulty) reveal that the inquiry-based experimental activity, despite its greater cognitive demand, did not reduce enjoyment, but actually maintained it (23% positive compared to 17% in the cookbook-style group) and led to fewer comments associated with confusion (5% compared to 11%). This suggests that inquiry-based environments can not only be cognitively effective but also motivating and emotionally sustainable (Seyed Fadaei, 2022).

The most decisive variable was V7 (Perception of meaningful learning), which captures the students' recognition of having learned something important, useful or transferable. 64% of the inquiry-based group expressed such reflections, while only 6% of the cookbook-style group did so. This result reinforces the hypothesis that the inquiry approach generates deeper and more lasting learning, compatible with contemporary definitions of deep learning in educational contexts: Active meaning-making, conceptual integration, transfer, and metacognitive reflection (Feriyanto and Anjariyah, 2024; Maley et al., 2013).

Overall, these results support the fourth research hypothesis, showing that the inquiry-based experimental activity not only fosters deeper conceptual learning but also enhances self-reflection, epistemic awareness, and the transferability of learning to other contexts. In contrast, the cookbook-style experimental activity, although effective at generating procedural and visual recall, shows clear limitations in fostering students' deep understanding and critical engagement with scientific processes.

Limitations of the Study

This study has several limitations that should be considered when interpreting the results. First, a quasi-experimental design with non-randomized groups was used, which makes it impossible to ensure full equivalence between the comparison conditions. Although both groups attended the same school and were taught by the same teacher, following the same program of study, uncontrolled contextual factors cannot be ruled out. Second, the sample was relatively small and restricted to a single school, which limits the generalizability of the findings to other educational contexts with different socio-cultural or institutional characteristics. Third, the intervention consisted of a single laboratory experiment. Complex skills such as critical thinking and deep learning usually require sustained inquiry-based experiences. Finally, some variables were assessed using self-report instruments (critical thinking, satisfaction), which may be subject to social desirability bias. Although validated instruments were used, future research could complement these data with direct observations, performance rubrics, or interviews, expand the sample, and explore the implementation of IBSE as a structural part of an annual program to assess its cumulative impact on learning and the construction of vocational identity.

CONCLUSION AND IMPLICATIONS

This study compared two forms of laboratory practice in secondary science education: A cookbook-style approach, focused on technical execution, and an inquiry-based approach grounded in IBSE. Both contributed to improved immediate academic performance, but the inquiry-based experimental activity was associated with a more functional understanding of concepts, explicit references to the scientific method and a sustained perception of meaningful learning over time.

The findings indicate that cookbook-style experimental activities largely fulfill a demonstrative function and tend to encourage superficial learning centered on procedures and end products. In contrast, the inquiry-based approach supports deep learning, characterized by conceptual integration, self-reflection and the transfer of learning to new contexts, without reducing student satisfaction. On the contrary, students perceived the inquiry-based activity as more challenging and cognitively engaging.

From the perspective of science education, these findings substantiate the need to transition from traditional, verification-oriented laboratory protocols toward epistemic and participatory inquiry-based methodologies. This pedagogical paradigm shift is crucial for fostering critical scientific competencies in students, thereby promoting comprehensive scientific literacy. The ultimate goal is to achieve meaningful and enduring learning that transcends mere procedural execution to attain a deep understanding of phenomena and their underlying causal mechanisms. Furthermore, inquiry-based experimental activities provide vital opportunities for students to adopt dispositions and attitudes characteristic of scientific communities. This contributes to the early construction of a reflective and active mindset, preparing students to navigate future contexts with greater agency and purpose beyond the immediate scope of the classroom.

For science teachers who wish to make laboratory activities more inquiry-based, several practical steps can be considered. First, closed protocols can be transformed into guiding questions that require students to predict, justify and test possible procedures. Second, teachers can allow students to make at least one meaningful methodological decision, such as selecting a variable, comparing conditions or proposing a control. Third, students should be asked to explain the function of each reagent or step, rather than only following the sequence of actions. Fourth, laboratory reports can include short sections on hypotheses, evidence, interpretation of results and limitations, even when the activity is brief. Finally, inquiry-based laboratory work can be introduced progressively, starting with guided inquiry before moving towards more open-ended formats, so that teachers can manage time, safety and curriculum constraints.

ETHICS STATEMENT

The instructional experience was carried out in accordance with the ethical principles established by the scientific community and the LOPD, respecting the confidentiality of data and safeguarding the data protection of the informants. Approval from an ethics committee was not required, as no sensitive personal data was collected by the researchers. The implementation was carried out within the students' regular academic process, following the annual programming established by the teacher, who is also one of the researchers conducting the study. Therefore, the intervention was planned from the outset, before deciding which elements were to be measured. In any case, verbal authorization from the school administration was obtained to carry out the implementation, and the students were informed about it.

In addition, the limited use of generative AI tools described in the Data Analysis section was used only to support data organization and did not replace the researchers' judgment.

AUTHOR CONTRIBUTIONS

Following the CRediT taxonomy, Second B. Author. contributed to the conceptualization, data curation, formal analysis, methodology, visualization, supervision, and project management. Third C. Author. participated in the conceptualization, methodology, validation and writing of the original draft. First A. Author. contributed to conceptualization, methodology, and investigation, and also to the revision and final editing of the publication.

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CONFLICT OF INTERESTS

The authors state that there are no conflicts of interest in the publication of this manuscript.

REFERENCES

Abrahams, I., & Reiss, M.J. (2012). Practical work: Its effectiveness in primary and secondary schools in England. *International Journal of Science Education*, 49(8), 1035-1055.

Albertos Gómez, D., & De La Herrán Gascon, A. (2018). Development of critical thinking in secondary education students: Design, implementation, and evaluation of an educational program. *Journal of Curriculum and Teacher Education*, 22(4), 269-285.

Arana-Cuenca, A., Curto Prieto, M., Rodríguez Díez, E., & Ransanz Reyes, E. (2024). DNA extraction as a teaching strategy for learning about the cell in primary and secondary education. *EDUCA International Journal*, 4(1), 36-60.

Archer-Kuhn, B., Wiedeman, D., & Chalifoux, J. (2020). Student engagement and deep learning in higher education: Reflections on inquiry-based learning on our group study program course in the UK. *Journal of Higher Education Outreach and Engagement*, 24(2), 107-122.

Chen, Y.C., Pan, Y.T., Hong, Z.R., Weng, X., & Lin, H.S. (2020). Exploring the pedagogical features of integrating essential competencies of scientific inquiry in classroom teaching. *Research in Science and Technological Education*, 38(2), 185-207.

Constantinou, C.P., Tsivitanidou, O.E., & Rybska, E. (2018). What is inquiry-based science teaching and learning? In: Tsivitanidou, O., Gray, P., Rybska, E., Louca, L., & Constantinou, C. (Eds), *Professional Development for Inquiry-Based Science Teaching and Learning. Contributions from Science Education Research.* Vol. 5. Cham: Springer.

Duschl, R.A., & Bybee, R.W. (2014). Planning and carrying out investigations: An entry to learning and to teacher professional development around NGSS science and engineering practices. *International Journal of STEM Education*, 1(12), 1-9.

Feriyanto, N., & Anjariyah, S. (2024). Deep learning approach through meaningful, mindful, and collaborative learning. *International Journal of Instructional Technology and Educational Studies*, 5(2), 208-212.

Fritz, C.O., Morris, P.E., & Richler, J.J. (2012). Effect size estimates: Current use, calculations, and interpretation. *Journal of Experimental Psychology: General*, 141(1), 2-18.

Fullan, M., Quinn, J., & McEachen, J. (2017). *Deep Learning: Engage the world, Change the World*. Thousand Oaks: Corwin Press.

Furtak, E.M., Seidel, T., Iverson, H., & Briggs, D.C. (2012). Experimental and quasi-experimental studies of inquiry-based science teaching: A meta-analysis. *Review of Educational Research*, 82(3), 300-329.

García-Carmona, A. (2020). From inquiry-based science education to the approach based on scientific practices. *Science and Education*, 29, 443-463.

Goodey, N., & Talgar, C.P. (2016). Guided inquiry in a biochemistry laboratory course improves experimental design ability. *Chemistry Education Research and Practice*, 17(4), 1127-1144.

Guerrero, J.S., & Bautista, R.G. (2023). Inquiry-based teaching in secondary science. *International Journal of Social Sciences and Humanities*, 8(2), 146-154.

Herron, S.S. (2009). From cookbook to collaborative: Transforming a university biology laboratory course. *American Biology Teacher*, 71 (9), 548-552.

Julien, B.L., & Lexis, L.A. (2015). Transformation of cookbook practicals into inquiry oriented learning. *International Journal of Innovation in Science and Mathematics Education*, 23(5), 32-51.

Lara Quintero, V., Avila Palet, J.E., & Olivares, S.L. (2017). Development of critical thinking through the application of problem-based learning. *School and Educational Psychology,* 21, 65-77.

Louca, L., Skoulia, T., Tsivitanidou, O.E., & Constantinou, C.P. (2018). Concluding remarks: Theoretical underpinnings in implementing inquiry-based science teaching/learning. In: Tsivitanidou, O., Gray, P., Rybska, E., Louca, L., & Constantinou, C. (eds), *Professional Development for Inquiry-Based Science Teaching and Learning. Contributions from Science Education Research*. Vol. 5. Cham: Springer.

Maley, T., Stoll, W., & Demir, K. (2013). Seeing an old lab in a new light: Transforming a traditional optics lab into full guided inquiry. *The Physics Teacher*, 51(6), 368-371.

McComas, W.F. (2005). Laboratory instruction in the service of science teaching and learning: Reinventing and reinvigorating the laboratory experience. *The Science Teacher*, 72, 24-29.

Minner, D.D., Levy, A.J., & Century, J. (2010). Inquiry-based science instruction-what is it and does it matter? Results from a research synthesis years 1984 to 2002. *Journal of Research in Science Teaching*, 47(4), 474-496.

Olivares, S.L., & López, M.V. (2017). Validation of an instrument to evaluate self-perception of critical thinking in medical students. *Electronic Journal of Educational Research,* 19(2), 67-77.

Osborne, J. (2014). Teaching scientific practices: Meeting the challenge of change. *Journal of Science Teacher Education*, 25(2), 177-196.

Özel, M., & Luft, J. (2013). Beginning secondary science teachers' conceptualization and enactment of inquiry-based instruction. *School Science and Mathematics*, 113(6), 308-316.

Petersen, M.R. (2022). Strategies to scaffold students' inquiry learning in science. *Science Education International*, 33(3), 267-275.

Putri, M.N., & Malik, A. (2024). The use of science laboratories with cookbook and inquiry-based methods to enhance students' 21st-century thinking skills. *Journal of Biology Education*, 5(1), 52-59.

Ridlo, Z.R., Ningsih, S.P.A., & Anggraini, A.L. (2025). Computational thinking and deep learning on science education framework: A systematic review. *Science Education International*, 36(4), 480-489.

Roehrig, G., & Luft, J. (2004). Constraints experienced by beginning secondary science teachers in implementing scientific inquiry lessons*. International Journal of Science Education*, 26(1), 3-24.

Romero-García, C., Buzón-García, O., Sacristán-San-Cristóbal, M., & Navarro-Asencio, E. (2020). Evaluation of a program to improve learning and digital competence in future teachers through active methodologies. *Studies in Education,* 39, 179-205.

Seyed Fadaei, A. (2022). Comparing the effects of cookbook and non-cookbook based lab activities in a calculus-based introductory physics course. *International Journal of Physics and Chemistry Education*, 13(4), 65-72.

Seyed Fadaei, H. (2022). Inquiry-based learning and employability skills in science education. *Journal of Science Teaching***,** 41(3), 201-218.

Sung, H.Y., Hwang, G.J., Wu, P.H., & Lin, D.Q. (2018). Facilitating deep-strategy behaviors and positive learning performances in science inquiry activities with a 3D experiential gaming approach. *Interactive Learning Environments*, 26(8), 1053-1073.

Van Wyk, A.L., Frederick, K.A., Lieberman, M., & Cole, R.S. (2024). Increasing authenticity of the laboratory through the MICRO Project: Analysis of analytical chemistry laboratory experiments for their level of inquiry. *Journal of Chemical Education*, 102(3), 3-14.

Wallace, C.S., Tsoi, M., Calkin, J., & Darley, M. (2003). Learning from inquiry-based laboratories in non-major biology: An interpretive study of the relationships among inquiry experience, epistemologies, and conceptual growth. *Journal of Research in Science Teaching*, 40(10), 986-1024.

Windschitl, M. (2003). Inquiry projects in science teacher education: What can investigative experiences reveal about teacher thinking and eventual classroom practice? *Science Education*, 87(1), 112-143.

Winje, Ø., & Løndal, K. (2020). Bringing deep learning to the surface: A systematic mapping review of 48 years of research in primary and secondary education. *Nordic Journal of Comparative and International Education*, 4(2), 25-41.