Explicit Instruction about the Nature of Science and its Impact on Students' Understanding of Evolution: A Meta-Analysis

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Article Info

Abstract

Understanding evolution remains a persistent challenge in science education. This meta-analysis evaluated whether explicit instruction on the Nature of Science (NOS) can enhance students' comprehension of evolutionary theory. A systematic review following PRISMA 2020 guidelines identified eight studies (2017–2024), yielding nine independent effect sizes and a total sample of 1,543 students across secondary and undergraduate levels. Using a random-effects model, the overall effect of explicit NOS instruction was large and statistically significant (Hedges' $g = 1.18$, 95% CI [0.698, 1.669], $p < .001$). Moderator analysis showed that educational level significantly influenced outcomes, with secondary students benefiting more than undergraduates. A Two One-Sided Tests (TOST) procedure confirmed that these differences were not practically equivalent within a ± 0.20 margin. Qualitative synthesis revealed that the most effective interventions explicitly addressed NOS concepts, such as theory vs. law, empirical evidence, and subjectivity through historical case studies and structured reflection designed to counter evolution misconceptions. No evidence of publication bias was detected. These findings underscore the pedagogical value of embedding epistemological instruction within evolution education and support the development of context-sensitive curricula and teacher training.

Introduction

Understanding the theory of evolution is essential for scientific literacy, yet it remains one of the most conceptually challenging and socially contested topics in science education (Brandt et al., 2022; Kampourakis, 2022; Selba et al., 2024). Despite its foundational role in biology, students often complete formal education with persistent misconceptions and limited understanding of evolutionary mechanisms (De Lima & Long, 2023; Gregory, 2009; Wei et al., 2012). These difficulties stem not only from the complexity of the content but also from an underdeveloped understanding of how scientific knowledge is generated, justified, and revised (Deniz & Borgerding, 2018; Nadelson & Hardy, 2015; Pain, 2023). One instructional strategy that shows promise in addressing these challenges is the explicit teaching of the Nature of Science (NOS).

The Nature of Science refers to the epistemological foundations of science. It encompasses values, assumptions, and practices that underlie scientific inquiry. Core NOS aspects include the empirical and tentative nature of scientific knowledge, the role of creativity and inference, the theory-laden nature of observations, and the distinction between scientific theories and laws (National Science Teaching Association, 2020). When these aspects are taught explicitly and reflectively alongside evolution content, students may better grasp how scientific claims are constructed and validated over time. This deeper epistemological grounding can foster not only improved conceptual understanding but also greater acceptance of evolutionary theory, particularly in sociocultural contexts where science and religion are perceived to be in conflict (Barnes et al., 2020; Borgerding & Deniz, 2018; Lombrozo et al., 2008; National Academy of Sciences, 2025; Nelson et al., 2019).

A growing body of empirical research has investigated the integration of explicit NOS instruction into evolution education. While many studies report positive effects, the magnitude and consistency of these outcomes vary. Differences in research design, instructional context, duration, and participant characteristics likely contribute to this variability. Furthermore, it remains unclear whether explicit NOS instruction is equally effective across educational levels, such as secondary versus undergraduate settings. Although explicit NOS strategies are common across studies, the instructional approaches themselves differ in structure, focus, and degree of contextualization.

Given this complex and fragmented landscape, a systematic and quantitative synthesis of the literature is warranted. This meta-analysis addresses the following research questions:

1. How effective is explicit NOS instruction in enhancing students' understanding of evolution?
2. Do the effects of explicit NOS instruction on students' understanding of evolution vary significantly across educational levels?
3. What instructional approaches to explicitly teaching NOS in the context of evolution have been examined in the empirical literature?

By answering these questions, this meta-analysis aims to clarify the overall impact of explicit NOS instruction on students' understanding of evolution, examine the moderating role of educational level, and map the instructional strategies used across studies. The findings are intended to inform curriculum design, teacher professional development, and evidence-based pedagogy in science education.

Method

Literature Search Strategy

A comprehensive literature search was conducted in May 2025 using three academic databases: ERIC (n = 30), Google Scholar (n = 36), and Scopus (n = 15). An additional 84 records were identified through manual citation tracking, resulting in 165 total records. After removing 25 duplicates, 140 unique records (56 from databases, 84 from citation searching) were screened for eligibility. The search strategy used Boolean combinations of the following keywords: "nature of science," "NOS," "evolution." Reference lists of relevant articles were also manually reviewed to identify additional eligible studies.

Eligibility Criteria

Studies were included if they met all of the following criteria: they were published between 2016 and 2025; written in any language, with non-English studies translated by the author; investigated the effects of explicit nature of science (NOS) instruction on students' understanding of biological evolution; involved participants at the secondary or post-secondary level; employed a quantitative design with pre-/post-measures; reported sufficient statistical data to allow for the calculation of effect sizes (e.g., means and standard deviations, or t- or F-values); and were published in a peer-reviewed journal, dissertation, or other reputable academic outlet. Studies were excluded if they did not feature explicit NOS instruction as the intervention (n = 77), did not focus on evolution (n = 3), or failed to report sufficient statistical data for effect size calculation (n = 2).

Study Selection

Of the 56 database records, 50 were excluded during title and abstract screening. A full-text review was conducted for six database-sourced and four citation-sourced studies. Two were excluded at the full-text stage due to insufficient statistical data. The final sample comprised eight studies.

Data Extraction and Coding

A standardized coding protocol was used to extract key study characteristics, including the author(s) and year of publication, the country of the study, the sample size (N), the educational level (coded as secondary or undergraduate), the research design (e.g., quasi-experimental, pretest–posttest), the NOS instructional approach (e.g., explicit-reflective, integrated with history of science or inquiry-based frameworks), and the instructional duration (reported in number of sessions, total weeks, or instructional minutes). These variables were selected based on their relevance to the research questions and their potential to moderate or contextualize effect sizes.

Effect Size Calculation and Meta-Analytic Model

Effect sizes were calculated using Hedges' g to correct for small sample size bias and provide more accurate estimates than Cohen's d (Lin & Aloe, 2021). A random-effects model was used to account for between-study

heterogeneity. Heterogeneity was assessed using the Q statistic and quantified using I^2, τ^2, τ, and H^2 values.

Moderator and Qualitative Analyses

To address the second research question, a meta-regression was conducted to examine the moderating role of educational level (coded as 0 = secondary, 1 = undergraduate) on effect sizes. A weighted least squares (WLS) approach was used. Inverse-variance weights derived from study-level sampling variances were applied. Due to the small sample size (N = 8), heteroskedasticity-consistent standard errors (HC3 estimator) were used to improve inferential accuracy. This method approximates the Knapp–Hartung adjustment recommended for small-sample meta-regression. Moderator significance was evaluated using t-tests for regression coefficients and an F-test for overall model fit. The direction and magnitude of effects were interpreted based on regression coefficients, 95% confidence intervals, and p-values. To address the third research question, key instructional features were qualitatively synthesized, including instructional duration, contextual approach (e.g., decontextualized vs. embedded), pedagogical strategy (e.g., History of Science, Argument-Driven Inquiry), and the integration of NOS content with evolution instruction.

Equivalence Testing

To assess the practical equivalence of effects across educational levels, a Two One-Sided Tests (TOST) procedure was conducted. Equivalence bounds were set at ±0.20, representing a small effect size. This procedure tested whether the observed differences in effect sizes could be considered both statistically and practically negligible.

Publication Bias Assessment

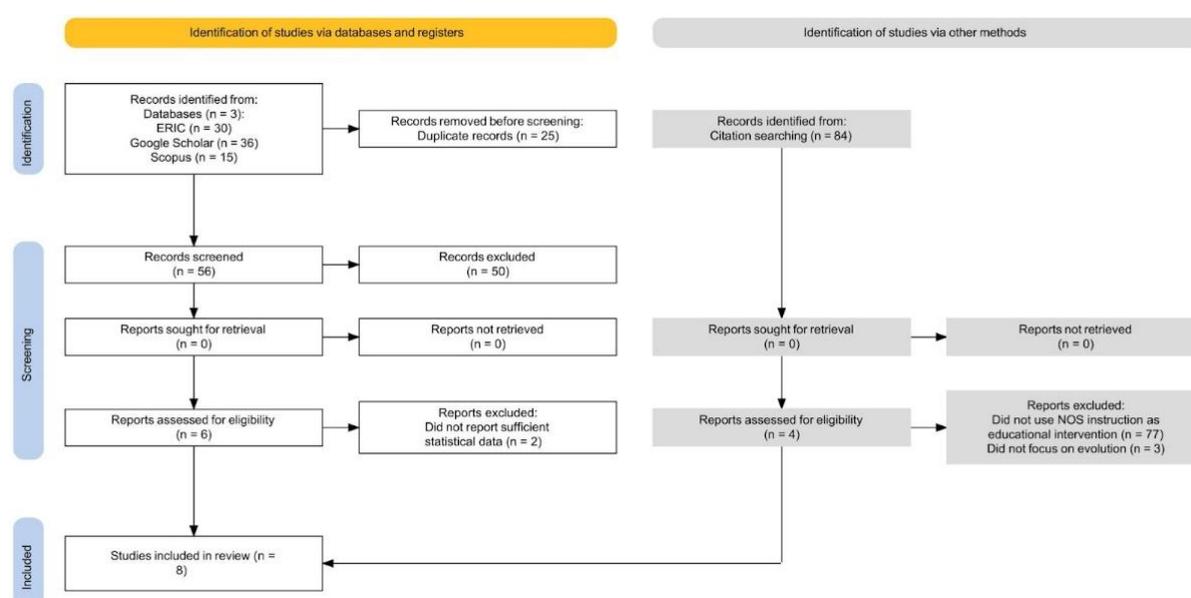The study selection process is illustrated in the PRISMA 2020 flow diagram (see Figure 1).

Figure 1. PRISMA 2020 Flow Diagram Illustrating the Study Selection Process

Potential publication bias was evaluated using multiple complementary methods, such as Rosenthal's Fail-Safe N, Kendall's Tau rank correlation, Egger's regression test and visual inspection of funnel plot symmetry. These approaches provided triangulated evidence to assess the risk of bias in the included literature.All analyses were conducted using Jamovi (Version 2.6.44.0). The review followed the PRISMA 2020 guidelines for systematic reviews and meta-analyses (Page et al., 2021).

Results

Study Characteristics

The final meta-analysis included eight studies conducted between 2017 and 2024, spanning four countries: Chile (five studies), Turkey, Indonesia, and the United States. These studies yielded nine independent effect sizes. They encompassed a total of 1,543 participants. Sample sizes ranged from 36 to 627; several studies reported group-specific subsamples. One study (Cofré et al., 2018b) experienced participant attrition between pre- and post-intervention.

In terms of educational level, five studies targeted secondary students (grades 8–11) and three studies involved undergraduate students, including pre-service science teachers and biology majors. All studies employed quasi-experimental designs. These typically involved pretest–posttest comparisons. Moreover, three studies utilized mixed-methods designs. They combined quantitative analysis with follow-up interviews or other qualitative data sources.

Instructional approaches were consistently explicit and reflective, though varied in format. Several studies employed History of Science (HOS) as a pedagogical strategy (e.g., Cofré et al., 2017, 2018a), while others integrated NOS instruction with Argument-Driven Inquiry (ADI) (Eymur et al., 2024) or problem-based learning (PBL) (Saefi et al., 2024). Instructional duration ranged from three class periods (60 minutes total) to 14 weeks. Most interventions consisted of four to six sessions of 90 minutes each. A detailed description of the study characteristics is provided (see Table 1).

Table 1. Study Characteristics of Included Articles

Study	N	Educational level	Design	NOS approach	Duration
Cofré et al. (2017) [Chile]	MATE (n = 48), ACORNS (n = 75), VNOS (n = 54)	Secondary (ages 16–17)	Quasi-experimental; pretest–posttest with control and two experimental groups	Explicit-reflective; HOS as instructional strategy	4 sessions of 90 minutes each
Cofré et al. (2018a)	Control (n = 25), Treatment (n	11th grade	Quasi-experimental; pretest–posttest with control and	Explicit-reflective; integrated with HOS	4 lessons of 90 minutes each

Study	N	Educational level	Design	NOS approach	Duration
[Chile]	= 50)		treatment groups		
Cofré et al. (2018b) [Chile]	Treatment (n = 19), Control (n = 20)*	11th grade (ages 15–16)	Quasi-experimental; pretest–posttest with control and treatment groups	Explicit-reflective; contextualized (e.g., sickle-cell anemia) and decontextualized (e.g., black box) activities	6 lessons total (2 NOS, 4 evolution)
Eymur et al. (2024) [Türkiye]	36	Pre-service science teachers	Quasi-experimental mixed-methods; pretest–posttest with interviews	Explicit-reflective; embedded within ADI	7 weeks, 3 sessions/week (45 minutes each)
Jiménez Pavez (2022) [Chile]	Intervention (n = 231), Control (n = 222)	Secondary (9th grade)	Quasi-experimental; NECGD	Explicit-reflective; focused on NOSK and NOSI	5 weeks, instruction delivered twice weekly
Moreno et al. (2018) [Chile]	48	8th grade (lower secondary)	Quasi-experimental; explanatory, quantitative design	Explicit and semi-explicit NOS instruction	5 sessions
Saefi et al. (2024) [Indonesia]	136 (after excluding 5 students)	Undergraduate (third-year biology majors, ages 20–22)	One-group pretest–posttest; concurrent mixed-methods design	Explicit-reflective; integrated with constructivist, PBL; addressed science–religion boundaries	14 weeks
Sloane et al. (2023) [United States]	Quantitative (n = 627), Qualitative subset (n = 308)	Undergraduate (Introductory Biology)	Quasi-experimental mixed-methods; convergent design	Explicit-reflective; NOS tenets taught individually; integrated along a context continuum	3 class periods (total 60 minutes)

Note. ADI = Argument-Driven Inquiry; HOS = History of Science; NECGD = nonequivalent control group design; NOSK = nature of scientific knowledge; NOSI = nature of scientific inquiry; PBL = problem-based learning.

* Original sample size was 46; reduced to 39 after attrition.

Effect of Explicit NOS Instruction on Understanding of Evolution

A random-effects meta-analysis was conducted to estimate the overall impact of explicit NOS instruction on students' understanding of biological evolution (see Table 2). The analysis included nine effect sizes (k = 9) and used the restricted maximum-likelihood (REML) estimator. The pooled effect size was Hedges' g = 1.18 (SE = 0.248); the 95% confidence interval ranged from 0.698 to 1.669. This indicates a large and statistically significant effect, Z = 4.78, p < .001.

Table 2. Random-Effects Meta-Analysis of the Impact of Explicit NOS Instruction on Students' Understanding of Evolution (k = 9)

	Estimate	se	Z	p	CI Lower Bound	CI Upper Bound
Intercept	1.18	0.248	4.78	<.001	0.698	1.669

Note. Tau² Estimator: Restricted Maximum-Likelihood

Moreover, the forest plot displays consistent positive effects across studies (see Figure 2). Individual effect sizes range from 0.15 to 2.05. Studies such as Jiménez Pavez (2022), Moreno et al. (2018), and Eymur et al. (2024) reported large effects (g > 1.80), whereas Saefi et al. (2024) and Sloane et al. (2023) reported smaller effects (g < 0.40). Despite variability, all effect sizes favored explicit NOS instruction over pre-instruction measures.

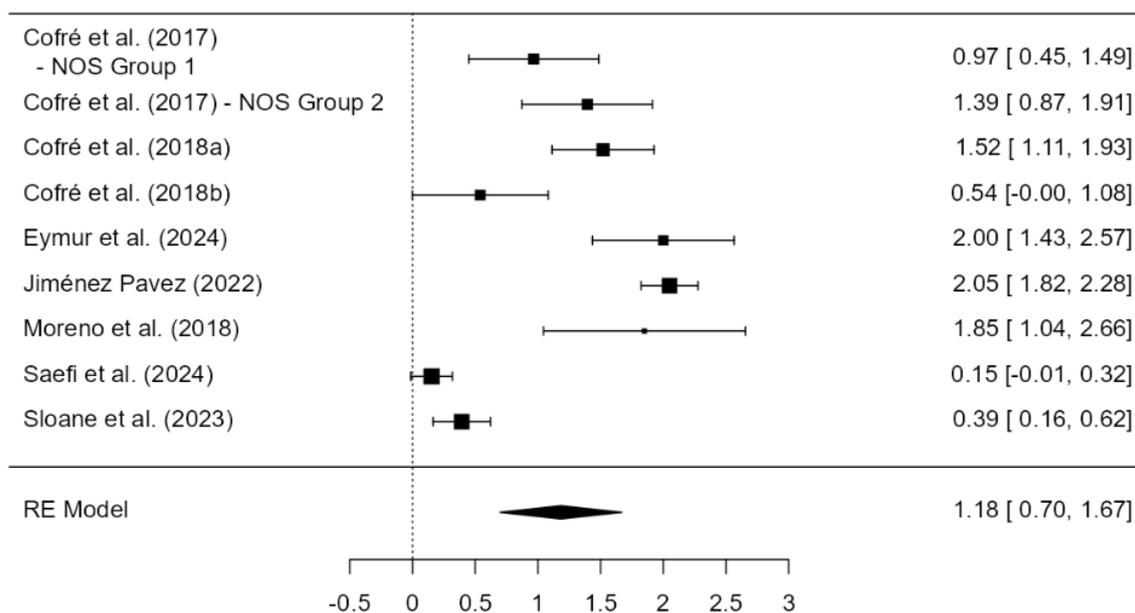
Figure 2. Forest Plot of Effect Sizes for the Impact of Explicit NOS Instruction on Understanding of Evolution (k = 9)

Furthermore, heterogeneity was substantial: Q(8) = 228.67, p < .001; I² = 94.63%. This indicates that nearly all variance in observed effect sizes was due to true differences across studies rather than sampling error. Additional heterogeneity statistics included τ^2 = 0.4951 (SE = 0.2754), τ = 0.704, and H² = 18.62. These values confirm meaningful between-study variability and support the use of a random-effects model (see Table 3).

Table 3. Heterogeneity Statistics for the Random-Effects Meta-Analysis (k = 9)

Tau	Tau²	I²	H²	R²	df	Q	p
0.704	0.4951 (SE= 0.2754)	94.63%	18.621	.	8.000	228.670	<.001

*Note.* τ^2 = 0.4951 (SE = 0.2754); *p* < .001 for Q statistic (df = 8).

Moderator Analysis: Educational Level

To address the second research question, a meta-regression was conducted to examine whether educational level (secondary vs. undergraduate) moderated the effectiveness of explicit NOS instruction. Educational level was coded as a binary variable (0 = secondary, 1 = undergraduate) (see Table 4). The analysis revealed a significant moderating effect. The intercept, representing the average effect size for secondary students, was Hedges' g = 1.651 (SE = 0.444), 95% CI [0.781, 2.520], p < .001. The coefficient for the undergraduate group was –1.321 (SE = 0.539), 95% CI [–2.377, –0.265], p = .014, indicating a statistically and practically significant reduction in effect size for undergraduate students. These results suggest that explicit NOS instruction is more effective at the secondary level than at the undergraduate level.

Table 4. Meta-Regression Results Examining the Moderating Effect of Educational Level on the Effectiveness of Explicit NOS Instruction

Predictor	B	SE	95% CI Lower	95% CI Upper	p
Intercept	1.65	0.44	0.78	2.52	< .001
Educational Level (1 = undergraduate)	–1.32	0.54	–2.38	–0.27	.014

Equivalence Testing
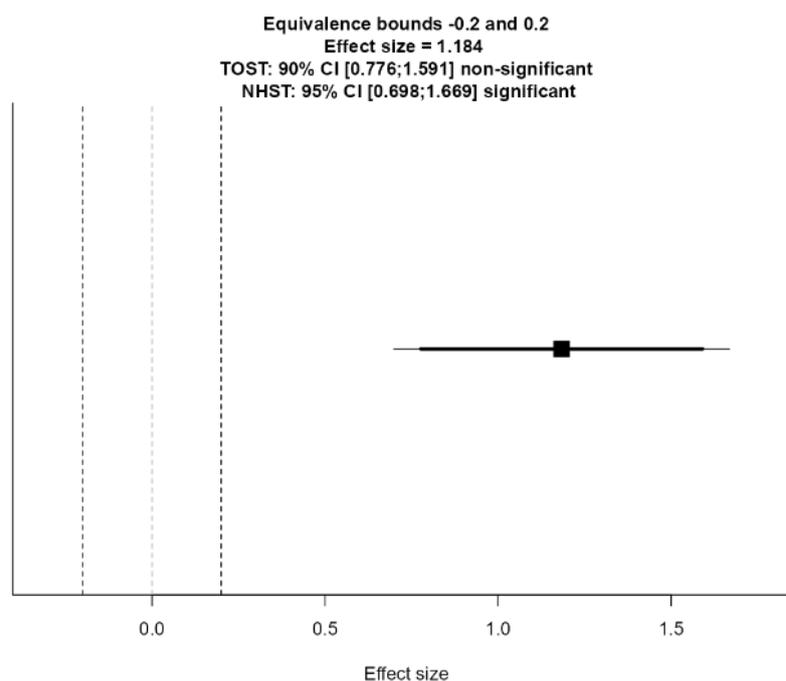
Figure 3. Equivalence Test Plot comparing Observed Effect Size to Pre-Specified Equivalence Bounds (±0.20)

To evaluate whether the difference in effect sizes across educational levels could be considered practically negligible, a Two One-Sided Tests (TOST) procedure was conducted with equivalence bounds set at ±0.20, representing a small effect size. The observed effect size was 1.18, with a 90% confidence interval of [0.776, 1.591] and a 95% NHST confidence interval of [0.698, 1.669]. The Z-value for the lower bound was 5.587 (p < .001), and the Z-value for the upper bound was 3.971 (p = 1.000). Because the 90% CI exceeded the predefined bounds, the difference was not statistically equivalent. Moreover, the observed confidence interval lies well outside the equivalence region (see Figure 3). This further supports the moderator finding that educational level meaningfully influences the effectiveness of explicit NOS instruction.

Instructional Features of Explicit NOS Interventions

To address the third research question, the instructional features across the eight included studies were qualitatively synthesized. Across studies, five NOS aspects emerged as the most frequently addressed, each associated with specific misconceptions and instructional strategies (see Table 5). This synthesis highlights how strategic alignment of NOS content with known conceptual difficulties in evolution contributes to instructional effectiveness.

Table 5. NOS Aspects Targeted by Instructional Interventions, Associated Misconceptions, and Instructional Strategies

NOS Aspect	Addressed In	Misconception Targeted	Instructional Strategy
Theory vs. Law	Cofré et al. (2017, 2018a, 2018b); Eymur et al. (2024); Jiménez Pavez (2022); Moreno et al. (2018)	"Evolution is just a theory" or "Theories become laws when proven"	Historical case studies and guided discussions emphasized that theories and laws are distinct, non-hierarchical forms of scientific knowledge; evolution is a robust theory.
Empirical Nature of Science	Cofré et al. (2017, 2018b); Jiménez Pavez (2022); Eymur et al. (2024); Moreno et al. (2018)	"Evolution lacks evidence" or "Science is based on opinion"	Students examined empirical data (e.g., finch evolution, fossil records) to illustrate that science relies on systematic observation, experimentation, and data interpretation.
Observation vs. Inference	Cofré et al. (2018b); Eymur et al. (2024); Moreno et al. (2018)	"Scientists observe evolution happening directly"	Lessons distinguished raw observations (e.g., fossil traits) from inferences (e.g., evolutionary relationships), showing how explanations are constructed.

NOS Aspect	Addressed In	Misconception Targeted	Instructional Strategy
Subjectivity and Creativity in Science	Cofré et al. (2018b); Moreno et al. (2018); Saefi et al. (2024)	"Science is purely objective and follows one method"	Reflective tasks and classroom dialogue highlighted how creativity, prior knowledge, and cultural perspectives shape scientific interpretation, especially in evolution.
Provisional Nature of Scientific Knowledge	Cofré et al. (2017); Jiménez Pavez (2022); Saefi et al. (2024)	"Scientific knowledge is fixed and unchanging"	Instruction traced the development of evolutionary theory from Darwin to the modern synthesis, emphasizing that science is dynamic and self-correcting.

While all interventions adhered to an explicit and reflective nature of science (NOS) instructional framework, they differed notably in instructional context, pedagogical strategies, integration with evolution content, and alignment with common student misconceptions. Although each study incorporated explicit NOS instruction, the level of contextualization varied. Several studies combined decontextualized activities, such as black box tasks and exercises distinguishing observation from inference with contextualized examples drawn from evolutionary biology, including cases like sickle-cell anemia and finch evolution. This blended approach allowed students to first isolate NOS concepts in abstract form and then apply them within meaningful biological contexts.

Five NOS aspects were most frequently addressed across the studies: the distinction between theory and law, the empirical nature of science, observation versus inference, the role of subjectivity and creativity in science, and the provisional nature of scientific knowledge. The theory-versus-law distinction was addressed by Cofré et al. (2017, 2018a, 2018b), Eymur et al. (2024), Jiménez Pavez (2022), and Moreno et al. (2018). These studies targeted the common misconception that "evolution is just a theory" or that "theories become laws when proven." Instructional strategies emphasized that theories and laws represent different, non-hierarchical forms of scientific knowledge. Historical examples and guided discussions reinforced that evolution as a theory is robust and well-supported by evidence.

The empirical nature of science was similarly emphasized in studies by Cofré et al. (2017, 2018b), Jiménez Pavez (2022), Eymur et al. (2024), and Moreno et al. (2018). To counter the belief that science is opinion-based or that evolution lacks evidentiary support, students engaged with empirical case studies, such as finch evolution and fossil records that demonstrated how scientific knowledge emerges from systematic data collection and evidence evaluation. The distinction between observation and inference was a focus in studies by Cofré et al. (2018b), Eymur et al. (2024), and Moreno et al. (2018), which addressed the misconception that scientists directly observe evolutionary change in all instances. Instruction clarified the difference between raw observations (e.g., physical traits, fossil specimens) and the inferences scientists make (e.g., evolutionary relationships), thereby deepening

students' understanding of how scientific explanations are constructed.

Subjectivity and creativity in science were explored by Cofré et al. (2018b), Moreno et al. (2018), and Saefi et al. (2024). Their work challenges the misconception that science is entirely objective and follows a single, rigid method. Reflective discussions highlighted how scientific inquiry is shaped by prior knowledge, cultural perspectives, and creative thinking, especially in fields like evolutionary biology. Finally, the provisional nature of scientific knowledge was addressed in studies by Cofré et al. (2017), Jiménez Pavez (2022), and Saefi et al. (2024). These interventions targeted the belief that scientific knowledge is fixed and unchanging. By presenting historical shifts in evolutionary theory from Darwin's original proposals to the modern synthesis, students were encouraged to see science as dynamic, self-correcting, and continually refined through new evidence.

Instructional strategies varied in complexity and depth. The Chilean studies, for example, incorporated the History of Science (HOS) to contextualize NOS instruction using case studies of key figures such as Darwin, Wallace, Dobzhansky, and the Grants' work on Galápagos finches. In contrast, Eymur et al. (2024) utilized an Argument-Driven Inquiry (ADI) framework. This approach enabled students to engage in peer argumentation and justify their conclusions with evidence. Saefi et al. (2024) offered a particularly distinctive approach by integrating NOS instruction with religious and philosophical discourse. This helped students reconcile evolutionary theory with Islamic worldviews.

The duration of interventions ranged from a single 60-minute session to 14 weeks. More significant learning gains were generally observed in multi-session programs (four to six sessions) that deeply integrated NOS and evolution instruction. The most effective studies systematically aligned specific NOS aspects with evolution-related misconceptions, making abstract epistemological ideas directly relevant to students' conceptual challenges. This strategic pairing not only strengthened conceptual understanding but also enhanced students' epistemic awareness of how science operates.

Publication Bias Assessment

To assess the risk of publication bias, three complementary methods were employed (see Table 6). Rosenthal's Fail-Safe N indicated that 1,010 unpublished null-result studies would be required to reduce the overall effect size to non-significance ($p < .001$); this suggests a robust and stable effect. Kendall's Tau was not significant ($\tau = 0.222$, $p = .477$) and Egger's regression test showed no evidence of funnel plot asymmetry (intercept = 1.253, $p = .210$).

Table 6. Publication Bias Assessment Using Multiple Statistical Indicators

Test Name	value	p
Fail-Safe N	1010.000	<.001
Kendall's Tau	0.222	0.477
Egger's Regression	1.253	0.210

Note. Fail-Safe N was calculated using the Rosenthal approach.

The funnel plot (see Figure 4) visually supported these results; it displayed a generally symmetrical distribution of effect sizes around the overall mean. Taken together, these findings indicate that the meta-analytic results are unlikely to be affected by publication bias and can be interpreted with confidence.
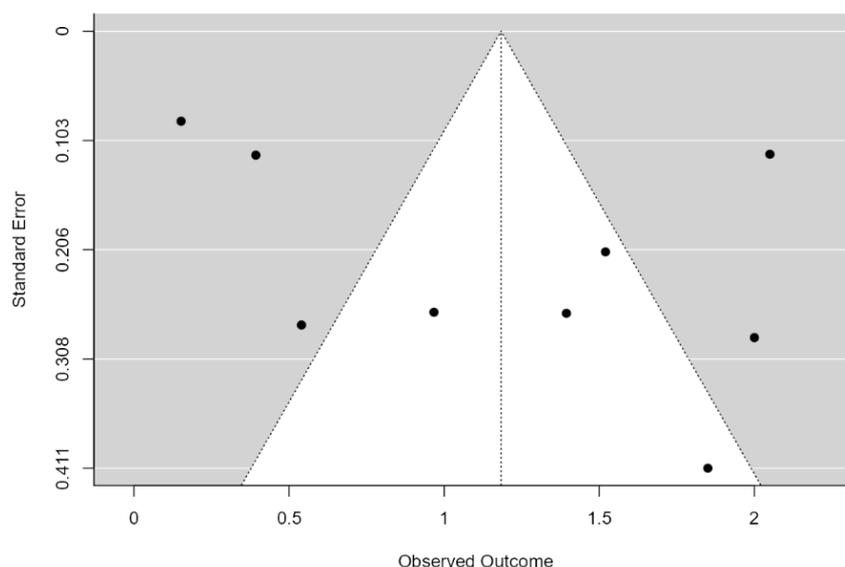

Figure 4. Funnel Plot Assessing Publication Bias among Included Studies

Discussion

This meta-analysis synthesized quantitative findings from eight empirical studies investigating the effects of explicit Nature of Science (NOS) instruction on students' understanding of biological evolution. Drawing from a diverse range of contexts, instructional approaches, and participant populations, the results provide compelling evidence supporting the effectiveness of explicit NOS-focused pedagogy in evolution education. Three core findings are discussed below, each corresponding to the study's research questions.

Effectiveness of Explicit NOS Instruction on Understanding of Evolution

The first research question asked whether explicit NOS instruction improves students' understanding of evolution. The meta-analysis yielded a large and statistically significant overall effect size (Hedges' $g = 1.18$, 95% CI [0.698, 1.669], $p < .001$), indicating that explicit NOS interventions consistently enhance students' comprehension of evolutionary concepts. This finding aligns with prior research suggesting that understanding the nature of scientific knowledge is essential for conceptual change in evolution learning (Balgopal, 2014; Lombrozo et al., 2008).

Despite notable variability among effect sizes, all included studies favored explicit NOS instruction over pre-instruction measures. This consistency underscores the robustness of explicit NOS-based pedagogy even when implemented with different age groups, instructional durations, or regional contexts. Importantly, the strong effect supports efforts to incorporate explicit NOS instruction into evolution curricula as a foundational pedagogical

strategy rather than an optional enrichment.

Educational Level as a Moderator

The second research question explored whether the effectiveness of explicit NOS instruction varies between secondary and undergraduate students. Meta-regression revealed a significant moderating effect: interventions were significantly more effective for secondary students (intercept $g = 1.651$, 95% CI [0.781, 2.520]) than for undergraduates, who demonstrated a reduced average effect (coefficient $= -1.321$, $p = .014$). These results suggest that secondary education represents a particularly effective window for implementing explicit NOS instruction. Accordingly, educators and policymakers should consider prioritizing NOS integration at the secondary level and tailoring instructional approaches for undergraduates, potentially through more advanced, contextualized, or discipline-specific methods to enhance its impact across educational stages (Nouri et al., 2021).

Equivalence testing (TOST) with ±0.20 bounds confirmed that the difference in effect sizes between educational levels was not practically negligible. The 90% confidence interval ([0.776, 1.591]) exceeded the predefined equivalence range. This reinforces the conclusion that educational level meaningfully moderates the effectiveness of NOS instruction in evolution education.

These findings suggest that explicit NOS interventions may be particularly well-suited to early secondary education, where they can support foundational shifts in students' understanding of science and evolution. For undergraduates, especially pre-service teachers, more intensive or specialized NOS integration may be necessary to foster a deep, pedagogically grounded understanding of NOS; develop the skills to teach it explicitly and reflectively; and build the motivation, confidence, and professional identity needed to integrate NOS meaningfully into future science instruction.

Instructional Features of Effective Explicit NOS Interventions

The third research question explored how specific instructional features influenced the effectiveness of nature of science (NOS) interventions. A qualitative synthesis revealed that successful programs shared several core attributes.

First, all studies implemented an explicit-reflective approach using pedagogical strategies that encouraged students to deliberately identify, analyze, and apply NOS concepts rather than learning them implicitly. Second, many interventions provided contextual grounding through historical case studies or empirical datasets to demonstrate how NOS principles are embedded in the development and justification of evolutionary theory (e.g., Cofré et al., 2017; Eymur et al., 2024). Third, the most impactful programs directly addressed widespread misconceptions about evolution, such as the belief that "evolution is just a theory" or that "science is purely objective" by linking these misunderstandings to specific NOS themes, including the distinction between theories and laws and the inferential nature of scientific reasoning. Finally, interactive, reflective learning experiences, such as decontextualized "black box" activities and structured discussion sessions fostered metacognitive

engagement and deeper conceptual understanding.

In general, these instructional features appear to significantly mediate the success of NOS-based teaching, particularly in facilitating conceptual change related to evolution. These findings underscore the importance of integrating explicit NOS instruction into teacher preparation programs and curriculum design as a strategic means of addressing persistent misconceptions in biology (Borgerding & Deniz, 2018; Campbell, 2018; Cheng & Chan, 2018; Fouad, 2018; Osman et al., 2018; Partosa, 2018; Stasinakis & Kampourakis, 2018).

Limitations

Several limitations should be acknowledged. First, the number of included studies (k = 9) was relatively small, which may constrain generalizability. However, consistent effects across diverse educational levels and national contexts enhance confidence in the findings. Second, substantial heterogeneity was observed ($I^2 = 94.63\%$). This likely reflects variation in sample characteristics, instructional approaches, and measurement tools. While this variability is anticipated in education research, it underscores the importance of reporting and analyzing moderator variables in future studies. Third, despite using multiple methods to assess publication bias (e.g., funnel plot, Egger's test, Fail-Safe N), the presence of unpublished null findings cannot be entirely ruled out. Ongoing monitoring of emerging studies will be essential to maintain a robust evidence base. Finally, the geographic concentration of included studies, particularly the predominance of research conducted in Chile, may limit cross-cultural applicability. Broader international representation in future research will be critical to evaluating the universality of these findings across different educational systems and sociocultural contexts.

Implications and Future Directions

The findings of this meta-analysis carry several important practical implications for science education policy, curriculum design, and teacher preparation. In terms of curriculum development, integrating explicit instruction on the nature of science (NOS) into secondary-level evolution units offers a proactive strategy for addressing persistent misconceptions and strengthening students' epistemological foundations (Johnston et al., 2022; Nelson et al., 2019; Scharmann, 2018).

For teacher education, professional development programs should prioritize the seamless integration of NOS concepts with core content and equip educators with reflective, student-centered pedagogies that make epistemological principles explicit and contextually meaningful (Kahana & Tal, 2014; Lederman & Lederman, 2019; Namakula & Akerson, 2024).

At the undergraduate level, further research is needed to explore how NOS instruction can be adapted for adult learners, particularly pre-service teachers and biology majors using discipline-specific approaches or culturally responsive frameworks. Several key research gaps remain. Notably, none of the studies included assessed long-term retention of NOS or evolution-related learning gains. Future investigations should incorporate delayed post-tests or longitudinal designs to determine the durability of instructional effects. Additionally, studies should

examine the cross-cultural transferability of NOS interventions and evaluate the effectiveness of digital or blended delivery models in promoting conceptual change. Collectively, addressing these directions can enhance the long-term impact and global relevance of NOS-based instruction in evolution education.

Conclusion

This meta-analysis provides robust evidence that explicit instruction on NOS significantly enhances students' understanding of evolution. With a large overall effect size and consistent gains across diverse contexts, the findings affirm that NOS-focused pedagogy is a powerful tool for addressing conceptual difficulties in evolution education. Importantly, the effectiveness of these interventions varies by educational level, with secondary students demonstrating greater benefits than undergraduates. This suggests that early, developmentally appropriate engagement with NOS concepts may be particularly impactful in shaping students' epistemological understanding. Successful interventions were those that explicitly linked NOS principles to common misconceptions about evolution, used contextualized case studies, and fostered reflective and inquiry-driven learning experiences. While the findings are compelling, they also highlight the need for further research, particularly into the long-term retention of NOS and evolution concepts, the scalability of interventions across cultural contexts, and the development of tailored approaches for higher education. Overall, this study underscores the importance of integrating explicit NOS instruction into science curricula and teacher education programs as a foundational strategy for promoting scientific literacy and deepening conceptual understanding in biology.

Recommendations

In light of the findings from this meta-analysis, several evidence-based recommendations are proposed to enhance evolution education through the integration of explicit NOS instruction. First, science curricula at the secondary level should embed NOS concepts systematically and explicitly within evolution units. Instruction should target foundational epistemological themes such as the distinction between theories and laws, the empirical and inferential nature of scientific knowledge, and the role of creativity and subjectivity in scientific practice. These elements should be explicitly linked to common misconceptions about evolution to promote conceptual change.

Second, teacher education and professional development programs must prioritize NOS pedagogy. Pre-service and in-service teachers should be equipped not only with accurate NOS content knowledge but also with reflective, student-centered instructional strategies. This includes using historical case studies, facilitating metacognitive dialogue, and modeling the integration of NOS into evolution instruction in contextually relevant and pedagogically effective ways.

Third, curriculum developers should design resources that blend decontextualized NOS activities with evolution-specific content. This dual approach allows students to first internalize abstract epistemological ideas and then apply them meaningfully within biology classrooms. Special consideration should also be given to adapting materials for cultural responsiveness, ensuring relevance in diverse educational settings.At the undergraduate level, particularly in biology and teacher preparation programs, NOS instruction should be tailored to deepen

disciplinary engagement and foster pedagogical reasoning. Embedding NOS within upper-level coursework and practicum experiences can strengthen future educators' confidence and competence in teaching evolution effectively and epistemologically.

Finally, future research should explore the long-term retention of NOS and evolution understanding, evaluate the impact of digital and hybrid instructional models, and expand the cultural and geographic diversity of study populations. These efforts will help ensure the scalability, adaptability, and global relevance of NOS-integrated evolution education. Collectively, these recommendations provide a roadmap for transforming evolution instruction into a more conceptually rich, epistemologically informed, and pedagogically grounded component of science education.

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