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Popperian analysis of positivistic inquiry in Indonesian biology education

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ABSTRACT

This study aims to examine the epistemological tendencies underlying inquiry-based biology learning in Indonesia and to critically interpret them through Karl Popper's falsificationism. A systematic literature review was conducted using the PRISMA procedure across Google Scholar, SINTA, ERIC, DOAJ, and Garuda databases, focusing on studies published between 2018 and 2025. Fifteen articles that met the inclusion criteria were analyzed through open coding and philosophical interpretation to identify patterns of scientific rationality in inquiry-based biology education. The findings show that inquiry is predominantly implemented in a verification-oriented and procedural manner, with success mainly measured through quantitative learning outcomes, science process skills, and scientific literacy scores. These practices reflect a positivistic orientation and provide limited opportunities for students to formulate risky conjectures, examine counterevidence, and revise ideas through critical reflection. Based on these findings, biology education should reorient inquiry toward a reflective–critical approach that emphasizes severe testing, argumentation-based discussion, and contextual biological problem-situations so that students can develop stronger epistemic understanding and a more authentic view of scientific inquiry.

INTRODUCTION

Inquiry-based biology education has long been positioned globally as a central approach in modern science education because it offers learning experiences that resemble the work of scientific communities: posing questions, formulating conjectures, testing them empirically, and constructing evidence-based explanations. Recent studies, however, suggest that inquiry in classroom settings is not always equivalent to the epistemic practices of science. De Jong et al. (2023) note that many implementations of inquiry still operate within a confirmatory empiricist logic, in which students follow highly structured procedures, and success is measured through score gains and teacher-predesigned answers. In a similar vein, Strat et al. (2024) emphasize that inquiry should be understood not merely as a teaching method, but as an epistemic practice that enables students to engage with evidence, uncertainty, and argumentation. This means that inquiry may appear scientific at the level of classroom method, yet remain limited at the level of epistemology.

Within positivist paradigms in research and education, objectivity is commonly anchored in quantification, instrument standardization, and the demonstration of causal relations through experimental designs. Park et al. (2020) explain that positivism views knowledge as a representation of reality accessible through controlled observation and empirical verification, so truth is understood as the product of repeated confirmation. When this orientation enters biology education, the success of inquiry is often reduced to statistical effectiveness: a model is considered superior when N-gain increases, t-tests produce significant results, or effect sizes are large. Pedagogically, this cultivates verification-seeking inquiry, namely inquiry that looks for justification rather than critical testing. Epistemologically, it sustains the assumption that science is a body of certainties that can be proven through the accumulation of data (Hodson, 2014).

The state of the art in recent science education research shows that this problem is not isolated. Boon et al. (2022) argue that many contemporary science education practices remain trapped in traditional empiricist epistemologies, even when they are labeled constructivist or inquiry-based. In such cases, learning still treats science as a testing procedure aimed at strengthening conjectures, rather than as an activity of modeling, debate, and theoretical critique. At the same time, recent literature also shows growing attention to epistemic agency as a core competence in science learning. Strat et al. (2024) describe epistemic agency as the capacity to evaluate evidence, raise counter-arguments, and revise explanations when confronted with anomalies. This shift is important because it shows that the current discussion in science education is no longer only about whether inquiry works, but about what kind of scientific reasoning inquiry actually develops.

More deeply, the reduction of inquiry to verification-oriented proceduralism has serious consequences for students' understanding of the nature of science (NOS). Science is not a final edifice of knowledge, but a system of conjectures that is always open to challenge. When inquiry is emphasized mainly through score stability and hypothesis acceptance, students find it difficult to experience what is most distinctive about science: fallibility, uncertainty, and theoretical revision. Mueller and Reiners (2023) report that even preservice science teachers often hold naïve views about the tentative nature of scientific knowledge. In the Indonesian context, Safitri & Fadly (2024), similarly show that teachers' epistemic understanding, including awareness of bias, uncertainty, and argumentation, remains relatively weak. This condition makes inquiry classes prone to slipping into procedural drills rather than becoming spaces for reflective scientific thinking.

The urgency of this issue lies in the fact that inquiry-based learning continues to be widely promoted in Indonesian biology education, yet its epistemological foundation has rarely been examined in depth (Strat et al., 2024). Most studies still evaluate inquiry primarily through learning outcomes, science process skills, critical thinking scores, or scientific literacy scores (Fatimah et al., 2026). This means that inquiry is often treated as a pedagogical tool for producing measurable gains, while its deeper rational structure remains underexplored. In response to this gap, the present study argues that inquiry in biology education should not only be evaluated by whether it improves student achievement, but also by whether it develops a more authentic understanding of scientific rationality.

It is here that Popper's falsificationism offers crucial philosophical clarity. Popper rejects verificationism as the route of scientific progress; for him, scientific theories advance not because they are increasingly confirmed, but because they become more resilient to attempts at refutation (conjecture–refutation) (Gonçalves & Adúriz-Bravo, 2022). To be scientific is to place conjectures under severe tests that could bring them down, and then to revise or replace them with stronger theories

(Popper, 2010). Accordingly, genuine scientific rationality is not a rationality of proof, but a rationality of critical testing. This perspective provides a sharp evaluative lens for reading inquiry practices: to what extent do classroom activities open space for fallible, risk-laden hypotheses? To what extent are students trained to seek counter-evidence rather than only supporting evidence? To what extent do classroom discussions function as communities of intersubjective critique rather than as mechanisms for affirming predetermined correct answers? (Chmielewski, 2022).

Yet to assess these questions fairly, a rigorous and comprehensive mapping of the research landscape is required. For that reason, this study employs a systematic literature review combined with Popperian philosophical analysis. This approach is important for two reasons. First, a systematic literature review enables the identification of epistemological patterns across studies, reducing bias from single findings and capturing systemic tendencies more robustly (Kranz et al., 2023). Second, philosophical analysis allows us to evaluate the rationality embedded behind designs, instruments, and researchers' interpretations of data, rather than merely inspecting learning outcomes at the surface level (Okasha, 2016). By integrating both, the study moves beyond the conclusion that inquiry is effective or ineffective toward a more fundamental question: within what kind of scientific rationality does inquiry operate, and which rationality ought to be cultivated in biology education?

The novelty of this study lies in its attempt to read inquiry-based biology learning not only as an instructional model but also as an epistemological practice. While previous studies have largely focused on the effectiveness of inquiry in improving student outcomes Lazonder & Harmsen, (2016). This study examines the scientific rationality underlying those practices through the lens of Popperian falsificationism. In this way, the study contributes a different perspective by showing that a learning model may be pedagogically active, yet still epistemologically positivistic. Therefore, the central problem addressed in this study is not simply whether inquiry works, but what kind of scientific thinking it promotes and how it can be recontextualized so that it aligns more closely with the fallible and open character of scientific knowledge (Furtak et al., 2012).

Therefore, this inquiry is situated in a problem field that is not merely methodological but epistemological. It begins with the premise that inquiry practices in Indonesian biology education have evolved into active pedagogy, yet may still retain residues of positivism that shape how students understand science. Through systematic literature review and Popperian critique, this study seeks to reveal the map of rationalities currently at work, their limitations, and directions for recontextualization toward a more reflective-critical inquiry.

METHODS

Research Design

This study was designed as a systematic review to understand how positivistic scientific rationality operates within inquiry-based biology learning practices in Indonesia and to examine and rearticulate their epistemological foundations using Karl Popper's falsificationism. To achieve these aims, the study employed a Systematic Literature Review (SLR) integrated with philosophical analysis. In this way, the investigation did not merely compile empirical findings, but also traced the patterns of reasoning that shape how inquiry is taught and understood in biology education (Snyder, 2019) This approach was selected because an SLR enables researchers to map an entire research landscape in a rigorous and transparent manner, while philosophical analysis provides a reflective framework to evaluate the epistemological quality of empirical findings (Okasha, 2016). Accordingly, the method not only documented what has been done in inquiry-based learning, but also assessed what has not yet been considered and what can be further developed from the standpoint of philosophy of science (Nola & Sankey, 2007).

Eligibility Criteria and Study Selection

The population of this study comprised all research articles on inquiry-based biology learning in Indonesian secondary education contexts published between 2018 and 2025. The literature search was conducted through major academic databases, including Google Scholar, SINTA, ERIC, DOAJ, and Garuda Ristekdikti. Keywords were constructed using Boolean combinations to ensure comprehensive coverage of relevant publications, following established systematic review procedures (Boon et al., 2022). The sample of this study consisted of articles that met specific inclusion criteria. The selection was limited to studies: (1) conducted at the senior secondary level (SMA/MA/SMK), (2) focused on biology learning, (3) implemented inquiry-based learning models, (4) published within the 2018–2025 timeframe, and (5) available in full-text format in either Indonesian or English. This publication period was chosen because it reflects the growing emphasis on inquiry-based learning within the revised 2013 Curriculum and Indonesia's 21st-century education framework (Trilling & Fadel, 2009).

To enhance transparency and rigor, the characteristics of the included studies, such as publication year, research design, sample size, and instructional context, are summarized in Table 1. Studies that did not meet the methodological or epistemological relevance criteria were excluded during the screening process.

Table 1.
Demographic Characteristics of Included Studies

Code	Author(s) (Year)	Research Design	Sample Characteristics	Context
A1	Wisanggeni & Pranata (2024)	Experimental	Senior secondary students	Biology learning
A2	Fausy & Muis (2023)	Quasi-experimental	Grade X students	Biology learning
A3	Zaini & Rezeki (2018)	Experimental	Senior secondary students	Biology learning
A4	Ali et al. (2023)	Quasi-experimental	Senior secondary students	Biology learning
A5	Hartini et al. (2018)	Experimental	Senior secondary students	Biology learning
A6	Afwadi et al. (2024)	Quasi-experimental	Senior secondary students	Biology learning
A7	Siboro (2024)	Classroom Action Research	Senior secondary students	Biology learning
A8	Zulkarnain et al. (2022)	Classroom Action Research	Senior secondary students	Biology learning
A9	Putri & Zulfiani (2025)	Experimental	Senior secondary students	Biology learning
A10	Wardani & Djukri (2019)	Experimental	Senior secondary students	Biology learning
A11	Nopiya et al. (2020)	Quasi-experimental	Senior secondary students	Biology learning
A12	Lestari et al. (2021)	Experimental	Senior secondary students	Biology learning
A13	Nasir et al. (2020)	Experimental	Senior secondary students	Biology learning
A14	Damayanti & Gayatri (2019)	Experimental	Senior secondary students	Biology learning
A15	Fitriah et al. (2025)	Quasi-experimental	Grade XI students	Biology learning

Data Extraction Framework

To maintain analytic consistency, this study used the PICO framework as the main instrument for data extraction and categorization. Beyond functioning as a systematic tool, PICO also carries epistemic value because it helps identify how particular pedagogical interventions shape students' scientific ways of thinking (Schardt et al., 2007). The PICO components were defined as: Population (senior secondary students in biology learning contexts), Intervention (inquiry-based learning models such as guided inquiry, structured inquiry, open inquiry, inquiry-based practicum, POGIL, and 5E inquiry), Comparison (conventional/expository instruction or non-inquiry models), and Outcomes (representations of positivistic scientific rationality and the potential for reorientation toward Popperian falsificationism).

To ensure trustworthiness, the PICO framework was applied consistently across all studies. An iterative coding process was conducted to identify and refine epistemological categories, such as verificationism, proceduralism, and data objectivism. Reliability was maintained through careful cross-checking of data and interpretations, while an audit trail was documented to enhance transparency. Furthermore, the analysis was theoretically grounded in Popper's concepts of conjecture–refutation and falsifiability Popper (2010), ensuring that interpretations are systematic, transparent, and conceptually rigorous.

Procedure

As an initial step in examining how inquiry-based biology learning practices are represented in the literature, this study conducted a systematic selection of relevant studies. This stage aimed to ensure that the articles analyzed were genuinely aligned with the focus of the review, namely the representation of scientific rationality and epistemological tendencies in the implementation of inquiry models at the senior high school level in Indonesia.

Article selection followed the PRISMA flow, comprising identification, screening, eligibility assessment, and final inclusion (Page et al., 2021). The identification and screening processes were conducted systematically to guarantee transparency, reproducibility, and accuracy in study selection. After identification through database searching, duplicates were removed, and titles and abstracts were screened based on their relevance to inquiry-based biology learning and epistemological analysis. Full-text articles were then assessed against the predefined inclusion criteria to determine their eligibility.

The study selection process followed the PRISMA guideline and is presented in Figure 1.

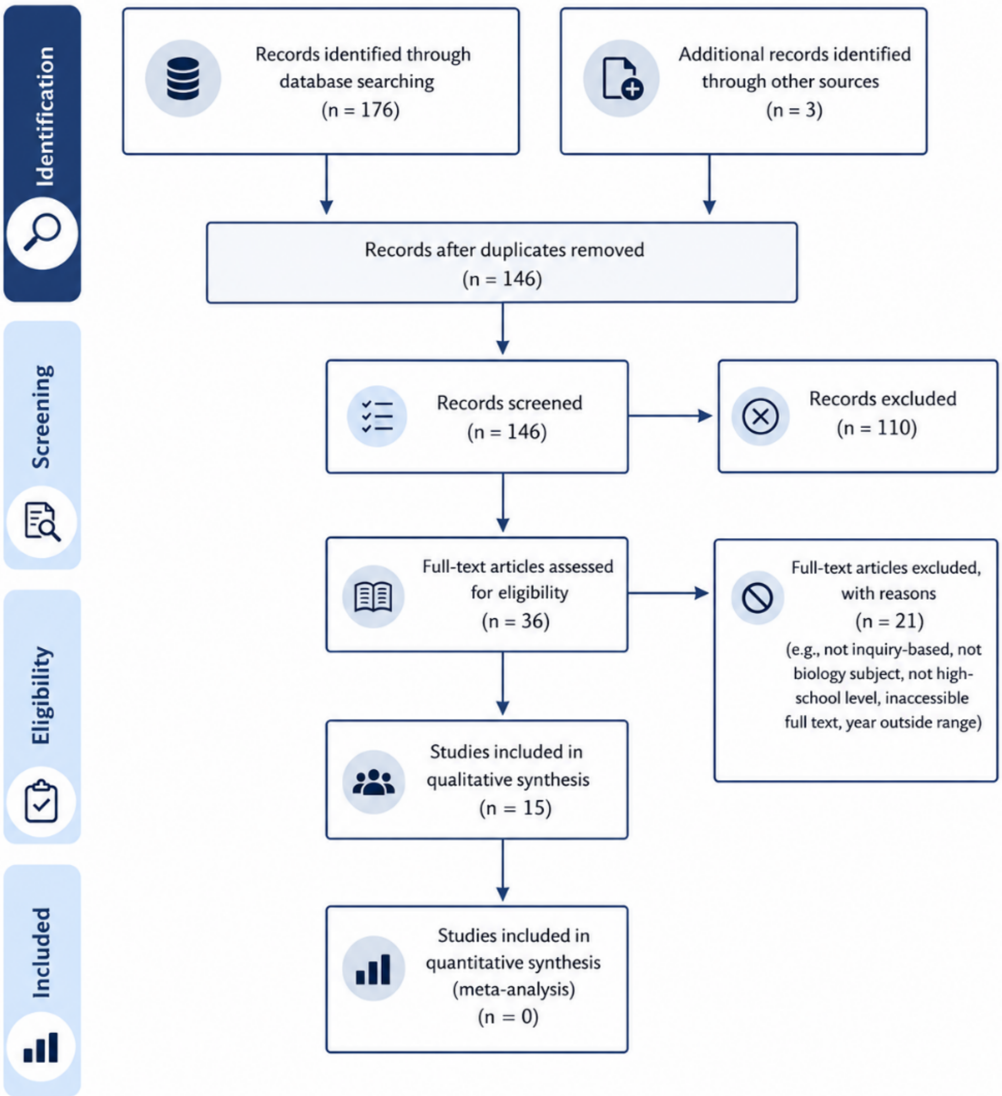

Figure 1. PRISMA flowchart of study selection. From 179 records identified, 146 remained after duplicates, 36 full texts were assessed, and 15 studies were included in the qualitative synthesis.

As shown in Figure 1, a total of 179 records were initially identified through database searching. After removing duplicates, 146 articles remained and were screened based on their titles and abstracts. During this stage, 110 articles were excluded for not meeting the initial criteria, leaving 36 articles for full-text eligibility assessment. Following a thorough evaluation of content relevance, methodological focus, and alignment with the context of inquiry-based biology learning, 21 articles were excluded because they were irrelevant, unavailable in full text, or outside the specified publication range. Consequently, 15 articles met the inclusion criteria and were included in the qualitative synthesis.

The final set of included studies was extracted into a PICO-based matrix to support systematic synthesis and comparison across articles. Furthermore, the selected studies were mapped into a synthesis table describing the inquiry models employed, the main findings, and their epistemological implications for biology learning practice. This table serves as the foundation for further analysis of the character of scientific rationality emerging in inquiry-based biology learning in Indonesia.

Data Analysis Techniques

Data from the selected articles were analyzed using thematic analysis. The analysis focused on identifying patterns related to the implementation of inquiry-based learning, the science competencies measured, and the epistemological orientation reflected in each study. Open coding was used to classify recurring themes such as verificationism, proceduralism, and data objectivism (Akuma & Koenen, 2025). The identified themes were then interpreted using Popper's concepts of falsificationism, particularly conjecture–refutation, fallibility, and critical testing (Popper, 2010). This analysis was conducted to examine whether inquiry practices in Indonesian biology education emphasize critical scientific reasoning or tend to position scientific knowledge as fixed and empirically verified (Chmielewski, 2022). The interpretation of findings was further supported by contemporary literature on scientific rationality and science education (Okasha, 2016).

RESULTS AND DISCUSSION

Representation of Positivistic Scientific Rationality in Inquiry-Based Biology Learning Practices in Indonesia (2018–2025)

Table 2.
Characteristics, Study Purposes, and Epistemological Implications of Inquiry-Based Biology Learning Studies in Indonesia (2018–2025)

Code	Author(s) (Year)	Inquiry Model	Main Findings	Implications
A1	Wisanggeni and Pranata (2024)	General Inquiry Model (unspecified)	Improved mastery of biology concepts.	Indicates an empirical-verification orientation focused on score outputs, reflecting a positivistic tendency in inquiry implementation.
A2	Fausy and Muis (2023)	Guided Inquiry	Effective in improving biology learning outcomes.	Frames inquiry as a technical intervention to raise measurable performance, reinforcing data objectivism.
A3	Zaini and Rezeki (2018)	General Inquiry Model (unspecified)	Improved learning outcomes and critical thinking.	Treats inquiry as a tool for increasing scores; epistemic dimensions are less visible, confirming a verificationist character.
A4	Ali et al. (2023)	Guided Inquiry	Increased critical thinking ability.	Uses pretest–posttest score-based evaluation, showing a positivistic pattern without exploring theoretical critique.
A5	Hartini et al. (2018)	Environmental Inquiry (Contextual Inquiry)	Improved concept mastery and science process skills.	"Science process" is reduced to procedural steps and observable indicators, showing proceduralism in inquiry practice.
A6	Afwadi et al. (2024)	Guided Inquiry	Improved student learning outcomes.	Presents highly structured inquiry verified through statistics, with little epistemological reflection.
A7	Siboro (2024)	Guided Inquiry (Classroom Action Research)	Improved digital literacy, critical thinking, and conceptual understanding.	Despite using action research, success is still defined through quantitative indicators; reflection is not directed toward epistemic aspects.
A8	Zulkarnain et al. (2022)	General Inquiry Model (unspecified) – Classroom Action Research	Improved scientific competence.	Scientific competence is treated as a measurable variable that rises across cycles, not as an argumentative or critical process.
A9	Putri and Zulfiani (2025)	General Inquiry Model (unspecified)	Improved concept mastery and entrepreneurial values.	Shows extension of objectivism into the affective domain, supporting critique of reducing values to numbers.
A10	Wardani and Djukri (2019)	Guided Inquiry + Starter Experiment	Improved science process skills.	Treats inquiry as a structured protocol; provides no critical evaluation of ideas or evidence.
A11	Nopiya et al. (2020)	Guided Inquiry	Improved SPS and interpersonal skills.	Highlights an output-based orientation that strengthens verificationist character in science

Code	Author(s) (Year)	Inquiry Model	Main Findings	Implications
				learning.
A12	Lestari et al. (2021)	Guided Inquiry	Improved ability to use the scientific method.	The scientific method is treated procedurally, underscoring a view of science as an algorithm rather than reflective rationality.
A13	Nasir et al. (2020)	General Inquiry Model (unspecified)	Improved SOLO thinking levels.	Thinking levels are measured statistically, indicating inquiry is used to increase scores rather than as a space for critiquing ideas.
A14	Damayanti and Gayatri (2019)	Inquiry 5E (Learning Cycle 5E)	Improved scientific literacy.	Scientific literacy is reduced to indicator scores, raising philosophical questions about its authentic meaning.
A15	Fitriah et al. (2025)	POGIL (Process-Oriented Guided Inquiry Learning)	Improved scientific literacy and problem-solving ability.	Presents a modern inquiry model but still prioritizes measurable performance, opening room for reorientation toward more critical-reflective approaches.

Table 2 summarizes the main characteristics of the fifteen selected articles, including the inquiry models used, the empirical outcomes emphasized, and the epistemological tendencies reflected in their research designs and interpretations. The review shows that inquiry-based biology learning in Indonesia during 2018–2025 is predominantly evaluated through measurable learning indicators, such as learning outcomes, science process skills, scientific literacy, critical thinking, and problem-solving ability. This pattern is consistent with previous inquiry-based learning literature, which shows that inquiry is often assessed through its effectiveness in improving achievement and conceptual understanding rather than through its capacity to develop epistemic reflection (De Jong et al., 2023; Lazonder & Harmsen, 2016; Strat et al., 2024). Therefore, the findings of this review provide an initial basis for examining how inquiry is not only practiced as a teaching model, but also shaped by particular assumptions about scientific knowledge and educational success.

In science education theory, inquiry is ideally understood as a learning process that involves questioning, evidence evaluation, explanation construction, and revision of ideas. Chinn and Malhotra (2002) argue that school inquiry often differs from authentic scientific inquiry because classroom tasks tend to simplify the epistemic complexity of real scientific investigation. Similarly, Sandoval (2005) emphasizes that inquiry learning should develop students' practical epistemologies, namely their understanding of how scientific knowledge is constructed, justified, and revised. When viewed against these theoretical positions, the studies reviewed in this SLR show that inquiry-based biology learning in Indonesia still tends to emphasize procedural completion and outcome improvement more than students' engagement with uncertainty, critique, and theory revision.

The synthesis of the fifteen articles indicates a strong tendency toward quantitative verification. In most studies, especially A1, A2, A5, A6, A10, A11, and A15, inquiry models are positioned as instructional treatments, while their success is determined through posttest scores, N-gain, statistical significance, or other numerical indicators. This finding is in line with Park et al. (2020), who explain that positivist research commonly values measurement, objectivity, and empirical confirmation as the basis for knowledge claims. In this sense, the reviewed studies reflect a verification-oriented logic because inquiry is considered effective when it produces measurable improvement. Such a pattern supports Dewi et al. (2025), who also show that inquiry-based learning is frequently framed as a strategy for optimizing specific student competencies through empirical measurement.

Moreover, the reviewed studies show that inquiry is often represented as a linear sequence of learning steps rather than as an open-ended process of knowledge construction. Activities such as formulating problems, proposing hypotheses, conducting experiments, analyzing data, and drawing conclusions are commonly presented as fixed procedures that guide students toward expected curricular concepts. This tendency is relevant to Chinn and Malhotra's (2002) critique that many school inquiry tasks only imitate the surface structure of science without fully representing the epistemic demands of authentic scientific practice. It also resonates with Popper's (2010) criticism of inductive reasoning, where scientific activity is reduced to the accumulation of confirming observations rather than critical attempts to test and challenge conjectures. In this review, such proceduralism is evident in studies such as A10, A7, and A8, where inquiry success is mainly associated with score improvement rather than with students' ability to evaluate competing explanations.

The findings also reveal a tendency toward data objectivism, in which quantitative scores are treated as direct representations of students' scientific thinking. Variables such as conceptual understanding, science process skills, scientific literacy, critical thinking, and problem-solving are commonly operationalized through standardized indicators and statistical comparisons. This pattern is related to the positivist assumption that valid knowledge can be obtained through objective measurement and controlled empirical observation (Park et al., 2020). However, science education scholars have emphasized that scientific understanding also involves argumentation, uncertainty, justification, and awareness of the tentative nature of knowledge (Lederman et al., 2002; Osborne, 2010). From this perspective, the studies in the corpus tend to capture the measurable products of inquiry more strongly than the argumentative and reflective processes that characterize authentic scientific reasoning.

An instrumental orientation is also visible across the reviewed articles. Most studies frame inquiry as a pedagogical tool for improving particular outcomes, such as learning achievement, science process skills, scientific literacy, or critical thinking. This pattern can be connected to Dewey's (2015) view that educational methods should not be detached from meaningful experience and reflective thinking. When inquiry becomes merely a technique for producing higher scores, its epistemological function as a means of developing reflective judgment becomes weakened. Even in more contemporary inquiry models such as POGIL in A15, the emphasis remains largely on measurable performance, indicating that inquiry is still treated more as an instructional intervention than as an epistemic practice that positions students as active knowledge agents.

Another important finding concerns the role of hypotheses in inquiry activities. In several studies, particularly A3, A6, and A10, students are asked to formulate hypotheses, but these hypotheses often function as formal steps leading toward expected results. Previous research on nature of science has emphasized that students need to understand scientific knowledge as tentative, revisable, and dependent on evidence and interpretation (Lederman et al., 2002). Osborne (2010) further argues that scientific learning should involve critical discourse because students need opportunities to defend, question, and revise claims. In contrast, the reviewed studies rarely show hypotheses being used as risky conjectures that may be refuted, which strengthens the interpretation that inquiry is frequently practiced as confirmation rather than critical testing.

Based on this synthesis, the corpus A1–A15 indicates three interrelated layers of positivistic rationality. At the methodological level, experimental and quasi-experimental designs position quantitative data as the main basis for validating inquiry effectiveness. At the pedagogical level, inquiry is commonly enacted as a structured procedure aimed at achieving correct concepts and improved scores. At the epistemological level, scientific knowledge tends to be represented as something that can be verified through empirical data, while fallibility, disagreement, theoretical revision, and counter-evidence receive limited attention. This finding does not suggest that the reviewed studies are methodologically incorrect, but it shows that inquiry-based biology learning in Indonesia remains strongly shaped by verificationist, procedural, and product-oriented assumptions.

Therefore, the relevance of Popperian falsificationism lies in its capacity to offer a critical alternative to this dominant pattern. Popper's view of science emphasizes conjecture, refutation, fallibility, and severe testing rather than the mere confirmation of hypotheses (Popper, 2010). When connected to contemporary science education literature, this perspective supports the need to move inquiry from a verification-oriented model toward a reflective-critical model that gives students opportunities to question evidence, identify counter-examples, revise explanations, and understand the tentative nature of scientific knowledge. In this way, inquiry-based biology learning can become not only methodologically active, but also epistemologically meaningful.

Popperian Analysis of the Positivistic Foundations of Scientific Rationality in Inquiry-Based Biology Education

The Dominance of Pedagogical Verificationism and the Reduction of Scientific Progress to Score Gains

Research in science education has increasingly emphasized that inquiry should not be reduced to procedural activity or measurable achievement alone, but should involve students in epistemic practices such as questioning, constructing explanations, evaluating evidence, and revising claims. Duschl (2008) argues that science education needs to balance conceptual, epistemic, and social learning goals so that students do not merely learn scientific content but also understand how scientific knowledge is constructed and evaluated. Similarly, Berland and Reiser (2009) emphasize that explanation and argumentation are central practices in inquiry because students need to make sense of phenomena, articulate claims, and justify them through evidence. When these theoretical perspectives are used to read corpus A1–A15, the reviewed studies show that inquiry-based biology learning in Indonesia still tends to emphasize measurable score improvement more strongly than epistemic engagement with uncertainty, argumentation, and revision.

The findings of this SLR indicate that many studies formulate inquiry success in affirmative and outcome-oriented terms, such as "inquiry improves learning outcomes," "inquiry increases critical thinking," or "inquiry enhances scientific literacy." In A2, inquiry success is demonstrated through pretest–posttest gains and N-gain categories, while A9 concludes model effectiveness through a significant t-test result. Similar patterns appear in A10 and A15, where ANCOVA, mean comparison, and statistical significance are used as the main basis for affirming the effectiveness of inquiry models. This pattern is consistent with a broader tendency in educational research to evaluate instructional models through measurable learning outcomes, but it also shows that inquiry is more often treated as an intervention to produce score gains than as a process of critical scientific reasoning.

From the perspective of science education theory, this emphasis on score gains becomes limited when it does not include students' participation in evaluating claims, identifying weaknesses in evidence, or considering alternative explanations. Erduran et al. (2015) show that argumentation has become an important goal in science education because it enables students to coordinate evidence and theory in order to support or refute claims. This means that scientific progress in classroom inquiry should not only be represented by higher posttest scores, but also by students' ability to examine whether their explanations can survive criticism. When compared with this theoretical expectation, corpus A1–A15 still provides limited evidence that students are engaged in argumentation as a systematic process of testing and revising scientific ideas.

This tendency can be interpreted more deeply through Popper's falsificationism. Popper argues that scientific knowledge does not progress through the accumulation of confirmations, but through risky conjectures that are exposed to possible refutation through severe testing (Popper, 2010). Mitra (2020) explains that falsifiability is central to Popper's philosophy because a scientific claim must be open to conditions under which it could be rejected. When the reviewed studies mainly seek to confirm that inquiry improves certain outcomes, their hypotheses become relatively "safe" because the research design is oriented toward proving effectiveness rather than exploring the possibility of failure. Therefore, the corpus reflects pedagogical verificationism, in which inquiry is treated as a model to be validated rather than as an epistemic space for testing and challenging claims.

The dominance of quantitative indicators also shapes how scientific progress is understood in the reviewed studies. A7, for example, reports rising scores across classroom action research cycles as evidence of guided inquiry success, and similar score-based interpretations appear across several quasi-experimental studies. Although such evidence is methodologically useful for evaluating learning outcomes, it does not fully represent the epistemic quality of inquiry as a scientific practice. From a Popperian standpoint, progress should involve error detection, criticism, and the improvement or rejection of weak conjectures, not merely the accumulation of positive numerical changes (Popper, 2010). In this sense, the positivistic rationality identified in RQ1 is closely related to how educational success is defined: not primarily as theoretical critique, but as stable and predictable quantitative improvement.

The issue of objectivity also requires further interpretation. In the reviewed corpus, objectivity is commonly associated with instrument reliability, normality and homogeneity tests, statistical significance, and standardized measurement, especially in studies such as A10 and A15. This view is consistent with positivistic assumptions that reliable measurement and controlled empirical data can serve as the main basis for valid knowledge claims. However, Popper's conception of objectivity is different because he locates objectivity in intersubjective criticism, where claims become stronger when they are publicly examined, criticized, and revised (Popper, 2010). Therefore, when classroom discussions in studies such as A11 remain oriented toward teacher-validated correct answers, they do not yet fully represent objectivity as critical dialogue.

This limitation is important because contemporary science education increasingly emphasizes the tentative and revisable nature of scientific knowledge. Mueller and Reiners (2023) show that understanding the tentative character of science remains a major challenge in science teacher education, indicating that students and teachers often still struggle to view scientific knowledge as open to revision. This concern is relevant to the present review because inquiry activities in A1–A15 rarely position anomalies, failed hypotheses, or counter-evidence as valuable elements of learning. Instead, inquiry tends to guide students toward expected concepts and successful outcomes. As a result, the reviewed studies show data objectivism rather than critical objectivity, because data are treated mainly as proof of effectiveness rather than as material for public criticism and conceptual revision.

Through Popper's demarcation principle, inquiry in corpus A1–A15 can therefore be understood as procedurally scientific but not yet fully scientific at the epistemological level. Many inquiry activities contain recognizable scientific steps, such as problem formulation, hypothesis development, experimentation, and conclusion drawing. However, these steps are often directed toward confirming established curricular concepts rather than exposing students' ideas to possible rejection. This condition resonates with Gonçalves and Adúriz-Bravo (2022), who emphasize that Popper's critical rationalism is relevant for science education because it shifts the focus from confirmation to critique. Thus, the main problem is not that inquiry-based biology learning in Indonesia lacks scientific procedures, but that these procedures have not yet fully embodied the critical logic of science.

Overall, the Popperian reading of corpus A1–A15 shows that the positivistic foundation of inquiry-based biology education is expressed through three dominant tendencies: affirmative hypotheses, score-based progress, and measurement-centered objectivity. These tendencies are not methodologically wrong, but they narrow the epistemological meaning of inquiry when they are not accompanied by critical argumentation, counter-evidence, and theory revision. By connecting the SLR findings with contemporary science education theory, it becomes clear that inquiry needs to move beyond verification-oriented pedagogy. A more epistemologically robust inquiry model should allow students to formulate risky conjectures, test them against possible refutation, and understand scientific knowledge as tentative, critical, and open to improvement.

Inquiry Structure as a Method of Confirmation and Its Limits for Popperian Critical Rationalism

Inquiry-based learning is generally expected to involve students in questioning, investigating, interpreting evidence, and constructing explanations through active engagement with scientific problems. Pedaste et al. (2015) explain that inquiry learning consists of interrelated phases such as orientation, conceptualization, investigation, conclusion, and discussion, but these phases should not be understood merely as fixed procedural steps. Hmelo-Silver et al. (2007) also emphasize that inquiry learning requires appropriate scaffolding so that students can engage meaningfully in problem solving, explanation building, and knowledge construction. When these theoretical perspectives are compared with the findings of this SLR, corpus A1–A15 shows that inquiry in Indonesian biology learning is more frequently structured as a guided sequence for confirming expected concepts than as an open epistemic process for testing and revising ideas.

The reviewed studies indicate that inquiry activities commonly follow steps such as formulating hypotheses, observing phenomena, conducting experiments, analyzing data, and drawing conclusions. However, these steps often function as pathways toward predetermined curricular concepts rather than as opportunities to examine the limits of students' initial explanations. This pattern is visible in A12, where students test hypotheses within guided scenarios and then decide whether to accept or reject them based on data that generally support the expected claim. A11 shows a similar tendency because students compare their findings with initial hypotheses in order to reach conclusions already directed by the teacher. This finding is consistent with Chinn and Malhotra's (2002) argument that many school inquiry tasks imitate the surface features of scientific investigation but do not fully represent the epistemic complexity of authentic scientific inquiry.

From the perspective of science education theory, authentic inquiry should involve uncertainty, competing explanations, and the possibility that students' initial ideas may be revised or rejected. Ford (2008) argues that scientific learning requires students to participate in disciplinary practices where knowledge claims are accountable to evidence, critique, and standards of scientific reasoning. Manz

(2012) similarly shows that students' scientific understanding develops when they participate in modeling practices that require them to refine explanations in response to empirical and conceptual challenges. In contrast, the corpus A1–A15 shows limited evidence that students are systematically invited to treat hypotheses as provisional conjectures that may fail. Therefore, inquiry in these studies tends to emphasize confirmation and conceptual alignment rather than uncertainty, critique, and theoretical revision.

This tendency becomes clearer when read through Popperian falsificationism. Popperian critical rationalism requires science learning to provide students with opportunities to generate fallible conjectures, design tests that deliberately search for weaknesses in those conjectures, and treat discrepant results as part of intellectual progress. From this standpoint, the inquiry practices reflected in A11 and A12 are not yet fully aligned with conjecture–refutation because hypotheses are mostly treated as formal steps expected to be validated. Popper's view challenges this logic by emphasizing that scientific progress occurs not when claims are repeatedly confirmed, but when they are exposed to the possibility of refutation. Thus, the main epistemological limitation of the reviewed inquiry practices is that they guide students to prove concepts more often than to challenge, revise, or abandon weak explanations.

The consequence of this pattern is that students may learn science as a process of proving conjectures rather than disputing them and searching for their vulnerabilities. This is problematic because contemporary science education increasingly views inquiry as an epistemic and social practice, not only as a method for completing experimental procedures. Scientific learning should enable students to experience cognitive conflict, defend claims, evaluate counter-evidence, and revise explanations through reasoned discussion. Such an orientation is consistent with critical rationalism, which places critique at the center of scientific knowledge development (Chmielewski, 2022). In Popper's view, science learning should not merely lead students toward predefined answers, but should train them to understand why some explanations fail and how stronger explanations can be constructed from criticism.

In addition, the weak integration of intersubjective criticism limits students' opportunities to understand scientific theories as public objects that can be debated, revised, and even rejected. Popper (2002) describes scientific knowledge as part of "World 3," namely objective knowledge products that exist beyond individual belief and can become the object of public criticism. However, many studies in the corpus assess individual performance through scores without positioning students' explanations, arguments, or models as discursive objects to be tested within a classroom community. This limitation is important because inquiry-based science education should help students experience science as a collective practice of critique, not merely as individual completion of learning tasks. As a result, the inquiry practices reflected in A1–A15 do not yet fully enable students to experience the epistemic dynamics of science as a social activity shaped by argumentation and revision.

Overall, the findings of this SLR show that inquiry structure in Indonesian biology education remains strongly shaped by confirmation-oriented pedagogy. The reviewed studies contain the procedural components of inquiry, but these components are often directed toward validating expected answers, improving scores, and confirming curricular concepts. When connected with inquiry learning theory, epistemic practice theory, and Popperian falsificationism, this pattern reveals that the main issue is not the absence of inquiry steps, but the limited function of those steps as tools for critique. Therefore, Popperian falsificationism serves as a diagnostic epistemological framework showing that inquiry in corpus A1–A15 remains bounded by positivism: claims are falsificationally safe, confirmation dominates over refutation, progress is reduced to quantitative gains, objectivity is equated with measurement, and classroom inquiry has not yet become a public forum for overturning or improving ideas. These findings provide the conceptual foundation for constructing a more reflective and critical Popperian reorientation, as discussed in RQ3.

Recontextualizing Popper's Falsificationism in Inquiry-Based Biology Education in Indonesia

Transforming Verification-Oriented Inquiry into Reflective–Critical Inquiry from a Popperian Perspective

Most studies in the corpus (A1, A2, A3, A5, A6, A9, A10, A11, A13, A15) indicate that inquiry is practiced primarily as a series of steps culminating in the acceptance of hypotheses once student scores increase. Popper's principle of conjecture–refutation offers a powerful philosophical basis for recontextualizing this approach. Students should not only be taught to formulate conjectures, but also be encouraged to generate hypotheses that are genuinely at risk of being wrong and to design tests that deliberately have the potential to refute them. Within a Popperian framework, experiments are not intended to "find the correct answer," but to identify the limits of students' initial explanations. Hence, teachers can shift classroom prompts from "prove that X is true" toward questions such as "under what conditions does X fail to explain the data?" or "what kind of evidence could overturn your conjecture?" Such moves cultivate scientific critical reasoning (Chmielewski, 2022).

This change in logic is crucial because many studies in the corpus display falsification-safe claims, hypotheses structured to increase and therefore difficult to reject. A Popperian recontextualization requires learning designs that explicitly legitimize the possibility of error, allowing students to internalize that science is not a body of certainties, but an ongoing process of critique.

At the level of classroom practice, falsificationism demands a transformation from proceduralism toward epistemic reflexivity. Studies A7 and A8 include reflection, but it is mainly directed toward improving scores across cycles. For Popper, reflection must also involve evaluating the status of ideas after they encounter anomalies or peer criticism. Scientific knowledge is a public object (World 3) that can be collectively criticized (Popper, 2002). Therefore, inquiry outcomes should be treated as shared objects of argumentation: students present explanations, and the classroom community functions as a testing forum that challenges the coherence and explanatory power of those ideas. Scientific argumentation models and evidence-based discussion support this reorientation by placing critique at the heart of science learning (Gonçalves & Adúriz-Bravo, 2022). Inquiry syntax that has long been linear can be reconfigured into a reflective cycle: conjecture, severe testing, emergence of anomalies, critique and negotiation, and revision of conjectures. Such a transformation positions inquiry not merely as a procedural sequence, but as an epistemic experience aligned with the dynamics of science.

The corpus A1–A15 also shows that objectivity is commonly understood as instrument reliability and statistical significance. Popper offers a different view: objectivity arises from the openness of claims to intersubjective criticism (Popper, 2002). This implies that learning should assess not only final outcomes but also the quality of critique, argumentation, and theoretical revision. In studies emphasizing science process skills (SPS) and scientific literacy (A5, A10, A11, A14, A15), Popper's principles can extend these competencies beyond procedural skills into epistemic skills, such as evaluating arguments, searching for weaknesses in evidence, and proposing alternative explanations. Contemporary science education likewise stresses understanding the tentative nature of scientific knowledge so that students do not fall into numeric dogmatism (Mueller & Reiners, 2023). Consequently, assessment must be recontextualized: evaluation should include the sharpness of questions, the ability to identify counter-evidence, the courage to reject one's own conjectures, and the quality of explanatory revision. In this way, indicators of "scientific thinking" shift from scores to practices of critique.

Strengthening Epistemic Autonomy and Contextualizing Popperian Inquiry within Indonesian Biological Issues

The dominance of guided inquiry across many studies (A2, A4, A6, A7, A10, A11, A12) suggests that students remain strongly dependent on teacher-provided structures. Popper does not reject guidance; rather, he insists that guidance should lead to epistemic autonomy. Students need space to choose conjectures, test claims, and develop meaningful critiques. Contemporary literature shows that successful inquiry depends on well-calibrated teacher guidance, not on abandoning students without direction (Newton & Zeidler, 2020). In the Indonesian context, guided inquiry can be transformed into critical guided inquiry: a model that scaffolds how to critique, detect confirmation bias, distinguish supporting from disconfirming evidence, and construct relevant severe tests. This approach serves as a bridge to a reflective, critical inquiry.

Furthermore, several studies (A5, A14, A15) already incorporate real-world contexts, such as environmental issues, health, and local ecosystems. A Popperian recontextualization can strengthen this potential by treating local biological issues as problem-situations that force students' theories to face severe tests. For Popper, scientific problems are not merely laboratory topics; they are problematic situations that demand students to test, refine, or even replace their initial conjectures. Issues such as air pollution, tropical diseases, climate change, biodiversity conservation, or food security challenges in Indonesia can provide contradictions and anomalies that destabilize students' early theories. By centering inquiry on these problem-situations, students do not merely verify concepts; they learn how concepts operate, or fail to operate, in the surrounding biological realities.

This approach aligns with modern trends in science education that frame inquiry as an epistemic and social practice rather than a narrow laboratory procedure (Nicol, 2021). Integrating Popper's falsificationism in this way can recontextualize inquiry-based biology education from a positivistic-verification paradigm toward a more reflective, contextual, and critical paradigm. The reorientation emphasizes shifting inquiry aims from confirmation to severe testing of conjectures; transforming linear syntax into reflective conjecture–refutation cycles; moving from data objectivism toward critical intersubjective objectivity; strengthening epistemic autonomy through critical guided inquiry; and employing local biological issues as problem-situations that generate anomalies and theoretical revision.

Overall, the integration of Popperian falsificationism enables inquiry to become active not only at the methodological level but also at the epistemological level. This perspective reorients inquiry from a procedure for confirming concepts into a critical process for testing, revising, and improving scientific explanations. In the Indonesian context, it helps position biology learning as a fallible, open, and meaningful activity of critique.

CONCLUSION

This review concludes that inquiry-based biology learning in Indonesia during 2018–2025 predominantly reflects positivistic scientific rationality, where inquiry is implemented as a procedural approach focused on improving quantitative outcomes rather than fostering epistemic critique. The findings reveal consistent verification-oriented practices, data objectivism, and limited opportunities for conjecture and refutation, which constrain students' understanding of the tentative nature of scientific knowledge. These results imply the need to reorient inquiry toward a more reflective–critical approach by emphasizing argumentation, severe testing of ideas, and contextual biological problem-situations. Such a shift is important for guiding teachers, informing curriculum development, and directing future research toward more epistemically meaningful science learning.

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