

INTEGRATING EPISTEMIC COMPETENCE, SCIENTIFIC ARGUMENTATION, AND CRITICAL THINKING: A SYSTEMATIC REVIEW TOWARD EVIDENCE-BASED SCIENCE LEARNING

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ABSTRACT

Epistemic competence, scientific argumentation, and critical thinking are considered key components in the development of evidence-based competence in science learning. However, research on these constructs is often fragmented and rarely examined in an integrated framework. Therefore, this study aims to analyze the relationship between epistemic competence, scientific argumentation, and critical thinking in the science education literature. This study employed a Systematic Literature Review following the PRISMA 2020 guidelines. Articles were identified through Google Scholar using the Publish or Perish software for publications between 2020 and 2026. Based on predetermined inclusion and exclusion criteria, sixteen empirical studies were selected and analyzed through thematic synthesis. The results indicate consistent yet context-dependent patterns showing that epistemic competence shapes how students establish standards for knowledge justification, while argumentation practices provide opportunities to evaluate evidence, construct claims, and engage in reasoning processes. Through these interactions, critical thinking emerges as an outcome of evidence-based reasoning. These findings suggest that epistemic competence, scientific argumentation, and critical thinking operate as an interconnected system underpinning evidence-based competence in science learning. This study highlights the importance of integrating epistemic, argumentative, and critical thinking dimensions within a unified framework to strengthen students' scientific reasoning and science literacy across diverse educational contexts.

Keywords: epistemic; scientific argumentation; critical thinking

INTRODUCTION

Science education in the 21st century requires students to master scientific concepts, also to understand how scientific knowledge is constructed, tested, and applied to explain various natural phenomena. Accordingly, contemporary science education increasingly emphasizes the development of higher-order thinking skills, including critical thinking, scientific reasoning, and an understanding of the nature of scientific knowledge itself (Alzate, 2025; García-Carmona, 2025). Within this context, learning is no longer oriented toward the transmission of factual knowledge, but toward the development of

competencies that enable students to engage with knowledge in a reflective, analytical, and evidence-based manner.

In line with this shift, this study focuses on three interrelated constructs: epistemic competence, scientific argumentation, and critical thinking. Epistemic competence is defined as students' understanding of the nature of knowledge and the processes through which knowledge is constructed and justified (Duncan et al., 2022; Greene et al., 2016). Scientific argumentation refers to the process of constructing claims supported by evidence and reasoning, commonly operationalized through the

claim-evidence-reasoning (CER) framework (Erduran et al., 2004; McNeill & Krajcik, 2009). Critical thinking is conceptualized as higher-order cognitive processes involving analysis, evaluation, and inference based on evidence (Ennis, 2011; Facione, 2015). Although analytically distinguishable, these constructs function in an integrated manner, epistemic competence establishes the standards for what counts as valid knowledge, scientific argumentation operationalizes these standards in practice, and critical thinking enables the evaluation of both the process and the outcomes of reasoning. This interdependence forms the analytical basis of the present review and underscores the importance of examining these constructs in relation rather than in isolation.

From this integrative perspective, critical thinking can be understood as a key cognitive mechanism through which students engage with scientific information. It involves analyzing data and evaluating arguments, and making justified decisions based on evidence and logical reasoning. In science learning contexts, this capability allows students to assess the validity of scientific claims and to distinguish between stronger and weaker arguments (Rahmawati et al., 2025). Instructional approaches such as problem-based learning and STEM-based learning have been widely implemented to support this process, as they explicitly emphasize problem-solving, inquiry, and evidence analysis (Isra et al., 2025; Nale et al., 2023). Empirical studies indicate that such approaches can enhance students' engagement in higher-order thinking processes while simultaneously improving the quality of their scientific reasoning. However, the effectiveness of these

approaches is closely linked to how students understand the nature and justification of knowledge, indicating the relevance of epistemic competence in shaping critical thinking practices.

In this regard, epistemic competence provides the foundational framework that guides how students interpret information and justify knowledge claims. It influences how individuals evaluate sources of knowledge, perceive the certainty of information, and determine the validity of scientific explanations (Alzate, 2025). This competence enables students to recognize that scientific knowledge is provisional and evolves through processes of testing, evidence evaluation, and scientific discourse. As a result, students with more sophisticated epistemic understanding are better positioned to engage in critical evaluation and to construct well-justified explanations. Research consistently shows that such students demonstrate stronger scientific reasoning, as they are more capable of aligning their conclusions with evidence and methodological considerations (Küçükaydın & Ayaz, 2025). This suggests that critical thinking, when grounded in epistemic awareness, becomes more disciplined and scientifically oriented.

Building on this epistemic foundation, scientific argumentation represents the primary practice through which students apply both epistemic standards and critical thinking skills. Scientific argumentation involves formulating claims, selecting and interpreting relevant evidence, and constructing reasoning that explains the relationship between evidence and claims. Through engagement in argumentative activities, students are required to evaluate competing explanations, consider

alternative perspectives, and defend their positions using scientifically acceptable justifications (Kharisma et al., 2025; M Fauziah et al., 2024). The integration of argument-driven inquiry with the scientific method further reinforces this process, as it situates argumentation within authentic scientific practices and has been shown to enhance both the quality of students' arguments and their cognitive performance (Nurjannah et al., 2025). In this way, argumentation functions as a bridge that connects epistemic understanding with the enactment of critical thinking in concrete learning situations.

Consistent with this view, research on scientific argumentation in science education has expanded significantly in recent years, with a growing body of evidence demonstrating its impact on students' reasoning processes. Argumentation based learning environments have been shown to improve students' ability to understand how scientific knowledge is constructed, thereby strengthening their scientific reasoning (Casas-Quiroga & Crujeiras-Pérez, 2020; Cheng & Yang, 2022). Moreover, such environments enhance students' capacity to evaluate evidence and make data-driven decisions, which are central components of critical thinking (Ceyhan et al., 2021; Nussbaum et al., 2024). Active participation in argumentation also promotes reflective thinking, as students must continuously assess the coherence and validity of their own and others' arguments, leading to deeper conceptual understanding.

Further evidence highlights the reciprocal relationship between scientific argumentation and epistemic competence. Students' understanding of how knowledge is constructed directly

influences how they evaluate arguments and determine the credibility of scientific claims (He et al., 2020; Jin & Kim, 2021). At the same time, engagement in argumentation practices can refine students' epistemic beliefs by exposing them to the processes of justification, critique, and revision inherent in scientific inquiry. Additionally, empirical studies indicate that students' epistemic beliefs are associated with the quality of the arguments they produce in scientific discussions (Yang, Bhagat, Brandmo, et al., 2025). These findings reinforce the view that epistemic competence and argumentation are mutually constitutive and jointly shape the development of critical thinking within science learning.



Figure 1. Conceptual framework
(reconceptualized from Demircioglu et al.
(2023))

Despite this growing body of research, a significant limitation remains, such as many studies continue to examine epistemic competence, scientific argumentation, and critical thinking as separate constructs. This fragmentation constrains the development of coherent instructional and assessment frameworks, as it overlooks the inherently integrated nature of these competencies in authentic scientific practice (Kisworo, 2025). As a consequence, curriculum design often struggles to align epistemic understanding

with argumentation-based pedagogy and the assessment of critical thinking. Addressing this issue requires a more systematic synthesis that explicitly captures the interconnections among these constructs across different educational levels.

Responding to this gap, the present study conducts a Systematic Literature Review of science education publications from 2020 to 2026 to analyze the relationships among scientific argumentation, epistemic competence, and critical thinking skills in science learning. Specifically, this study aims to provide a cross-level synthesis spanning primary to higher education and to propose an integrated conceptual model for evidence-based competence in science learning. The review is guided by the following research question: What patterns of conceptualization and empirical relationships among epistemic competence, scientific argumentation, and critical thinking emerge in recent science education literature? The findings are expected to offer a more systematic understanding of the interrelationships among these constructs and to generate conceptual implications for the development of evidence-based competence in science learning.

METHOD

This study uses a Systematic Literature Review (SLR) approach to identify, select, and synthesize empirical evidence regarding the relationship between epistemic competence, scientific argumentation, and critical thinking in science learning. The review procedure follows the PRISMA 2020 guidelines to ensure transparency, traceability, and

replication of the literature selection process.

The literature search was conducted on January 2026 using Publish or Perish (PoP) software with the Google Scholar database for publications from 2020 to 2026. Google Scholar was selected because it indexes a broader range of education journals, including regional publications relevant to science education research. The search strategy utilized a combination of Boolean operators with the query: (“epistemic competence” OR “epistemic cognition”) AND (“scientific argumentation”) AND (“critical thinking”) AND (“science education” OR “science learning”). The search was limited to peer-reviewed journal articles available in full text. Table 1 shows the inclusion and exclusion criteria that limited the article search. The strict inclusion criteria resulted in a focused corpus of studies.

Table 1. The inclusion and exclusion criteria

Criteria	Inclusion	Exclusion
Year of Publication	2020–2026	< 2020
Type of Publication	Peer-reviewed journal article	Proceedings, book chapters, dissertations, purely conceptual articles
Type of Research	Empirical (quantitative, qualitative, or mixed methods)	No empirical data
Context	Science education	Outside the domain of science education
Construct	Examines at least two of the three main constructs	Does not discuss the main constructs operationally
Language	English and Indonesian	Other than English and Indonesian
Accessibility	Full text available	Full text not available

A quality appraisal was conducted to ensure that the included studies met minimum methodological standards. The assessment was guided by the Critical Appraisal Skills Programme (CASP) framework (Singh, 2013), with criteria

adapted for quantitative, qualitative, and mixed-methods research in science education. Five aspects were evaluated, research objectives, research design, data collection, data analysis, and validity of findings. Each criterion was scored dichotomously (1 = met; 0 = not met). Studies scoring ≥ 3 (out of 5) were included, while lower-scoring studies were excluded to reduce bias. The appraisal followed predefined criteria to ensure consistency, and the results informed the interpretation of findings.

Based on the initial identification results, 211 articles were obtained. After removing 65 duplicate articles, 146 articles remained for the screening stage. The screening process through title and abstract review eliminated 66 articles that were not relevant to the focus of science education constructs and contexts. A total of 80 articles were submitted for full-text retrieval, but 41 articles were not fully accessible. At the eligibility stage, 39 articles were comprehensively analyzed and 23 articles were excluded because they did not match the established topic focus and research type. Thus, 16 articles met all the criteria and were included in the final synthesis stage. The process is shown in Figure 2 with the PRISMA flowchart.

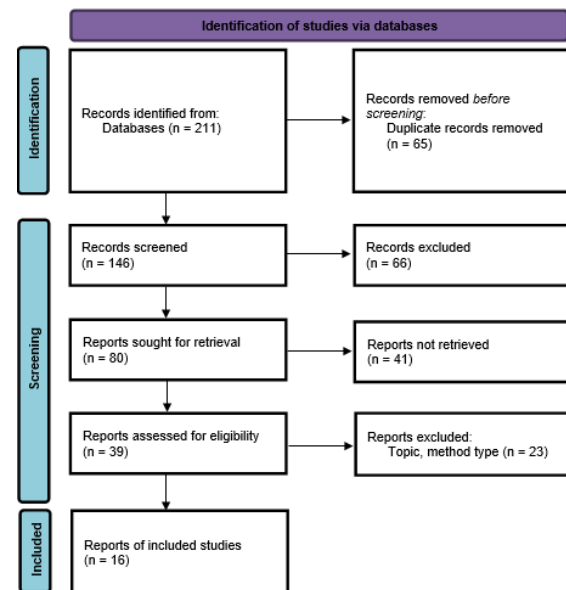


Figure 2. PRISMA flowchart

Data analysis was conducted through thematic synthesis with the following stages: (1) extraction of study characteristics (year, country, education level, research design, instruments, and main findings), (2) coding of relationships between constructs, (3) identification of direct and indirect relationship patterns, and (4) development of a conceptual model of evidence-based competency relationships. The analysis focused on the contribution of epistemic competencies to the quality of scientific argumentation, the influence of argumentation on critical thinking, and the integration of the three constructs in an evidence-based learning framework.

RESULTS AND DISCUSSION

Results

Based on 16 articles that met the inclusion criteria (2020-2026), it appears that research on the relationship between epistemic competence, scientific argumentation, and critical thinking in science education has grown significantly in the last five years. However, the integration of these three constructs into a

single analytical framework remains relevant articles.
 limited. Table 2 summarizes the 16

Table 2. Reviewed research summary

Author & year	Title	Method	Education Level	Conclusion	Contribution in Science Learning
(Casas-Quiroga & Crujeiras-Pérez, 2020)	Epistemic operations performed by high school students in an argumentation and decision-making context: Setrocia's alimentary emergency	Qualitative	High School	Students performed different epistemic operations during group discussions and classroom debates.	Demonstrates that argumentation based on socio-scientific issues encourages evidence evaluation and scientific decision-making.
(Ceyhan et al., 2021)	Probing into Pre-Service Science Teachers' Practices of Scientific Evaluation and Decision-Making on Socio-scientific Issues	Qualitative	Higher Education (Pre-service Teachers)	Pre-service teachers showed varying abilities in evaluating the relationship between evidence and claims.	Highlights the importance of explicitly teaching evidence evaluation in science teacher education.
(Cheng & Yang, 2022)	Analyzing visual attention during TAP learning and the effect of epistemic beliefs on the understanding of argument components	Quantitative	High School	Epistemic beliefs influenced how students understood the components of scientific arguments.	Indicates that epistemic beliefs shape cognitive processes involved in analyzing scientific arguments.
(Tucel Deprem et al., 2023)	Effectiveness of Argument-Based Inquiry Approach on Grade 8 Students' Science Content Achievement, Metacognition, and Epistemological Beliefs	Quantitative	Junior High School	Argument-based inquiry improved conceptual understanding and epistemological beliefs.	Supports the use of argument-based inquiry in science learning.
(Gürkan & Arduç, 2025)	Effect of socio-scientific issue-based argumentation on middle school students' epistemological, and pseudo-scientific beliefs	Quantitative	Junior High School	SSI-based argumentation improved epistemological beliefs and reduced pseudo-scientific beliefs.	Shows that socio-scientific issues are effective in fostering critical scientific literacy.
(He et al., 2020)	The Influence of Context on the Large-Scale Assessment of High School Students' Epistemic Cognition of Scientific Argumentation	Quantitative	High School	Context affects how students demonstrate epistemic cognition during argumentation.	Emphasizes the importance of problem context when assessing students' argumentation abilities.
(Jin & Kim, 2021)	Elementary Students' Epistemic Understandings in Their Classroom Scientific	Qualitative	Elementary School	Elementary students can develop epistemic understanding through classroom	Indicates that scientific argumentation can be introduced from early science

Author & year	Title	Method	Education Level	Conclusion	Contribution in Science Learning
	Argumentation			argumentation.	education.
(Ludwig et al., 2021)	Assessing Secondary School Students' Justifications for Supporting or Rejecting a Scientific Hypothesis in the Physics Lab	Quantitative	High School	Many students struggled to provide evidence-based justifications.	Highlights the need to train students in justification and evidential reasoning.
(Manassero-Mas & Vázquez-Alonso, 2022)	An empirical analysis of the relationship between nature of science and critical thinking through science definitions and thinking skills	Quantitative	High School	Understanding the nature of science is positively related to critical thinking ability.	Suggests that science learning should integrate NOS and critical thinking.
(Nussbaum et al., 2024)	Extending science instruction beyond the CER: Use of critical questions in the argumentation of middle school science students	Quantitative	Junior High School	The use of critical questions improved the quality of students' scientific argumentation.	Proposes a beyond-CER approach to enhance argumentation in science classrooms.
(Puig et al., 2021)	"Fake News" or Real Science? Critical Thinking to Assess Information on COVID-19	Qualitative	High School	Critical thinking helps students distinguish scientific information from misinformation.	Demonstrates the role of science education in combating scientific misinformation.
(Rodríguez-Mora et al., 2022)	An Assessment Using Rubrics and the Rasch Model of 14/15-Year-Old Students' Difficulties in Arguing About Bottled Water Consumption	Mixed Methods	High School	Students experienced difficulties in argument structure and evidence use.	Provides an assessment approach for argumentation using rubrics and the Rasch model.
(Sparks et al., 2022)	Using Critical Integrative Argumentation to Assess Socioscientific Argumentation across Decision-Making Contexts	Mixed Methods	University	Integrative argumentation helped students make evidence-based decisions.	Shows the importance of integrative argumentation in socioscientific decision-making contexts.
(Tian & Osman, 2025)	Enhancing Scientific Argumentation Skills in the Classroom: Strategies for Fostering Critical Thinking in Science Education	Quantitative	General	Argumentation and scientific discussion are effective strategies for promoting critical thinking.	Offers pedagogical strategies to develop critical thinking in science education.
(Yang, Bhagat,	Modeling relationships among	Quantitative	High School	Justification beliefs influence students'	Shows a strong relationship

Author & year	Title	Method	Education Level	Conclusion	Contribution in Science Learning
Brandmo, et al., 2025)	beliefs about scientific knowledge, beliefs about justification for knowing in science, and argumentative reasoning about a climate-related issue			argumentative reasoning ability.	between epistemic beliefs and scientific argumentation.
(Yang, Bhagat, Zhang, et al., 2025)	Analysing the relationships between argumentative reasoning and justification beliefs and the effects of prior experience of scientific information	Quantitative	High School	Prior experience with scientific information affects the quality of argumentation.	Highlights the importance of scientific literacy experience in developing argumentation skills.

An analysis of sixteen articles that met the inclusion criteria indicates that recent research in science learning consistently emphasizes the interconnected roles of epistemic competence, scientific argumentation, and critical thinking skills. Across the reviewed studies, these three aspects are not treated as isolated abilities, but as mutually reinforcing components that support students in understanding how scientific knowledge is constructed, evaluated, and applied in evidence-based decision making.

At the same time, the findings reveal notable inconsistencies in the strength and nature of these relationships. While several studies report strong associations between epistemic beliefs and the quality of scientific argumentation (Cheng & Yang, 2022; Yang, Bhagat, Brandmo, et al., 2025), others identify only moderate relationships or highlight persistent difficulties among students in constructing evidence-based arguments (Ludwig et al., 2021; Rodríguez-Mora et al., 2022). These discrepancies appear to be influenced by variations in measurement approaches as well as contextual factors, including task

design, assessment conditions, and the level of cognitive demand required (He et al., 2020; Rodríguez-Mora et al., 2022). In particular, students with limited prior exposure to scientific literacy practices tend to demonstrate weaker performance in both reasoning and argumentation, suggesting that these competencies develop cumulatively rather than emerging spontaneously (Puig et al., 2021; Yang, Bhagat, Zhang, et al., 2025).

Despite these variations, a consistent pattern emerges regarding the central role of scientific argumentation as a mediating practice. Across multiple studies, engagement in argumentation activities enables students to perform key epistemic operations, such as evaluating evidence, comparing alternative explanations, and assessing the validity of claims. For instance, Casas-Quiroga & Crujeiras-Pérez, 2020 showed that argumentative discussions create opportunities for students to actively negotiate meaning and justification, while Jin & Kim (2021) demonstrated that even at the elementary level, such activities can initiate students' understanding of how scientific knowledge

is constructed through evidence and reasoning. Taken together, these findings suggest that argumentation functions not merely as a communication skill, but as a core mechanism through which epistemic competence is enacted and developed.

Extending this perspective, the relationship between epistemic competence and argumentation is further reflected in how students interpret and construct arguments. Studies consistently indicate that students' beliefs about the nature of scientific knowledge shape their ability to identify and use argument components, including claims, evidence, and reasoning (Cheng & Yang, 2022). Similarly, (Yang, Bhagat, Zhang, et al., 2025) found that students' understanding of scientific justification directly influences the sophistication of their argumentative reasoning. This pattern indicates that argument quality is not solely determined by procedural skills, but is deeply rooted in students' epistemic orientations toward knowledge and evidence. Consequently, students who view scientific knowledge as tentative and evidence-based tend to produce more coherent, structured, and logically grounded arguments.

In parallel, a number of studies highlight the effectiveness of argumentation-based instructional approaches in strengthening these interconnected competencies. Approaches such as argument-based inquiry and socio-scientific issue discussions not only improve students' conceptual understanding, but also promote the development of epistemological awareness and metacognitive regulation (Gürkan & Arduç, 2025; Tucel Deprem et al., 2023). More importantly, these approaches position students in situations where they

must actively evaluate information, justify claims, and respond to alternative viewpoints, thereby simultaneously engaging critical thinking processes. This suggests that well-designed argumentation environments can serve as an integrative space in which epistemic competence and critical thinking are jointly developed through practice.

However, the effectiveness of such approaches is highly dependent on the learning context in which argumentation is implemented. Evidence indicates that task characteristics and assessment formats significantly influence how students demonstrate both epistemic competence and argumentation skills (He et al., 2020). For example, Rodríguez-Mora et al. (2022) found that many students struggle to construct complete arguments, particularly in establishing explicit connections between claims and relevant evidence. These findings underscore that argumentation skills require explicit scaffolding and cannot be assumed to develop automatically through exposure alone. Instead, structured instructional support is necessary to guide students in applying epistemic standards during reasoning processes.

Beyond epistemic competence and argumentation, the reviewed studies also demonstrate a clear linkage to the development of critical thinking and science literacy. Understanding the nature of science has been shown to correlate positively with students' critical thinking abilities, particularly in evaluating the credibility and relevance of information (Manassero-Mas & Vázquez-Alonso, 2022). This is especially relevant in real-world contexts, where students must assess the validity of scientific claims circulating in society, such as during the

dissemination of information related to pandemics (Puig et al., 2021). In this sense, critical thinking emerges as an outcome of the interaction between epistemic understanding and engagement in argumentation practices, rather than as a standalone skill.

Further support for this integrative view is found in studies examining specific instructional strategies, such as the use of critical questioning in argumentation activities. Nussbaum et al. (2024) showed that structured questioning techniques can significantly improve the quality of students' arguments by prompting them to consider evidence more carefully, evaluate reasoning, and reflect on potential weaknesses in their claims. These processes directly engage critical thinking while reinforcing epistemic awareness, illustrating how targeted pedagogical interventions can strengthen the interaction among the three constructs.

When considered across educational levels, the findings indicate that the development of epistemic competence, argumentation, and critical thinking is a continuous process that can begin in early education and progressively evolve through more complex learning experiences. Studies spanning elementary to higher education contexts demonstrate that students are capable of engaging in increasingly sophisticated forms of reasoning when provided with appropriate instructional support. At the higher education level, Sparks et al. (2022) found that students involved in integrative argumentation activities are better able to make rational decisions in socio-scientific contexts, highlighting the long-term impact of these competencies on decision-making processes.

From a practical perspective, these findings collectively suggest that science instruction should explicitly integrate epistemic practices into classroom activities. Effective teaching requires designing tasks that prompt students to justify claims using evidence, evaluate competing explanations, and reflect on the reliability of knowledge sources. Assessment practices need to move beyond factual recall toward evaluating the quality of argumentation and the use of evidence. Professional development programs also play a critical role in equipping teachers with strategies to scaffold argumentation and to guide students in applying epistemic standards throughout scientific inquiry.

Overall, the synthesis of these studies demonstrates that epistemic competence, scientific argumentation, and critical thinking constitute an interdependent system within science learning. Argumentation provides the practical context in which students test ideas and negotiate meaning, epistemic competence shapes how knowledge is interpreted and justified, and critical thinking enables the evaluation of both processes and outcomes. Therefore, integrating argumentation-based approaches within science curricula represents a strategically grounded pathway for fostering students' science literacy and higher-order thinking skills in a coherent and sustained manner.

Discussion

Research Trends

The findings of this review indicate a clear and consistent shift in science education research toward the integration of epistemic competence, scientific argumentation, and critical thinking as

core components of meaningful science learning. Rather than functioning as isolated constructs, the literature increasingly positions these three competencies as an interdependent system that supports students in understanding how scientific knowledge is constructed, evaluated, and applied in evidence-based decision making. This trend reflects a broader movement in science education toward emphasizing not only what students know, but how they justify, evaluate, and use knowledge in authentic contexts.

Within this integrative framework, scientific argumentation emerges as a central pedagogical practice through which epistemic competence and critical thinking are enacted. Across the reviewed studies, argumentation-based activities consistently provide opportunities for students to formulate claims, evaluate evidence, and construct logical justifications within scientific discussions. Approaches such as argument-based inquiry and socio-scientific issue-based learning situate students in contexts that require them to engage in reasoning processes aligned with scientific practices. Importantly, the findings indicate that argumentation does not merely support communication, but functions as a mechanism that organizes cognitive and epistemic processes, enabling students to engage more deeply with the structure and justification of scientific knowledge.

The growing emphasis on epistemic competence highlights its foundational role in shaping how students participate in argumentation and apply critical thinking at the same time. The reviewed studies consistently show that students' beliefs about the nature of scientific knowledge influence how they interpret evidence,

evaluate arguments, and construct explanations. Students who view knowledge as tentative, evidence-based, and subject to revision are more likely to engage in sophisticated argumentative reasoning. This pattern suggests that epistemic competence operates as a guiding framework that determines the quality of both argumentation and critical evaluation, reinforcing the view that the development of higher-order thinking skills in science is inseparable from students' understanding of knowledge itself.

In parallel, the literature demonstrates an increasing concern with the development of critical thinking skills as an essential outcome of science education. However, rather than being treated as a standalone competency, critical thinking is increasingly conceptualized as emerging from students' engagement in epistemic practices and argumentation processes. The ability to evaluate information, assess the reliability of sources, and make evidence-based decisions is consistently linked to students' opportunities to engage in structured reasoning and justification activities. This is particularly relevant in contemporary contexts characterized by the rapid dissemination of scientific information, where the capacity to critically assess claims becomes a central component of scientific literacy.

From a methodological perspective, the reviewed studies employ a range of approaches, including quantitative, quasi-experimental, and qualitative designs. While quantitative studies tend to focus on measuring the effectiveness of argumentation-based interventions or examining relationships among variables, qualitative studies provide deeper insights

into how students construct arguments and develop epistemic understanding during learning processes. This methodological diversity reflects an increasing recognition that the development of scientific thinking involves both measurable outcomes and complex cognitive processes. Furthermore, the literature spans multiple educational levels, from elementary to higher education, indicating that the integration of epistemic competence, argumentation, and critical thinking represents a developmental trajectory that evolves across students' learning experiences. Nevertheless, the concentration of studies at the secondary level suggests that earlier stages of education remain underexplored, particularly in terms of how foundational epistemic and argumentative skills are established.

The Relationship Between Epistemic Competence, Scientific Argumentation, and Critical Thinking

Building on these trends, the findings of this review provide strong support for the conceptualization of scientific argumentation as a bridging mechanism that connects epistemic competence and critical thinking in science learning. Argumentation activities require students to formulate claims, justify them using evidence, and evaluate the strength of reasoning, thereby simultaneously engaging epistemic understanding and higher-order cognitive processes such as analysis, evaluation, and reflection. In this sense, argumentation serves as the practical context in which epistemic standards are applied and critical thinking is enacted.

Importantly, the results also indicate that the effectiveness of this relationship is not uniform, but contingent upon contextual and instructional factors.

Variations in task design, assessment conditions, and students' prior exposure to scientific literacy practices influence how effectively students are able to integrate epistemic understanding into argumentation and, consequently, how well they demonstrate critical thinking. These findings help explain the inconsistencies identified in the reviewed studies, where some report strong relationships among the constructs, while others observe only moderate effects or persistent difficulties in evidence-based reasoning.

Furthermore, engagement in argumentation practices appears to extend beyond classroom reasoning to influence students' ability to evaluate scientific information in broader social contexts. In environments characterized by the digital information, students are increasingly required to assess the credibility of scientific claims encountered outside formal education. The reviewed studies suggest that students who are actively engaged in evidence-based discussion and argumentative reasoning are better equipped to navigate such contexts, as they develop the capacity to critically evaluate information, identify unsupported claims, and make informed decisions. This reinforces the role of argumentation as a key mechanism for linking epistemic competence and critical thinking to real-world scientific literacy.

Research Gaps

Despite the growing body of research supporting the integration of epistemic competence, scientific argumentation, and critical thinking, this review identifies several significant gaps that warrant further investigation. First, although many studies examine relationships between pairs of constructs,

such as argumentation and epistemic competence or argumentation and critical thinking relatively few adopt a fully integrated analytical framework that simultaneously captures the interaction among all three. This limitation contributes to the inconsistencies observed in the findings, as it remains unclear how these competencies dynamically interact within the learning process.

Second, the distribution of research across educational levels remains uneven. The dominance of studies conducted at the secondary education level suggests that the early development of epistemic and argumentative competencies in primary education has not been sufficiently explored. Given that foundational beliefs about knowledge and reasoning begin to develop at early stages, the lack of research in this area limits our understanding of how these competencies can be effectively cultivated over time.

Third, while quantitative and quasi-experimental studies provide valuable evidence regarding the effectiveness of instructional interventions, there is still a need for research that more deeply examines the processes through which students develop epistemic reasoning during argumentation activities. Integrating process-oriented analyses with outcome-based measures would allow for a more comprehensive understanding of how and why certain instructional approaches are effective.

Finally, the geographical concentration of studies in developed countries highlights the need for broader contextual representation. Differences in educational systems, cultural perspectives on knowledge, and pedagogical practices may influence how students engage in argumentation and develop epistemic

understanding. Expanding research to diverse educational contexts, particularly in developing countries, is therefore essential for establishing the generalizability and adaptability of argumentation-based learning approaches.

Overall, the findings of this study reinforce the view that epistemic competence, scientific argumentation, and critical thinking form an interconnected system that underpins evidence-based science learning. Argumentation provides the context in which students actively construct and evaluate knowledge, epistemic competence shapes how knowledge is understood and justified, and critical thinking enables the evaluation of both reasoning processes and outcomes. Consequently, the integration of these three components within science instruction represents a coherent and theoretically grounded approach to developing students' scientific literacy and higher-order thinking skills. This integrative perspective aligns with the aim of this study to advance a model of evidence-based competence in science learning that reflects the complexity of contemporary scientific practice.

CONCLUSION

This systematic literature review reveals conceptual and empirical patterns in the relationship between epistemic competence, scientific argumentation, and critical thinking in science learning across educational levels. Epistemic competence shapes how learners understand knowledge and evaluate evidence, while scientific argumentation provides the context in which students construct claims, justify reasoning, and assess competing explanations. Through these processes, critical thinking emerges as an outcome of

sustained engagement in evidence-based reasoning. The findings indicate that the strength and nature of these relationships vary depending on contextual factors such as instructional design, assessment conditions, and students' prior exposure to scientific literacy practices. This suggests that these constructs are not independent, but form a dynamic and interconnected system that underpins evidence-based competence in science learning. However, most studies continue to examine them in isolation or focus on partial relationships, limiting a comprehensive understanding of how they interact in practice. These findings highlight the need to integrate epistemic competence, scientific argumentation, and critical thinking skills systematically into science curricula and teacher professional development, in order to strengthen students' evidence-based reasoning and decision-making abilities across different educational contexts.

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