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Profile of University Students' Nature of Scientific Knowledge Characteristics and Higher-Order Thinking Skills Revealed through Focus Group Discussions: Toward a Discourse-Based Epistemic Reasoning Theory (DERT)

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Nature of Scientific Knowledge; Higher Order Thinking Skills; Epistemic Reasoning; Discourse Analysis; Discourse-Based Epistemic Reasoning Theory.

ABSTRACT

Background: Epistemic reasoning constitutes a fundamental component of scientific literacy because it reflects how students construct, evaluate, and justify scientific knowledge through discourse.

Objective: This study aims to map the profile of students' epistemic reasoning through the convergence of the Nature of Scientific Knowledge (NOSK) and Higher Order Thinking Skills (HOTS) manifested in argumentative discourse.

Methods: The study employed a descriptive qualitative design involving 16 first-year students in the Biology Education Study Program at the University of Lampung. Data were collected through Focus Group Discussions (FGDs) and analyzed using discourse-based deductive coding across discourse segments.

Results: The findings revealed the dominance of the empirical dimension (24.36%) and HOTS analysis (23.08%), whereas the sociocultural dimension (3.85%), creativity (6.41%), HOTS evaluation (8.97%), and HOTS creation (5.13%) remained relatively low, indicating a tendency toward verification-oriented reasoning.

Conclusion: Based on the convergence of these empirical findings, this study proposes the Discourse-Based Epistemic Reasoning Theory (DERT) as a middle-range theory explaining that the quality of epistemic reasoning emerges from the interaction between epistemic structures (NOSK) and higher-order cognitive operations (HOTS) manifested through argumentative discourse, with implications for the quality of scientific literacy. This study contributes empirically, methodologically, and conceptually to the advancement of biology education.

1. Introduction

Scientific knowledge does not grow as a collection of permanent facts (Erduran & Dagher, 2014; Mueller & Reiners, 2022). It develops through an ongoing process of testing, reasoning, and revision (Lederman, 2007; Hodson, 2009). Science progresses because of new data and new interpretations (Erduran & Dagher, 2014; Allchin, 2011). Therefore, understanding how science works has become an essential need in modern science education (Osborne et al., 2003; Lederman, 2007; Allchin, 2011; Erduran & Dagher, 2014). This understanding serves as the foundation for students' scientific thinking abilities.

The characteristics of scientific knowledge are explained through the concept of the Nature of Scientific Knowledge (NOSK). NOSK describes science as empirical and evidence-based (Badmus & Jita, 2025). Science is also tentative because it can be revised (Khishfe & Jurdak, 2024). In addition, scientific knowledge involves creativity and is influenced by social contexts (Kara & Aslan, 2025).

McComas (2020) emphasizes that NOSK helps students understand the epistemic structure of science more realistically.

Understanding NOSK is directly related to scientific literacy (Badmus & Jita, 2025). Scientific literacy not only requires mastery of scientific content but also the ability to critically evaluate scientific claims. Scientific literacy requires the ability to critically evaluate scientific claims. Students who understand NOSK do not easily accept theories as final truths (Khishfe & Jurdak, 2024). They are able to recognize that science is constructed through argumentation and evidence evaluation. Handayani (2025) shows that understanding the Nature of Science (NOS) contributes to strengthening scientific literacy.

In addition to NOSK, science education also requires higher-order thinking skills. These competencies are known as Higher Order Thinking Skills (HOTS) (Yanti & Thohir, 2024). HOTS encompass the abilities of analysis, evaluation, and creation (Sun, Xie & Lavonen, 2022). HOTS are required to address complex scientific problems that demand higher-level reasoning beyond standard procedural steps. However, the integration of HOTS into science learning still faces implementation barriers (Yanti & Thohir, 2024). Zaiful Shah and Zakaria (2024) emphasize that HOTS practices often stop at simple analytical activities.

NOSK and HOTS are not two separate concepts. NOSK shapes the way students understand scientific knowledge as the result of thinking processes (Badmus & Jita, 2025). HOTS provide the cognitive tools to construct evidence-based arguments (Sun, Xie & Lavonen, 2022). When students understand that theories are tentative, they are encouraged to evaluate evidence more critically (Badmus & Jita, 2025). When students are able to think creatively, they are more likely to develop new scientific hypotheses or solutions (Sun, Xie & Lavonen, 2022). The integration of NOSK and HOTS is key to developing mature academic argumentation skills. Conceptually, higher-order thinking skills also cannot be separated from the depth of content mastery:

> *"The more deeply an individual masters a particular subject matter, the greater the likelihood that the individual will become an expert in that field."* **(Wulandari et al., 2025, p. 845).**

Nature of Scientific Knowledge in Science Education

NOSK is an epistemic concept that emphasizes how scientific knowledge is constructed and validated (Khishfe, 2023). Within the framework of the Nature of Science (NOS) as the conceptual foundation of NOSK, Lederman (2007) and Nakagomi, Kato, and Ogura (2024) state that understanding NOS must encompass both empirical and tentative aspects. This understanding also includes the relationship between scientific theories and laws. In addition, NOSK requires an awareness that creativity plays a role in the development of science (Khishfe, 2023). Sociocultural dimensions also influence scientific practices within the scientific community (Ampatzidis & Ergazaki, 2026). Therefore, several researchers emphasize the importance of clarifying the learning objectives of NOS in the classroom:

> *"Although teaching about the Nature of Science (NOS) is an important goal in science education, there is still debate about how to define NOS and the appropriate pedagogies and approaches for investigating NOS. ... In reporting teachers' and students' responses to research instruments, classroom activities, and assessments related to NOS, researchers have used a variety of different epistemological concepts, including attitudes, views, knowledge, beliefs, and understandings. The proliferation of these concepts has created confusion for both researchers and teachers regarding the goals of NOS instruction. ... An accurate description of how each learning objective relates to truth and the level of justification required has implications for the teaching and assessment of NOS."* **(Brock & Park, 2022, pp. 495–499).**

However, the conceptual debate and diversity of interpretations of NOS, as explained by Brock and Park (2022), indicate that the implementation of NOSK in science education does not always proceed in a clear and well-directed manner. This condition affects the quality of students' epistemic understanding, particularly among university students. University students' understanding of NOSK often has not developed optimally (Schaldach, Gya & Nyléhn, 2025). Many students still perceive science as a finished product. They regard textbooks as the ultimate source of truth. This condition leads to shallow epistemic understanding (Schaldach, Gya & Nyléhn, 2025). The representation of NOS in instruction is also often unbalanced (Khishfe, 2023). Nurazmi and Bancong (2025) show that the dimensions of NOS in learning resources are still incomplete and inconsistent.

Higher Order Thinking Skills and Academic Discussion

Higher Order Thinking Skills (HOTS) have become an important indicator of the quality of 21st-century science education (Shah & Zakaria, 2024). Alrawili, Osman, and Almuntasheri (2020) and Yanti and Thohir (2024) classify HOTS into three main levels: analysis, evaluation, and creation. Analysis focuses on the ability to examine information. Evaluation requires the ability to assess the quality of arguments or evidence. Creation requires the ability to design new ideas and develop innovative solutions. These three aspects constitute the core of scientific thinking in the context of science education. The relationship between HOTS and scientific argumentation is further reinforced by the following research findings:

> *"Higher Order Thinking Skills are closely related to argumentation skills. Argumentation has been claimed to be a more general human process, within which more specific forms of reasoning are embedded. Argumentation skills are required to respond to various scientific issues occurring in today's society, make decisions, and evaluate claims presented through mass media and other sources based on valid and reliable evidence. Argumentation skills are essential to be implemented in learning in order to develop the skills needed in the twenty-first century. Argumentation is a discursive process of constructing claims, providing evidence to support those claims, and engaging in critique. In education, argumentation skills can encourage students to present appropriate facts, data, and theories to support claims regarding a particular issue and to justify them responsibly."* **(Hasnunidah et al., 2024, pp. 352–353).**

The implication is that science education must provide opportunities for interaction that enable students to construct claims, evaluate evidence, and defend arguments rationally. In practice, HOTS do not always emerge automatically (Shah & Zakaria, 2024). HOTS must be stimulated through challenging argumentative activities. One of the most relevant contexts is academic discussion (Wilkinson, Reznitskaya, & D'Agostino, 2023). Discussion encourages students to formulate claims and reasons. Discussion also compels students to defend their ideas in the face of alternative viewpoints (El Majidi, Janssen, & de Graaff, 2021). Ismail et al. (2025) show that HOTS are associated with scientific literacy skills. Thus, academic discussion can serve as a strategic context for observing the actual emergence of HOTS.

Focus Group Discussion as a Context for Revealing Epistemic Understanding

Focus Group Discussion (FGD) is not merely a data collection technique (Nyumba et al., 2018). FGD can be understood as a context for the production of scientific discourse (Bennett et al., 2010). In this forum, students express arguments spontaneously (Bennett et al., 2010). They construct explanations based on concepts and experiences (Nyumba et al., 2018). They also demonstrate their ways of thinking when confronted with epistemic questions (Zetterqvist & Bach, 2023). Krueger and Casey (2015) emphasize that FGD is effective for revealing group perceptions and patterns of argumentation.

Through FGD, the characteristics of NOSK can emerge in the form of discourse segments. These segments may reflect empirical, tentative, or sociocultural orientations (Lederman et al., 2013). At the same time, HOTS can also be observed through patterns of analysis, evaluation, and creation manifested in students' utterances (Firetto et al., 2023). A discourse-based approach provides a more authentic representation than perception surveys alone (Davis & Miyake, 2004). This is because the data originate from real interactions and direct argumentative processes (Bennett et al., 2010). Thus, FGD serves as a relevant context for simultaneously mapping NOSK understanding and HOTS.

Research Gap and Study Novelty

Research on NOS and HOTS has been widely conducted in science education (Okamoto, 2023; Kobayashi, 2022). However, most studies still focus on measurement using test instruments or questionnaires (Nakamura et al., 2023). Many studies also treat NOS and HOTS as separate variables. In addition, NOS studies often emphasize the Nature of Science in general rather than NOSK as a more specific epistemic framework (Okamoto, 2023). As a result, the characterization of students' understanding has not yet fully captured the patterns of thinking that emerge in authentic academic discussions (Kobayashi, 2022).

Another gap is the limited number of studies that use discourse analysis as the primary data source (Nakamura et al., 2023). In fact, discussion-based argumentation represents an authentic form of scientific thinking practice. Students can demonstrate how they evaluate evidence and interpret concepts. They can also reveal whether they understand the tentative nature of knowledge (Tamayo Alzate, 2025). Therefore, this study offers novelty by mapping NOSK based on discourse segments generated through FGD. This study also integrates the analysis of NOSK and HOTS simultaneously through a theory-driven coding approach, with a codebook developed based on the NOSK framework (Lederman, 2007) and the HOTS cognitive levels in the revised Bloom's taxonomy (Anderson & Krathwohl, 2001), following the principles of coding-based qualitative analysis (Saldaña, 2021). This approach is expected to provide methodological and empirical contributions to basic biology education.

Research Objectives and Research Questions

This study aims to map the characteristics of students' Nature of Scientific Knowledge (NOSK) in the context of basic biology learning. The investigation was conducted through the analysis of discourse segments from academic discussions based on Focus Group Discussion (FGD). This study also analyzes how Higher Order Thinking Skills (HOTS) are manifested in these discussions, particularly in the aspects of analysis, evaluation, and creation. Thus, this study provides an empirical description of students' epistemic profiles in scientific argumentation.

The research question addressed in this study is: ***How are the characteristics of students' NOSK understanding reflected through the practice of HOTS in Focus Group Discussion discourse?***

2. Research Methods

Research Design and Epistemological Orientation

This study employed a descriptive qualitative design grounded in the interpretivist paradigm (Creswell, 2014), with the aim of revealing the profile of students' Nature of Scientific Knowledge (NOSK) understanding as manifested through the practice of Higher Order Thinking Skills (HOTS) in academic discursive interactions (Lederman, 2007). This study did not involve instructional intervention but instead focused on exploring the epistemic constructions that emerged naturally within the context of structured discussions.

The analytical approach employed was conceptually oriented discourse analysis, emphasizing patterns of argumentation, reasoning structures, and the epistemic positions articulated by students during the Focus Group Discussion (FGD). The analytical framework was deductively developed based on the dimensions of the Nature of Scientific Knowledge proposed by Norman G. Lederman (2007) and the cognitive levels of the revised Bloom's Taxonomy formulated by Lorin W. Anderson and David R. Krathwohl.

Research Context

This study was conducted in the Biology Education Study Program, Faculty of Teacher Training and Education, University of Lampung, with participants consisting of first-year students from the 2025 cohort who were in the early stage of developing their professional identity as prospective science educators. Data collection was conducted through Focus Group Discussion (FGD) sessions held online using the Zoom platform to ensure participation flexibility while providing comprehensive audio-visual documentation of discursive interactions (Krueger & Casey, 2015).

Participants and Sampling Strategy

A total of 16 students from the 2025 cohort were selected using purposive sampling based on the criteria of active participation in academic discussions and full enrollment status in the study program. This number was considered sufficient to obtain in-depth discursive interactions while achieving data saturation (Lincoln & Guba, 1985). The participants were subsequently divided into two Focus Group Discussion groups (FGD-1 and FGD-2), each consisting of eight students, with each discussion session lasting approximately 60 to 75 minutes.

The Researcher's Role and Reflexivity

All authors in this study served as active researchers.

- **Author 1** served as the Principal Investigator, conceptual designer of the study, director of the theoretical framework, analytical supervisor, final validator, and final decision-maker at every stage of data interpretation and categorization. The entire research design, codebook development, analytical direction, and synthesis of findings were conducted under the coordination and validation of Author 1.
- **Author 3** served as the moderator of FGD-1 as well as the primary coder for the FGD-1 data.
- **Author 5** served as the comparison coder for FGD-1.
- **Author 4** served as the moderator of FGD-2 as well as the primary coder for the FGD-2 data.
- **Author 2** served as the comparison coder for FGD-2.
-

Authors 2 and 3 were also responsible for the technical management of the FGD implementation through Zoom, including organizing the discussion rooms and conducting audio-visual recordings from the beginning to the end of each session. Verbatim transcription was carried out collaboratively by Authors 2, 3, 4, and 5.

To maintain reflexivity, the Principal Investigator deliberately positioned themselves as the director of the analysis without directly intervening in the discussion moderation process in order to minimize authoritative bias in participant dynamics.

Focus Group Discussion Procedure

The FGD was facilitated using three main guiding questions oriented toward exploring the nature of scientific knowledge in biology, namely:

1. Is scientific knowledge certain, or can it change? Explain.
2. What is the role of data and evidence in determining scientific validity?
3. Do differences of opinion among scientists indicate a weakness or a strength of science?

The moderator was responsible for maintaining balanced participation, ensuring an equitable distribution of speaking opportunities, and preventing the dominance of particular individuals (Krueger & Casey, 2015). The moderator did not provide substantive evaluations of participants' responses in order to preserve the natural emergence of epistemic reasoning.

Recording, Transcription, and Data Preparation

All Focus Group Discussion (FGD) sessions were audio-visually recorded using the integrated recording system on the Zoom platform to ensure complete documentation of discursive interactions. The recorded data were subsequently transcribed verbatim while preserving the participants' original linguistic structures in order to maintain the epistemic integrity of their utterances (Kvale & Brinkmann, 2009). The transcription conventions included the notation of pauses, overlapping speech, relevant non-verbal expressions, and inaudible segments. The unit of analysis was defined as a discourse segment based on a unit of meaning, in which each segment represented a coherent argument, conceptual reflection, or form of scientific reasoning. Each segment was assigned a unique identifier (e.g., FGD1-S01, FGD1-S02, and so forth) to ensure analytical traceability. All participant identities were systematically anonymized using the codes P1–P16 to ensure confidentiality and participant identity protection.

As part of the commitment to methodological transparency and the traceability of the analytical process, the entire research dataset, including the anonymized verbatim transcripts, discourse segmentation tables, NOSK and HOTS coding sheets, and the inter-rater consistency calculation documents (Cohen's Kappa), was systematically documented as part of the research audit trail and archived in the open-access data repository Figshare. This archiving was intended to enable independent verification of the analytical procedures, enhance scientific accountability, and support the principle of reproducibility in qualitative research.

Analytical Framework and Coding Procedure

Data were analyzed using a deductive coding (theory-driven coding) approach based on a codebook developed from the conceptual frameworks of Nature of Scientific Knowledge (NOSK) and Higher Order Thinking Skills (HOTS). The NOSK framework comprised five main dimensions: empirical, tentative, theory–law relationship, scientific creativity, and sociocultural, which represent the epistemological characteristics of scientific knowledge as understood in the science education literature (Lederman, 2007). Meanwhile, the HOTS framework comprised three higher-order cognitive categories: analysis, evaluation, and creation, which reflect the complexity of scientific reasoning in processing, evaluating, and constructing knowledge. Each discourse segment was analyzed according to its conceptual alignment with the operational definitions in the codebook, and in certain cases, a single segment could receive double coding if it simultaneously represented relevant NOSK dimensions and HOTS indicators.

The coding process began with the segmentation of the verbatim transcripts into units of meaning representing a single argument, conceptual reflection, or coherent form of scientific reasoning. Subsequently, coding was conducted independently by the primary coder and the comparison coder on a 25% subset of the data to examine the consistency of codebook application (Saldaña, 2021). Inter-rater agreement was calculated using Cohen's Kappa coefficient as an indicator of analytical reliability. Coding discrepancies were systematically discussed until conceptual consensus was achieved, with the Principal Investigator serving as the validator and final decision-maker in category assignment. After analytical consistency was confirmed, the validated codebook was applied to the entire dataset to identify dominant patterns of epistemic understanding and manifestations of higher-order reasoning in Focus Group Discussion discursive interactions.

Table 1. Codebook Analysis of Nature of Scientific Knowledge (NOSK) and Higher Order Thinking Skills (HOTS)

Category	**Code**	**Operational Definition**	**Example of Discourse Segment**
Nature of Scientific Knowledge (NOSK)	Empirical	Arguments emphasizing observation, data, or evidence as the basis of knowledge	"We observed the experiment, so the conclusion can be trusted."
	Tentative	Arguments indicating that scientific knowledge can change with new evidence	"So far this hypothesis is valid, but it could change if new data emerge."
	Theory-Law Relationship	Refers to the relationship between scientific theories and laws	"This law explains the phenomenon, but the theory provides its context."
	Scientific Creativity	Demonstrates novel thinking, unique hypotheses, or innovative ideas	"If we try this approach, we might obtain different results."
	Sociocultural	Arguments emphasizing social or cultural contexts, or human influences on science	"In the school laboratory, the equipment is limited, so this method is adapted."
Higher Order Thinking Skills (HOTS)	Analysis	Discourse segments that examine information, analyze relationships, or compare concepts	"This difference in results occurred because factor X differs from Y."
	Evaluation	Assesses the quality of data, arguments, or theories	"These data are less valid because the measurement method was incorrect."
	Creation	Generates new ideas, develops strategies, or designs experiments	"We can develop a new model based on these findings."

Note: *The NOSK codes were developed based on the dimensions of the Nature of Scientific Knowledge (NOSK) proposed by Lederman (2007), whereas the Higher Order Thinking Skills (HOTS) codes were based on the cognitive levels of the revised Bloom's taxonomy (Anderson & Krathwohl, 2001). This codebook was deductively developed by the researchers based on a review of the current literature and adapted to the context of students' academic discussions. To ensure the validity and credibility of the analysis, the application of the codes was examined through inter-rater reliability and alignment with the operational definitions of each indicator. Thus, this codebook is methodologically defensible and transparent in the qualitative data analysis process.*

Inter-Rater Reliability and Analytical Validation

To ensure the consistency and trustworthiness of the coding process, 25% of the discourse segments from each Focus Group Discussion (FGD) were independently double-coded. Each FGD was analyzed by two independent coders, consisting of a primary coder and a comparison coder, following the coding assignments described in Section 2.4. Inter-rater reliability was assessed using Cohen's Kappa, yielding a coefficient of $\kappa = 0.82$, indicating substantial agreement according to the criteria proposed by Landis and Koch (1977). Any discrepancies between the coders were subsequently resolved through consensus discussions until agreement was reached. Following this process, the Principal Investigator conducted a comprehensive review of all coding decisions, verified the consistent application of the codebook across both FGD datasets, and established the final categorization to ensure conceptual coherence and analytical rigor.

Trustworthiness and Methodological Rigor

The trustworthiness of the study was maintained through:

- Independent coding
- Inter-rater reliability assessment
- Consensus discussions
- Validation by the Principal Investigator
- An audit trail documenting the analytical process (Lincoln & Guba, 1985)
- Examination of category stability across the two FGDs

The final interpretations were drawn based on the recurrence of discourse patterns and the consistency of category emergence across both discussion groups.

Ethical Considerations

All participants provided voluntary informed consent prior to the implementation of the FGD. Participants were informed that the discussions would be recorded for research purposes and that their identities would be anonymized in all publications. The data were securely stored and used solely for academic purposes. This study was conducted in accordance with the research ethics principles applicable to the hosting institution.

3. Result and Discussion

3.1. Result

The FGD analysis focused on the nature of scientific knowledge in biology and the practice of students' Higher Order Thinking Skills (HOTS). The discussions were guided by three main prompting questions concerning the nature of scientific knowledge, the role of data and evidence, and differences of opinion among scientists. To map the characteristics of students' understanding, each discourse segment was analyzed using a codebook deductively developed based on the NOSK indicators (Lederman, 2007) and the revised HOTS taxonomy (Anderson & Krathwohl, 2001), as described in **Table 1** in the Methods section. The quantitative results of the discourse segment distribution are presented in **Table 2**, which subsequently served as the basis for interpreting patterns of argumentation, levels of participation, and students' ability to construct evidence-based academic discourse.

Table 2. Distribution of Students' Discourse Segments Based on NOSK and HOTS Indicators

Category	Indicator / Code	Segment Frequency	Percentage (%)
NOSK	Empirical	19	24.36
	Tentative	10	12.82

	Theory-Law Relationship	12	15.38
	Scientific Creativity	5	6.41
	Sociocultural	3	3.85
HOTS	Analysis	18	23.08
	Evaluation	7	8.97
	Creation	4	5.13
Total	-	**78**	**100.0**

Note: *The numerical values presented in Table 2 are visualized in Figure 1 to facilitate the interpretation of trends in the frequency of NOSK and HOTS discourse segments.*

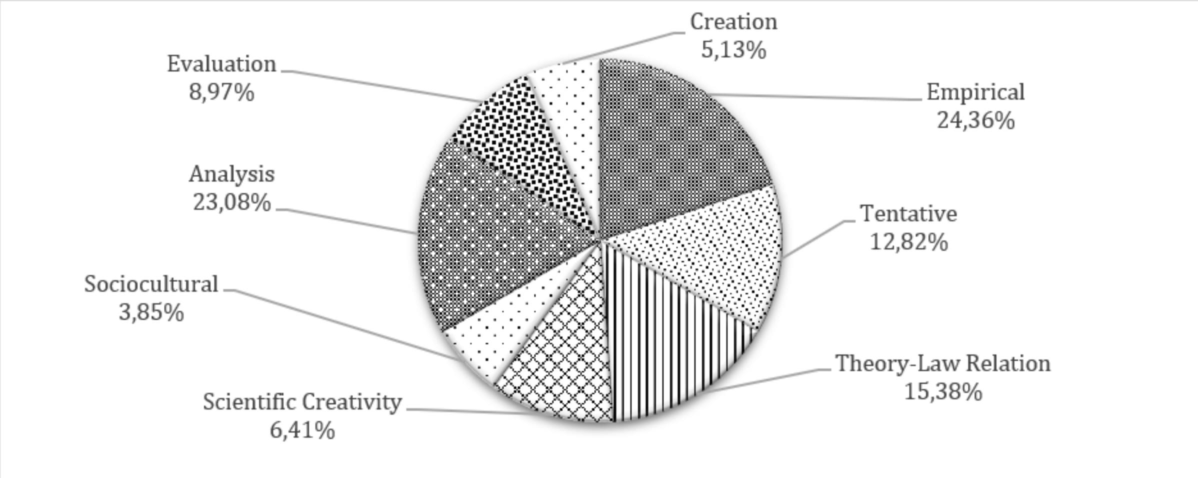

Figure 1. Frequency of Students' NOSK and HOTS Indicators (%)

Based on the FGD analysis, students demonstrated a predominance of Empirical discourse segments (19 segments, 24.36%) and Theory–Law Relationship segments (12 segments, 15.38%), indicating their ability to construct arguments based on evidence and theory. Tentative segments appeared in 10 segments (12.82%), Scientific Creativity in 5 segments (6.41%), and Sociocultural in 3 segments (3.85%), indicating that students' understanding of the tentative nature of science, scientific creativity, and social context remained relatively limited. Some students provided limited responses, for example: *"Biological knowledge is certain because there are already books and correct theories."* This response indicates a tendency to regard theories as final truths without considering the possibility of revision based on new evidence or scientific debate. This pattern suggests that students tend to repeat factual information and basic theories without developing new hypotheses or relating phenomena to social contexts, consistent with the findings of Jumaeni (2024), who reported that the integration of critical reflection and social context can improve understanding of the tentative nature of science.

Understanding NOSK should encompass the flexibility of theories and the ability to evaluate new evidence in order to revise knowledge (Lederman, 2007). In the context of the FGD questions, a more complete scientific response should demonstrate that theories can change as new research emerges, for example, when a scientist discovers evidence that challenges an existing model. Students in the FGD tended merely to mention facts they already knew without relating evidence to interpretation or theory revision. For instance, when discussing the role of evidence in determining scientific validity, several students simply responded: *"If the data match the experiment, then it is correct."* A complete scientific response should include discussion of data consistency, peer review, and how the scientific community evaluates evidence before accepting a theory (Bell & Linn, 2000). In other words, the students' responses remained descriptive and partial, whereas an ideal scientific response demonstrates the interrelationship between evidence, theory, and the dynamic process of knowledge revision. This pattern highlights the need for further guidance so that students can think critically and understand the tentative nature of science more comprehensively.

In discussions concerning the role of data and evidence in determining scientific validity, students largely focused on evidence they found in textbooks or through simple laboratory experiences. An example of a student's response was: *"If the data come from experiments or textbook records, then* *they are correct."* This response reflects an Analysis HOTS discourse segment (18 segments, 23.08%). However, Evaluation (7 segments, 8.97%) and Creation (4 segments, 5.13%) abilities remained relatively low. This finding is consistent with Hogan and Maglienti (2001), who stated that students often evaluate data only partially and rarely relate their findings to broader theoretical contexts. Students' discourse moves were dominated by information-seeking and expositional moves, whereas supportive or sociocultural clarification moves appeared only rarely.

Several expert opinions support these findings. Driver et al. (1996) emphasized that students tend to consider only part of the available evidence while overlooking the broader theoretical context. A similar pattern was observed in this study when students were asked: *"Do differences of opinion among scientists indicate a weakness or a strength of science?"* Students simply answered, *"If scientists disagree, it means someone is wrong."* A more complete scientific response should indicate that differences of opinion are an integral part of the scientific process, serving to test hypotheses, refine theories, and improve the accuracy of knowledge, in accordance with the principles of the Nature of Scientific Knowledge (NOSK) described by Lederman (2007). Thus, the students' responses remained partial and did not yet demonstrate an understanding of the flexibility of theories or the relationship between evidence and knowledge revision.

The analysis of NOSK and HOTS segments also revealed the predominance of discourse moves based on observation and analysis, whereas evaluation and creation skills remained limited. For example, when asked about the role of data and evidence in determining the validity of theories, several students referred only to simple experiments as the basis of their arguments without considering the processes of peer review, independent validation, or theory revision by the scientific community. These responses indicate that students' understanding remained partial and descriptive and did not yet reflect the flexibility of theories or the relationship among evidence, interpretation, and knowledge revision, as emphasized by Lederman (2007) and Hogan and Maglienti (2001).

In discussing differences of opinion among scientists, students tended to interpret disagreement as an error rather than as part of the scientific mechanism for testing hypotheses and refining theories. This analysis is consistent with Driver et al. (1996), who showed that students often overlook theoretical contexts when constructing scientific arguments. These observations indicate the need for instructional strategies that emphasize the combination of Empirical, Tentative, Analysis, Evaluation, and Scientific Creativity segments so that students can develop more comprehensive scientific thinking. Appropriate strategies may include case studies, guided discussions, and open-ended experiments that require the integration of evidence, theory, and social context, thereby enabling students' observational skills, analytical abilities, scientific creativity, and sociocultural understanding to be developed simultaneously.

3.2. Discussion

Empirical Reasoning as an Indicator of Evidence-Oriented Scientific Cognition

The overwhelming dominance of the empirical dimension in this study underscores a crucial fact: students fundamentally perceive evidence and observational findings not merely as complementary elements but as the absolute foundation for the construction of scientific knowledge. This strong dogmatic-positivist perspective is clearly reflected in the following participant statement:

> *"In my opinion, scientific knowledge is obtained through observation, data collection, and systematically conducted research, so that the results can be empirically verified."* **(P2-AY, FGD 1).**

This epistemic stance is not incidental but rather represents an ideological position in which students explicitly establish a clear boundary between science and pseudoscience by emphasizing the indispensable role of data as the absolute criterion of demarcation:

> *"Regarding data as evidence of scientific truth, I agree with everyone that it is absolutely necessary because without data, what we say is merely an opinion."* **(P6-M, FGD 1)**.

These two excerpts provide compelling empirical evidence that students do not merely engage in rhetorical simplification regarding the existence of data. Instead, they position evidence at the highest hierarchical level as the sole source of legitimacy for scientific claims. Therefore, this strong empirical orientation should be deconstructed as a rigid, evidence-centered cognitive reasoning structure.

At this point, the theoretical dialectic becomes particularly compelling. When the conceptualization of evidence-based reasoning proposed by Maghfiroh and Shofiyah (2023) is used to interpret this phenomenon as an inherent cognitive characteristic, a strong convergence emerges with the framework of Boğar (2019), who positions observation and empirical evidence as the primary anchors of knowledge validation. However, the analysis should not stop at passive confirmation. Students' arguments grounded in experimental results indicate the internalization of an active verification practice, as identified by Schlatter et al. (2021).

These three perspectives converge and find their conceptual culmination in the characteristics of scientific reasoning described by Pickal et al. (2023), who define this process as the rigorous mediation of claim testing through objectively verifiable evidence. Through this critical synthesis of cross-referenced literature, the dominance of the empirical dimension in the present findings convincingly indicates that students have progressed beyond passive recognition and have adopted a mature methodological awareness of the importance of evidence-based justification within the structure of their scientific argumentation.

Furthermore, the advancement in empirical reasoning identified in this study serves as a strong indication of the development of a far more complex and dynamic architecture of epistemic justification. The validity of knowledge, as conceived by the students, has evidently shifted from a linear-mechanistic conception to a dialectical process that requires repeated and cumulative testing. This rigid cognitive characteristic is embodied in the following compelling argument:

> *"Data and evidence must be accumulated through repeatedly conducted research, tested multiple times so that they produce mutually reinforcing results*." **(P3-D, FGD 1)**.

This statement reveals a highly advanced student epistemology: the validity of scientific knowledge is critically understood as an entity constructed through a continuous process of verification, fundamentally rejecting claims of absolute and instantaneous truth.

This pattern of critical thinking directly confirms and reinforces the philosophy of science framework radically articulated by Ford (2015), which positions evidence evaluation at the core of all scientific practice. Yet this is precisely where an interesting epistemic tension emerges. On the one hand, the awareness of the necessity for repeated testing demonstrates a strong affinity with the concept of tentative knowledge described by Cofré et al. (2019), namely that science is dynamic and continually subject to examination. On the other hand, this process of repeated data accumulation simultaneously reflects the operation of hypothetical-deductive reasoning, identified by Zimmerman (2007) as the principal driving mechanism of scientific inquiry.

These two perspectives, which appear contradictory—namely the *tentative nature of science* (Cofré et al., 2019) and the *rigor of hypothetical-deductive testing* (Zimmerman, 2007)—actually complement and reinforce one another and are further validated by the characteristics of scientific reasoning in modern science comprehensively elaborated by Pickal et al. (2023). Consequently, the dominance of the empirical dimension in this study should no longer be interpreted merely as a pragmatic tendency toward the use of data. Rather, it represents a small-scale cognitive revolution among students, reflecting the emergence of a well-established culture of evidence-based thinking—a context in which verification is positioned as the highest regulatory mechanism of argumentation as well as the principal compass guiding the development of responsible and accountable scientific literacy.

The Limited Presence of the Tentative Dimension as an Indicator of Weak Epistemic Flexibility

The relatively low occurrence of the tentative dimension reveals a crucial reality: students' understanding of the provisional nature of scientific knowledge has not yet been able to transform the dominant orientation of their reasoning. Indeed, at a superficial level, a small number of students have cognitively recognized that scientific knowledge is not absolute and can change dynamically as evidence develops and technological advances occur. This theoretical position is clearly reflected in the following participant statement:

> *"...... scientific knowledge is also tentative, meaning that it can change or be revised if new evidence is found through subsequent research. ......"* **(P1-AN, FGD 1).**

A similar reflection was expressed by another participant, who acknowledged the limitations of the current validity of scientific knowledge:

> *"...... scientific knowledge is built on the best evidence currently available, not on absolute truth. When new data, more advanced technology, or more accurate methods are discovered, scientific explanations can be revised or refined. ......"* **(P14-W, FGD 2).**

However, critical analysis should not stop at the level of verbal affirmation alone. Although the two statements above appear to demonstrate an awareness that scientific knowledge can change, such change is rather naively understood in a descriptive-mechanistic manner as merely the linear consequence of new data or technological development. An acute epistemic gap emerges here; there is almost no evidence of a more fundamental engagement with scientific controversy, scientific uncertainty, the crucial role of the scientific community in evaluating claims, or the possibility of deeper conceptual revision.

In other words, the tentative nature of science becomes trapped within a reductionist mode of thinking, in which it is understood merely as a process of gradual (cumulative) refinement rather than as an inherent and transformative characteristic of scientific knowledge itself. This tendency provides empirical evidence that students continue to perceive the dynamics of science in a linear and dogmatic manner, a rigid characteristic firmly grounded in naive epistemology, as described by Lederman (2007).

At this point, a critical dialogue across the literature is required to unpack this anomaly. Brock and Park (2022) directly characterize this condition as a clear indicator of the limited epistemic adaptability of individuals in responding to changes in knowledge. This theoretical position is further reinforced by Khishfe (2023), who argues that understanding the tentative nature of science is by no means sufficient if it consists only of a passive acknowledgment that knowledge can change; rather, it must encompass a philosophical understanding of why and how such structural changes occur.

On the other hand, when considered from the perspective of Allchin (2011), an interesting conceptual tension emerges. Allchin (2011) argues that the dynamics of evidence constitute the principal mechanism enabling the revision of scientific knowledge. However, the present findings indicate that students' understanding of Allchin's concept of *evidence dynamics* remains underdeveloped, as they fail to relate it to broader conceptual transformations and instead perceive it merely as the accumulation of data.

Furthermore, this epistemic limitation is exacerbated by discussion responses that rarely demonstrate acceptance of uncertainty as a normal aspect of scientific practice. A form of cognitive resistance emerges, in which students show little tendency to consider alternative explanations or reflect on the possible limitations of the claims they hold. This defensive pattern indicates a limited capacity to tolerate scientific ambiguity.

At this point, a clear conceptual conflict arises with the framework proposed by Barzilai and Zohar (2014), who regard tolerance for ambiguity as an essential component of advanced epistemic cognition. This limitation simultaneously challenges the premise advanced by Zetterqvist and Bach (2023), who position the acceptance of uncertainty as the core of mature epistemic understanding. Consequently, the disconnection between understanding ambiguity and uncertainty produces a destructive cascading effect. This limitation ultimately constrains students' ability to evaluate claims reflectively and undermines their readiness to consider multiple alternative explanations.

This pattern of epistemic limitation precisely confirms the concern described in Tamayo Alzate's (2025) work on epistemic judgment. Therefore, the limited occurrence of the tentative dimension in this study should no longer be interpreted merely as a technical issue resulting from insufficient information. Rather, it represents a structural problem reflecting that students' epistemic flexibility remains stagnant and has not yet developed optimally toward a mature and responsible level of scientific thinking.

Students Conceptions of Theory and Law as Indicators of Awareness of Conceptual Structure

The emergence of the theory–law relationship dimension in the findings reveals a crucial signal: some students have begun to move beyond simplistic views toward an understanding that scientific knowledge is composed of conceptual components with distinct epistemic functions. This structural awareness is explicitly reflected in the following participant statement:

> *"...... scientific knowledge is obtained through data and also through the research process ...... so that the results can be compared and evaluated whenever there are shortcomings. ......"* **(P16-S, FGD 2).**

The statement above indicates a cognitive leap in which students begin to recognize that scientific knowledge is not a collection of isolated, static facts but rather a network of interconnected concepts deliberately constructed through processes of rigorous testing and evaluation. This form of structural awareness directly confirms the development of the conceptual architecture of science as fundamentally described by Lederman (2007).

However, this theoretical legitimacy must be examined more critically through the perspective of Erduran and Dagher (2014). Within their framework, theories fundamentally function as macro-level explanatory tools for uncovering the deepest mechanisms and causal relationships underlying phenomena, whereas laws operate at the level of describing regularities in nature derived from observation and mathematical measurement. Consequently, the ability to distinguish the epistemic functions of theories and laws is not merely a technical skill but a fundamental pillar of conceptual organization in higher-order scientific thinking.

This dynamic perspective regarding the relational nature of knowledge becomes even more evident when students critically associate changes in knowledge with the introduction of new evidence and the rigorous evaluation of previous research findings. This theoretical position is articulated by the following participant:

> *"...... knowledge is also not permanent because it can change or be revised when new discoveries are made. This requires scientists to be careful and objective ...... and willing to evaluate and accept criticism from other research. ......"* **(P15-A, FGD 2).**

This compelling statement reveals that students are beginning to perceive scientific concepts as dynamic entities that are interconnected and open to substantial revision. This progressive mode of thinking serves as a major driving force supporting the development of scientific reasoning, robust argumentative structures, and systematic mechanisms for evaluating evidence, as comprehensively described by Pickal et al. (2023). At this stage, it becomes evident that students are no longer confined to the pragmatic outcomes of knowledge but are beginning to understand and engage with the upstream processes underlying the construction and epistemic development of science itself.

Despite this progress, students' understanding of the conceptual structure of science has not yet fully matured and continues to retain residual dogmatic elements. A cognitive tension emerges in which some student responses remain trapped within a linear mode of thinking; they perceive scientific development as a unidirectional process that invariably culminates in strengthening or refining previously established concepts. This paradox is clearly illustrated in the following argument:

> *"...... because of these differences of opinion, scientists can re-examine their research findings so that they obtain stronger and more accurate answers ......"* **(P13-J, FGD 2).**

Such a cumulative perspective demonstrates that changes in knowledge are still naively understood as conventional processes of accumulation rather than as arenas in which alternative explanations with fundamentally different conceptual functions emerge.

At this point, critical analysis must directly address this misconception. This tendency toward linear thinking closely resembles the classic misconception that positions theories as preliminary stages, or embryonic forms, that supposedly evolve hierarchically into superior scientific laws. This cognitive bias has also been extensively documented by Khishfe (2023). In reality, however, the epistemological relationship is fundamentally different. Theories and laws never exist within a hierarchical or pyramidal relationship but instead coexist with entirely distinct epistemic functions.

The implications of this misconception are profoundly detrimental. It has considerable potential to undermine students' understanding of the nature of scientific inquiry because theories are mistakenly perceived as incomplete or immature forms of knowledge. Within the context of controversial and complex issues in modern biology, such as evolution, molecular genetics, vaccine development, and the climate change crisis, the inability to distinguish the epistemic status of theories and laws is no longer merely an academic issue but a deficiency in scientific literacy that seriously compromises students' ability to evaluate the validity, status, and authority of scientific knowledge in the public sphere.

The Creativity Dimension as a Reflection of Hypothesis Generation and Model-Based Thinking

The relatively limited occurrence of the creativity dimension reveals the crucial fact that this aspect has not yet developed into a dominant characteristic within students' cognitive structures. Nevertheless, a deeper examination of the discussion discourse reveals promising epistemic indications. Students are beginning to reject the simplification of scientific activity as merely a mechanistic process of following laboratory procedures. Instead, they increasingly perceive it as an intellectual endeavor aimed at generating accountable and rational explanations. This perspective is clearly articulated by the following participant:

> *"...... scientific knowledge is obtained through data and also through the research process ...... so that the results can be compared and evaluated whenever there are shortcomings. ......"* **(P12-R, FGD 2).**

This compelling articulation demonstrates that scientific creativity operating within students' thinking is no longer viewed as unrestricted imaginative freedom (epistemic anarchism) but rather as a disciplined capacity to construct explanations grounded in observation and rigorous evaluation.

Within the conceptualization proposed by Erduran and Dagher (2014), creativity is established as an inherent and inseparable epistemic component of all scientific practice. Scientific creativity becomes manifest when individuals are capable of generating logical conjectures or bold hypotheses ready to be tested empirically, as emphasized by Zimmerman (2007). Accordingly, a strong theoretical convergence emerges. Creativity functions as the conceptual bridge connecting raw empirical data with the possibility of much more comprehensive scientific explanations (Pickal et al., 2023). Such thinking reflects the operation of *explanatory innovation*, namely the cognitive ability to establish fundamentally new conceptual relationships without necessarily producing entirely new theories (Kind & Osborne, 2017).

The development of this creativity dimension is also evident when students critically associate the evolution of knowledge with the necessity of reconstructing and expanding existing understanding. This dynamic pattern of thinking is reflected in the following statement:

> *"...... a great deal of knowledge continues to grow and new discoveries continue to be made. Therefore, we cannot simply maintain our previous opinions. ...... when one scientist disagrees with another, they will discuss the issue and conduct new research ...... thereby producing research that is better, more accurate, and more reliable. ......"* **(P12-R, FGD 2).**

This statement reveals that students are no longer resistant to anomalies. Instead, they position disagreement, conflicting findings, and scientific criticism as valuable catalysts for constructing new alternative explanations. The ability to integrate fragmented pieces of information into a coherent theoretical architecture represents the essence of scientific creativity (Pinar et al., 2025; Fauzi et al., 2025).

Epistemically creative individuals categorically reject the role of passive consumers of data. Rather, they are expected to propose plausible alternative mechanisms precisely when the available empirical evidence remains limited (Pinar et al., 2025). Within this domain, creativity functions as an essential instrument for comparing multiple explanatory possibilities while simultaneously predicting the logical consequences of conceptual models (Xu et al., 2025).

Another equally important aspect of scientific creativity is the reconstruction of students' understanding that scientific progress is always intertwined with the capacity to generate new interpretations of longstanding phenomena. This cognitive reality is illustrated in the following narrative:

> *"...... it turns out that bacteria are different and each has its own role; there are beneficial bacteria as well as harmful bacteria. ......"* **(P16-S, FGD 2).**

Although expressed in very simple language, this statement actually reflects students' efforts to construct a conceptual representation of the functional diversity of organisms based on the development of evidence and technological advances. Within science, this mode of thinking functions as a representational anchor driving prediction, reasoning, and the development of further explanations (Allchin, 2011).

Therefore, creativity should not be reduced merely to the generation of novel ideas but should instead be understood as the capacity to reorganize existing concepts in order to produce more meaningful understanding. This characteristic aligns closely with the principle of *scientific imagination within constraints*, a form of scientific imagination that operates freely while remaining firmly constrained by logic and empirical evidence (Lederman, 2007; Pinar et al., 2025).

However, this critical analysis must also acknowledge the less encouraging aspect of the findings. The low frequency of the creativity dimension provides compelling empirical evidence that students' ability to formulate hypotheses and develop explanatory models remains seriously underdeveloped. The majority of student responses remain confined to the comfortable domain of result verification, or passive justification, rather than exploring new theoretical possibilities.

This limitation in scientific imagination has considerable potential to hinder scientific inquiry because students tend to become trapped in the repetitive execution of conventional procedures without demonstrating the confidence to generate critical questions or alternative explanations (Pinar et al., 2025). Consequently, their capacity to formulate hypotheses and construct conceptual models becomes severely restricted. Yet modern biology, including molecular biology, systems ecology, and the regulation of gene expression, depends fundamentally on sophisticated modeling of complex systems.

Furthermore, scientific creativity constitutes a strategic instrument for designing experiments that are effective, efficient, and highly productive (Schiefer et al., 2022). Therefore, these findings serve as a powerful reminder of the urgent need to revitalize epistemic creativity as an integral pillar of science education. Students should no longer be educated solely to verify established knowledge but should instead be equipped with the intellectual capacity to generate, test, and evaluate new scientifically valid explanatory possibilities.

The Deficit of Sociocultural NOSK and Its Implications for Socioscientific Judgment

The findings of this study expose a critical weakness: the emergence of the sociocultural dimension occupies the lowest and most concerning position among all NOSK dimensions. This striking deficit reveals that the dialectical relationship between science and the sociocultural context has not yet permeated students' ways of thinking. Although there are fragments of evidence suggesting that a small number of students have begun to recognize the connection between scientific knowledge and the social environment, this awareness remains confined within highly primitive boundaries. This phenomenon is reflected in the following participant statement:

> *“...... differences of opinion among scientists actually become a strength in research because such differences encourage scientists to conduct new studies and re-examine previous research so that knowledge can continue to develop. ......”* ***(P10-SG, FGD 2).***

A similar perspective was expressed by another participant who attempted to rationalize the function of differing opinions within the academic sphere:

> *“...... differences of opinion can trigger further discussions so that knowledge can become truly valid and continue to be developed in the future. ......”* **(P16-S, FGD 2).**

These two bodies of data indicate that students merely recognize the importance of discussion and interaction among researchers in the progression of science. However, critical analysis must expose the reductionism underlying this perspective. Such social interaction is naively understood only as a technical instrument for improving data accuracy, functioning merely as an epistemic tool, rather than as a manifestation of broader social practices within the scientific community.

A profound discursive void is evident. Virtually no student narratives addressed the roles of values, social norms, the authority of scientific institutions, multidisciplinary collaboration, the rigor of peer review, or the influence of cultural contexts on the production of scientific knowledge. This cognitive limitation demonstrates that science is still perceived rigidly as an objective and sterile product emerging solely from laboratory procedures, rather than as a sociocultural activity involving negotiation among actors and institutional regulatory mechanisms.

This conceptual failure is consistent with the sharp critique advanced by Peters-Burton, Dagher, and Erduran (2023), who exposed the widespread bias in which learners frequently idealize science as a neutral, pure, and isolated activity detached from the dynamics of society. However, when viewed through the perspective proposed by Chan (2025), a substantial epistemic conflict emerges. Chan (2025) argues that a mature and comprehensive understanding of NOSK requires explicit recognition of the social and institutional dimensions of science, including collaboration, value conflicts, and adherence to the norms of the scientific community. The students' inability to adopt this perspective proposed by Chan (2025) demonstrates the existence of a systematic deficiency in sociocultural understanding.

The cascading effects of this deficit in the sociocultural dimension severely undermine the development of students' socioscientific reasoning. At this point, critical dialogue among the literature becomes essential to examine the consequences of this cognitive limitation. Ha, Park, and Song (2022) clearly explain that individuals' capacity to make informed decisions regarding socioscientific issues depends heavily on their ability to integrate scientific evidence with moral values and broader social consequences.

Ironically, however, the students' discourse segments in this study remain stagnant, focusing exclusively on factual information and the validity of empirical data. Discussions concerning deeper ethical implications, assessments of technological risks, scientists' social responsibilities, and the humanitarian consequences of scientific advancement were almost entirely absent. Consequently, the scientific reasoning that develops within students' cognition remains isolated from the dimensions of morality, empathy, and humanity.

Furthermore, this limited understanding of the sociocultural dimension reflects students' inability to recognize how scientific knowledge is collectively constructed within the ecosystem of the scientific community. Essential aspects such as cross-boundary collaboration, rigorous scientific debate, and mechanisms of social validation through peer review, which Hopkin et al. (2025) identify as the heart and an integral component of modern scientific practice, are entirely absent from the participants' responses.

As a result, science is mistakenly perceived as the product of the genius of solitary individuals conducting experiments, rather than as the outcome of compromise and sustained intellectual negotiation within the scientific community. This flawed individualistic perspective consequently obscures and even undermines students' understanding of the science-policy interface, a crucial domain identified by Ren and Yang (2025) as the dynamic arena in which scientists, policymakers, and civil society interact to produce knowledge-based public policy.

This severe limitation poses a genuine threat to students' capacity to make reflective socioscientific judgments regarding contemporary biological issues characterized by conflicting interests, including vaccination campaigns, controversies surrounding genetically modified organisms, environmental health crises, and global climate change mitigation. Therefore, these findings constitute a strong critique while simultaneously emphasizing the urgent need for a fundamental integration between NOSK instruction and the development of socioscientific reasoning. Biology education should no longer be limited to producing students who are merely proficient at evaluating evidence on paper. Instead, it must cultivate thinkers with the intellectual capacity to situate science within the broader contexts of society, ethics, and responsible public policy.

The Dominance of Analytical HOTS as a Product of a Classroom Verification Culture

The findings of this study portray a problematic instructional reality. Students' Higher Order Thinking Skills (HOTS) are overwhelmingly concentrated at the analytical level, whereas the levels of evaluation and creation exhibit pronounced stagnation. This asymmetrical pattern indicates that students are only proficient at identifying relationships among concepts and explaining the foundations of conclusions based on the mechanistic evidence presented to them. This linear cognitive architecture is clearly reflected in the following participant statement:

> *"...... scientific knowledge is obtained through scientific processes, for example experimental results or data analysis. All of these can be considered valid because they are not based on personal assumptions. ...... they are very important in research because knowledge is obtained through data and also through the research process. ......"* **(P16-S, FGD 2).**

This ability to connect empirical data with formal conclusions is reinforced by another participant:

> *"...... data and evidence are the primary basis for determining scientific truth because without strong evidence a statement cannot be accepted as scientific knowledge. ......"* **(P9-SD, FGD 2).**

These two bodies of data provide compelling empirical evidence that students have developed the ability to identify the relationship between evidence and the superficial validity of scientific claims. Such competence indeed constitutes a fundamental component of analytical thinking, namely the capacity to deconstruct complex problems into interconnected elements.

However, the overwhelming dominance of analytical thinking should not be interpreted as a purely cognitive achievement. Rather, it represents the product of a conventional science learning culture that excessively emphasizes rigid procedures and the identification of linear cause-and-effect relationships. Dogan et al. (2023) expose this anomaly through the argument that instructional models overly focused on technical procedures tend to confine students' understanding of science to cookbook science, while simultaneously diminishing the essence of science as a process of inquiry and reasoning. Consequently, students become trained merely to reduce complex problems into simplified components that can easily be matched with available evidence.

Although the investigation conducted by Wang et al. (2022) confirms that structured inquiry enhances scientific literacy as an indicator of HOTS, such intervention unfortunately produces an unintended consequence. The resulting cognitive development tends to evolve into a passive verification-oriented pattern of thinking.

This strong verification orientation becomes particularly evident when students continually emphasize the importance of repeated verification, or procedural replication, rather than critically examining the quality of the evidence itself. This deficiency in evaluative thinking is reflected in the following statement:

> *“...... differences of opinion among scientists actually demonstrate the strength of science because through these differences they discuss and re-examine research findings in order to obtain results that are more accurate and more trustworthy. ......”* **(P9-SD, FGD 2).**

The statement above demonstrates that students possess descriptive analytical abilities concerning the dynamics of scientific development. At the same time, however, it reveals a substantial deficiency. There is no cognitive sensitivity toward evaluating the reliability of evidence in depth, identifying methodological limitations, or considering the possibility of alternative and competing explanations.

This pattern of deficiency is deeply rooted in a biology learning culture that continues to be dominated by the regime of verification laboratories, an academic environment in which laboratory activities are reduced to confirming established theories and scientific doctrines rather than openly exploring natural phenomena (Muhamad Dah et al., 2024). At this point, an important theoretical contrast emerges. Rokos and Zavodska (2020) provide compelling evidence that open inquiry approaches are substantially more effective in developing students' ability to formulate independent questions and generate original hypotheses. In contrast, Chaerunisa et al. (2023) argue that excessively procedural learning activities systematically fail to cultivate critical evaluation of methodological quality and scientific evidence.

Furthermore, the stagnation observed in evaluation and creation is exacerbated by highly structured, predictable, and overly controlled academic assignments. Such uninspiring instructional designs compel students merely to imitate prescribed procedures rather than challenging them to develop flexible and adaptive thinking strategies (Irwandi et al., 2025; Cahyani, Gloria, & Roviati, 2024). Consequently, the reasoning produced by students becomes highly dependent on and compliant with established authoritative sources.

Across the majority of discourse segments, students' arguments repeatedly revolve around textbook concepts without demonstrating any willingness to question existing limitations or consider alternative interpretations. This unfortunate reality reinforces the findings of Jamaluddin et al. (2025) concerning the widespread pathology of textbook-centered reasoning in higher education. Safira and Agustina (2024) likewise confirm that such conventional instructional patterns are indeed effective in strengthening mechanical skills such as concept classification and identification. Tragically, however, they simultaneously eliminate opportunities for students to independently evaluate the validity of evidence or construct new explanatory frameworks.

Therefore, the dominance of HOTS confined to the analytical level in this study should not be interpreted simply as a personal limitation or an inherent characteristic of the students themselves. Rather, it represents a systemic consequence of an academic science culture that is far more comfortable facilitating safe rituals of verification than fostering the revolutionary capacities for critical evaluation and scientific creativity (Muhamad Dah et al., 2024).

Low Evaluative HOTS as an Indicator of Underdeveloped Use of Epistemic Criteria

The findings of this study confirm a concerning cognitive deficit: the emergence of the evaluative aspect (evaluative thinking) remains at a very low level. This reality exposes the fact that the activity of assessing the fundamental quality of scientific knowledge has not yet transformed into a dominant pattern of thinking among students. Indeed, there is a mechanical tendency to reexamine a knowledge claim, but the evaluative process operating in students' minds is generally still trapped in a primitive orientation, namely merely seeking confirmation and reinforcement of final outcomes (confirmatory bias). This paradox of thinking is clearly reflected in the following participant's statement:

> *"...... data and evidence must be accumulated based on research conducted repeatedly, tested several times so that they produce mutually reinforcing and trustworthy results. ......"* **(P3-D, FGD 1).**

The statement above constitutes empirical evidence of how limited the meaning of evaluation is at the student level; awareness of the importance of verification does exist, but evaluative activity is naively reduced to a process of technical repetition merely to obtain consistency of surface-level results.

Far more radical and profound epistemic criteria, such as methodological reliability, the quality of experimental design, interrogation of data limitations, and identification of potential interpretive bias, have not yet appeared to intervene in students' argumentation structures. In fact, there is a strong theoretical demand when viewed through the lens of the literature. Liang et al. (2023) argue forcefully that genuine scientific evaluation must not rely solely on the existence of physical evidence but must also possess the capacity to provide critical justification for the internal quality of that evidence. Students' failure to cross this boundary confirms the academic warning raised by Pieschl and Sivyer (2021), who exposed a cognitive pathology in which learners tend to passively accept information as absolute truth without conducting in-depth evaluations of source authority and the intrinsic strength of the accompanying evidence.

This acute limitation in the use of epistemic criteria becomes even more evident when students perceive anomalies in the form of differing research findings merely as pragmatic instruments for producing more accurate answers. This linear mode of thinking is emphasized by the following participant:

> *"...... with these differences of opinion, scientists can reexamine their research findings so that they obtain stronger and more accurate answers. ......"* **(P13-J, FGD 2).**

This cumulative perspective reveals that students' evaluative orientation is still used only as a means of reinforcing final conclusions, rather than functioning as a critical instrument for examining procedural quality or detecting weaknesses in data interpretation. The evaluative function has been diminished here; almost no discussion segments dared to question methodological reliability, scrutinize potential researcher bias, examine instrument validity, or assess the limitations of generalizing research findings.

This stagnant condition is a strong indicator that the operationalization of epistemic criteria has not yet become established as academic habits of mind at the university level. This phenomenon closely aligns with the findings of Alkış Küçükaydın and Ayaz (2025), who state that although the validity and reliability of evidence are indispensable components of scientific reasoning, they are often absent and disappear during students' evaluation of scientific claims. This systemic limitation in detecting hidden bias and the failure to evaluate source quality are further validated by Pieschl and Sivyer (2021) as major obstacles that hinder the development of scientific evaluation in education.

Therefore, the low occurrence of evaluative HOTS in this study leads to a clear theoretical conclusion: students have indeed begun to evaluate scientific knowledge, but such evaluation is structurally flawed because it is still dominated by a conservative verification-oriented perspective. The use of more complex and robust epistemic criteria, such as reliability, validity, and the deconstruction of potential bias, has not yet developed optimally and continues to experience functional stagnation. Consequently, scientific evaluation as a high-level epistemic skill in students' cognition is demonstrably still at an early stage of development and remains far from being fully mature.

Weak Creative HOTS as a Constraint on Experimental Design and Knowledge Production Skills

The low level of HOTS at the creation level reveals an undeniable fact: students' ability to produce original and radical scientific ideas is still experiencing structural stagnation. Indeed, an examination of the discussion process indicates the presence of cognitive efforts to understand the development of knowledge as a dynamic process that continuously undergoes improvement. This position is reflected verbally in the following participant's statement:

> *"...... scientific knowledge is not fixed, but can change or be revised when new evidence is discovered. Therefore, scientists must continue conducting research and remain open to criticism so that the knowledge produced becomes better and more accurate. ......"* **(P15-A, FGD 2).**

The statement above demonstrates that students have at least recognized the possibility of change in science. However, a critical examination of the text shows that the creativity expressed remains trapped in reductionist thinking; it manifests only as cosmetic refinement of established concepts, rather than as the courage to construct genuinely new and revolutionary alternative explanations. Students' discussions remained stagnant, revolving around the ritual of repeating and reinforcing conventional doctrines rather than exploring innovative conceptual breakthroughs.

This cognitive anomaly is consistent with the sharp critique of Ramadhani and Hardianti (2025), who argue that genuine scientific creativity cannot emerge without instructional designs that actively encourage the exploration of bold but well-grounded ideas. This concerning condition is further supported empirically by the findings of Irdalisa et al. (2024) and Sekar et al. (2024), which reveal that university students still rarely produce original alternative explanations and often struggle to do so. This limitation becomes a major obstacle to the development of productive thinking, even though the creation level represents the core of the entire ecosystem of scientific innovation.

This imaginative stagnation has a direct impact on students' experimental design thinking. When confronted with anomalous situations, their pragmatic way of thinking is clearly reflected in the following statement:

"...... when there are differences in research findings, scientists can conduct further research and develop the study so that they obtain more accurate and trustworthy results. ......" **(P13-J, FGD 2).**

This statement reveals an acute cognitive bias: students' attention is overwhelmingly concentrated on the expected final outcome (product-oriented), while neglecting the architecture of the investigative design (process-oriented), which is actually the driving force that enables such outcomes to be achieved. A serious methodological gap exists here; almost no discourse segment explicitly examined the isolation of research variables, the rigor of experimental controls, treatment manipulation, or the precision of measurement procedures.

In fact, the ability to design experiments systematically and precisely is an essential pillar of experimental design thinking (Yang et al., 2022). The absence of any discussion regarding control, manipulation, and measurement strategies, as strongly criticized by Mafugu (2024), constitutes empirical evidence that students' authentic biological investigation skills have not yet developed optimally. In other words, students are only thinking about what they want to achieve, while remaining unaware of how valid scientific knowledge is actually produced.

This deficit in creative HOTS also weakens students' readiness for inquiry planning. Although several students repeatedly emphasized the importance of data and research, as reflected in the following statement:

"...... data and evidence must be obtained through research conducted repeatedly so that the results reinforce one another and can be trusted. ......" **(P3-D, FGD 1).**

However, critical examination demonstrates that this emphasis remains merely a passive glorification of the existence of physical evidence rather than a tactical and systematic investigative plan. A strategic passivity is evident; there is almost no in-depth discussion regarding data collection strategies, macro and micro observation techniques, or critical consideration of the limitations of laboratory equipment and resources.

In fact, Sapriati et al. (2024) explain convincingly that inquiry planning is the primary foundation for developing accountable scientific investigations, while Mafugu (2024) positions the ability to consider available resources and observational strategies as a defining characteristic of authentic scientific inquiry. These findings strongly indicate that students have not yet understood inquiry as a strategic process for constructing knowledge, but rather merely as an administrative procedure.

Another equally critical systemic weakness appears in the aspect of problem formulation. Interestingly, a cognitive stagnation is evident, as almost no student responses demonstrated the intellectual courage to formulate new research questions emerging from conflicting evidence or situations of scientific uncertainty. Most students remained comfortable acting as passive respondents to questions already presented to them, rather than independently generating research problems.

This disappointing reality supports the findings of Mafugu (2024), who reported that students are often unaccustomed to and reluctant to formulate research questions that are sharp, critical, and well-defined. This stagnant condition also aligns with the perspective of Ramadhani and Hardianti (2025), who argue that scientific creativity cannot flourish if classrooms fail to provide genuine freedom to explore new problems. In the philosophy of science, however, the ability to formulate problems represents the primary gateway to the emergence of highly transformative scientific creativity.

Ultimately, all of these cognitive complications converge on a single philosophical conclusion: students still perceive science rigidly as a finished product of knowledge, rather than positioning it as a dynamic process of knowledge production (Yang et al., 2022). This dogmatic-positivistic perspective is strongly reflected in the following statement:

> *"...... scientific knowledge is obtained through observation, data collection, and research conducted systematically, resulting in knowledge that can be demonstrated empirically. ......"* **(P2-AY, FGD 1).**

The statement above shows that although students understand the procedures of scientific inquiry, science in their minds is still positioned merely as a body of information to be memorized, acquired, and verified. The essential dimension of creating knowledge through bold experimentation, conceptual modeling, and vigorous argumentative debate has not yet penetrated their patterns of thinking.

These findings fully confirm the concerns raised by Sapriati et al. (2024) and Mafugu (2024), who revealed that students frequently fail to perceive science as an activity of producing new knowledge. Consequently, valuable opportunities to generate innovation in biological investigation remain firmly constrained (Ramadhani & Hardianti, 2025), resulting in a complete stagnation of their capacity to design scientific solutions for real-world problems (Irdalisa et al., 2024).

Therefore, these findings constitute a strong critique while simultaneously underscoring the urgent need to transform creative HOTS through open investigation and problem-based inquiry learning models. Students must be encouraged to move beyond their comfort zone as passive consumers of knowledge and transform into resilient, independent, and responsible producers of scientific knowledge.

The Convergence of NOSK and HOTS as a Framework for Mapping Students' Epistemic Reasoning

The comprehensive findings of this study lead us to one fundamental epistemological conclusion: the profiles of Nature of Scientific Knowledge (NOSK) and Higher Order Thinking Skills (HOTS) do not develop independently in isolation, but rather are closely interconnected and converge fundamentally in shaping how students construct and justify scientific knowledge.

The asymmetric pattern between the dominance of the empirical dimension and analytical HOTS, which ironically contrasts with the weak presence of the tentative, sociocultural, evaluative, and creative dimensions, confirms a clear cognitive profile. Students' thinking is confined within the boundaries of relying on surface-level empirical evidence and the linear deconstruction of relationships among concepts, while demonstrating limited capacity for critical evaluation or for producing original new knowledge.

Therefore, the anatomy of students' scientific reasoning should no longer be simplistically reduced to merely an issue of higher-order cognitive ability, but should instead be understood as a direct representation of how they perceive and understand the very nature of scientific knowledge itself. This dualistic epistemic stance is clearly reflected in the following participant's statement:

"...... data and evidence are the primary basis for determining scientific truth, because without strong evidence, a statement cannot be accepted as scientific knowledge. ......" **(P9-SD, FGD 2).**

The corpus above reveals that the operationalization of HOTS among students is strongly governed by how they perceive the criteria for the legitimacy of scientific knowledge. The reasoning that develops in their cognition is characterized by an overemphasis on empirical proof and procedural verification, but is simultaneously weakened by the absence of evaluation regarding the fundamental quality of evidence, as well as by the lack of cognitive space for considering alternative explanations.

This crucial finding demonstrates that NOSK and HOTS operate convergently and simultaneously as architects shaping students' epistemic reasoning. This structural convergence is consistent with the thesis proposed by Shah and Zakaria (2024), which emphasizes that the integral integration of these two constructs is an essential requirement for understanding scientific reasoning comprehensively, accurately, and multidimensionally.

Within this dialectic, NOSK functions as the philosophical compass that guides how the architecture of scientific knowledge is understood (Handayani, 2025), whereas HOTS operates as the driving mechanism that facilitates the processing of that knowledge through higher-order cognitive activities (Yanti & Thohir, 2024). Therefore, the strengths and limitations of students' thinking cannot possibly be explained adequately if only one of these constructs is examined in isolation.

This chain of causal relationships becomes even more evident when examining the structure of the arguments produced throughout the group discussions. Students who strongly glorified the empirical dimension were found to construct arguments based rigidly on the justification of raw data alone. In contrast, their limited understanding of the tentative nature of science and the absence of awareness regarding the sociocultural dimension resulted in underdeveloped argumentative evaluation. This paradox is reflected in the following participant's statement:

"...... with these differences of opinion, scientists can reexamine their research findings so that they obtain stronger and more accurate answers. ......" **(P13-J, FGD 2).**

Although the statement above reflects students' awareness of the need to revise knowledge, its orientation remains critically limited because such revision is directed only toward strengthening the final outcome (confirmatory target), rather than functioning as a critical tool for examining the methodological quality of evidence or considering the possibility of contradictory alternative interpretations.

This pattern of deficit fully confirms the premise proposed by El Majidi, Janssen, and de Graaff (2021), who argue that the anatomy of an individual's argumentative structure is fundamentally shaped by how that individual understands the internal characteristics of scientific knowledge. This conclusion is further reinforced by Mueller and Reiners (2022), who demonstrated that internalizing the tentative nature of science is a primary prerequisite for developing the intellectual openness necessary to revise one's arguments. Conversely, a rigid empirical understanding merely produces an obsessive emphasis on data validity as the sole basis of scientific claims (Cahyani, Gloria, & Roviati, 2024).

At the same time, the limited understanding of the sociocultural dimension causes moral and ethical considerations, public policy implications, and sensitivity to humanitarian contexts to disappear almost entirely from students' arguments (Chan, 2025). As a consequence, the arguments produced by students emphasize only dry logical and factual aspects while failing to reach the level of complex and reflective epistemic justification required by Zetterqvist and Bach (2023).

This critical synthesis across the literature also provides a clear theoretical explanation for the anomaly identified by Alkış Küçükaydın and Ayaz (2025), regarding why students appear highly capable at the level of procedural analysis but suddenly struggle when confronted with demands for in-depth scientific evaluation.

The organic convergence between NOSK and HOTS also epistemically strengthens the position of this study as a breakthrough in discourse-based scientific literacy mapping. Within this methodological framework, group discussion is no longer reduced merely to a passive data collection instrument, but instead is transformed into an authentic dialectical space for tracing and identifying the actual epistemic patterns embedded within students' cognitive structures (Bennett et al., 2010; Firetto, Starrett, & Jordan, 2023).

The NOSK and HOTS profiles generated by this study do not merely present static numerical indicators of conceptual mastery, but instead reveal in detail both the strengths and the vulnerabilities of students' scientific reasoning within their authentic thinking ecosystem.

In line with the perspective of Handayani (2025), the integration of the epistemic aspect (NOSK) and the cognitive aspect (HOTS) reveals structural weaknesses among students that could never be identified using conventional and limited instruments such as multiple-choice tests. Consequently, the map of scientific reasoning constructed in this study should serve as a strategic blueprint for designing the reconstruction and intervention of modern biology instruction through learning models that are strongly grounded in rigorous argumentation, open inquiry, and deep epistemic reflection (Cahyani, Gloria, & Roviati, 2024).

Therefore, the integration of NOSK and HOTS offers a new conceptual framework that is considerably more comprehensive, robust, and relevant for advancing and shaping the future of scientific literacy in modern biology education.

Methodological Contribution of Discourse-Based Deductive Coding to NOSK and HOTS Profiling

This study provides a significant and distinctive methodological contribution through the tactical articulation of discourse-based deductive coding to simultaneously and multiperspectively profile the dimensions of NOSK and HOTS. Radically different from conventional approaches that are generally trapped in dependence on artificial written test instruments, this study boldly treats Focus Group Discussion (FGD) data as the primary corpus to capture, identify, and dissect patterns of scientific reasoning that emerge naturally (spontaneous epistemic reasoning) within the dynamics of student discourse.

The operationalization of segment-based coding in this study plays a crucial role, in which every smallest unit of utterance is mapped specifically and precisely into the matrix of NOSK indicators as well as HOTS levels. The methodological impact is substantial: the chain of cause-and-effect relationships between upstream epistemic dimensions and downstream cognitive processes can be traced and dissected in detail, strand by strand.

This acceleration of rigor is further secured through the use of a rigorous deductive codebook. This instrument compels the entire coding process to proceed systematically, purposefully, and in compliance with a solid conceptual framework blueprint, thereby tightly closing opportunities for arbitrary interpretations that depend solely on researcher intuition or subjectivity.

The transparency and trustworthiness of the interpretation of these qualitative data are further strengthened through the implementation of inter-rater reliability testing. This methodological intervention compels coding consistency to be examined within the academic public sphere in order to minimize bias and reduce the subjectivity of a single researcher in the process of categorizing complex discourse data.

The methodological synergy between segment-based coding, the rigor of the deductive codebook, and objective confirmation through inter-rater verification has successfully produced a qualitative analysis procedure that is far more transparent, accountable, and possesses a high level of auditability.

Thus, the methodology proposed in this study not only succeeds in raising the standard of academic rigor within the landscape of qualitative research, but also provides undeniable empirical evidence that the structural profiles of NOSK and HOTS can be rigidly mapped through active discourse analysis. This strategic contribution radically expands the boundaries of the possible use of discourse-based approaches in contemporary science literacy research, while simultaneously opening promising opportunities for replication across various contexts and levels of modern science education.

Implications for Biology Teacher Education and Epistemic Training

The findings of this study emit a strong signal: a radical restructuring of the competency development curriculum for prospective biology teachers can no longer be postponed. Teacher education must no longer be trapped in the false comfort of focusing solely on the transfer of conceptual mastery and the indoctrination of procedural laboratory skills. More than that, it requires the strengthening of epistemic cognition as the absolute foundation of their future scientific professionalism.

The structural imbalance characterized by the dominance of the empirical dimension and analytical HOTS, which is tragically inversely proportional to the paralysis of the tentative, sociocultural, evaluative, and creative aspects, confirms a paradox. Students' ability to use empirical evidence has indeed developed relatively well, yet their vital capacity to reflect, evaluate, and produce new knowledge remains in a state of serious stagnation.

These findings emphasize the urgency of fostering epistemic reflexivity so that prospective teachers do not merely become laboratory mechanics, but rather individuals who fully understand how scientific knowledge is constructed, validated, and held accountable in the public sphere, as progressively advocated by Foss (2025).

The position of epistemic cognition as a core competency finds its solid conceptual anchor in the work of Hofer (2016), who defines it as an internal belief system regarding the nature of knowledge and the process of knowing that dictates how individuals examine scientific truth. In its practical manifestation, this advanced competency is embodied through the capacity to construct evidence-based argument structures that integrate claims, data, and justification into coherent and indisputable scientific reasoning (Wei et al., 2021).

Another crucial implication of this study demands a paradigm shift in the way scientific inquiry is perceived. Inquiry must no longer be superficially reduced to a sequence of technical procedures (cookbook science), but must instead be restored to its true essence as an active process of knowledge production.

The imbalance demonstrated by students, in which they are proficient in using evidence yet deficient when required to critically evaluate the upstream quality of that evidence, provides empirical evidence that instructional practices must be redirected toward the development of reflective judgment and advanced epistemic awareness.

Within this line of thought, the reflective inquiry model elaborated comprehensively by Pfefferová and Plesch (2025) provides a philosophical foundation that scientific inquiry acquires profound epistemic meaning only when it is positioned as a dynamic activity of knowledge construction.

Such competence will reach its fullest level of maturity only when individuals possess the capacity for reflective judgment, namely a cognitive sharpness that enables them to evaluate the degree of certainty and dissect the boundaries of the validity of knowledge. It is precisely this radical skill that Kindlinger (2021) identifies as the true core of advanced epistemic development. In line with this perspective, Stathopoulou and Vosniadou (2024) reinforce this thesis by positioning epistemic cognition as the highest regulatory mechanism governing the entire process of evidence evaluation and the validation of scientific explanations in the minds of prospective teachers.

The urgency of strengthening this epistemic competence becomes even more evident and critical when prospective teachers are confronted with the reality of contemporary socioscientific issues, which are saturated with information distortion. The ability to critically evaluate complex claims concerning vaccination movements, controversies surrounding genetically modified organisms (GMO), and the global climate change crisis requires the radical cognitive capacity to clearly distinguish between valid scientific evidence and manipulative non-scientific opinions (Chinn, Rinehart, & Buckland, 2014).

Therefore, the transformation of the architecture of modern biology teacher education must be directed toward fostering epistemic literacy through instructional models that are aggressively grounded in critical argumentation, philosophical reflection, and open inquiry. This bold step is taken so that prospective teachers do not tragically end up merely as passive and compliant consumers of knowledge. Instead, they must be equipped to act as resilient and critical evaluators of every wave of scientific information.

This progressive orientation aligns perfectly with the framework of modern science education proposed radically by Nehm (2019), which positions the ability to evaluate knowledge as an absolute

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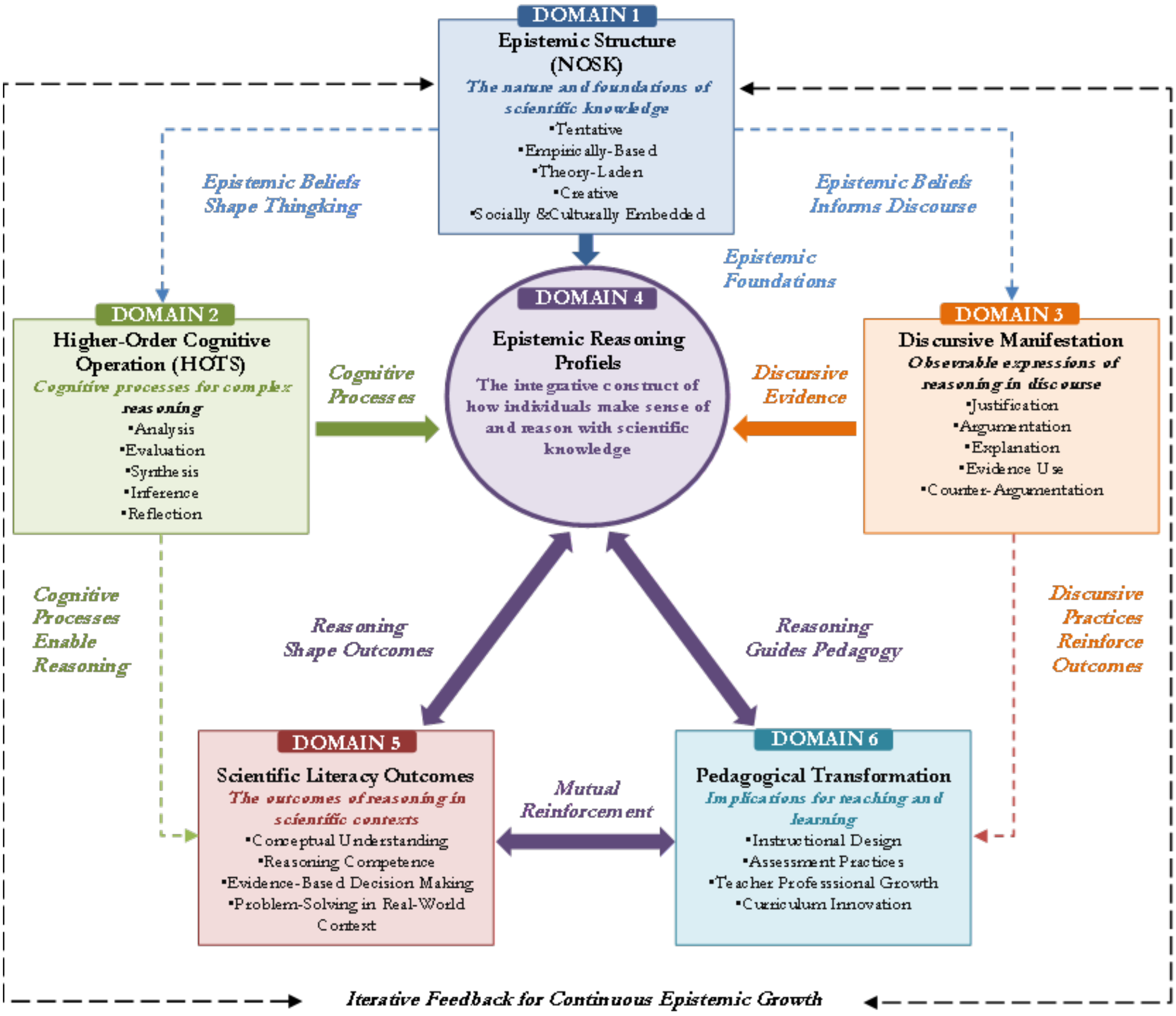
prerequisite for the rational participation of citizens in an increasingly science- and technology-based society.

Proposed Discourse-Based Epistemic Reasoning Theory (DERT)

Based on the convergence of empirical findings through discourse analysis, this study proposes the **Discourse-Based Epistemic Reasoning Theory (DERT)** as a middle-range theoretical framework to explain the mechanism of epistemic reasoning formation in science learning. This theory is built upon the premise that the quality of scientific reasoning is not determined separately by the understanding of the Nature of Scientific Knowledge (NOSK) or by Higher Order Thinking Skills (HOTS). Instead, DERT asserts that scientific reasoning is the product of the systematic interaction between an individual's epistemic structure and the higher-order cognitive operations that they employ. This interaction is manifested through argumentative discourse, which determines the achievement of scientific literacy, thereby establishing epistemic reasoning as a multidimensional construct that integrates epistemic beliefs, cognitive activities, and discursive practices.

DERT extends the perspective of science education by dissecting the convergence of epistemic structures and cognitive operations in shaping scientific literacy through the anchor of argumentative discourse. Group discussion forums function as active spaces of articulation in which these two constructs interact dynamically. Structurally, DERT consists of a series of domains that are hierarchically and recursively interconnected. This recursive nature emphasizes that the profile of scientific reasoning is neither static nor permanent, but can instead be systematically intervened upon, reconstructed, and transformed toward a more mature level through precisely designed pedagogical interventions.



Figur 2. The Architecture of Discourse-Based Epistemic Reasoning Theory (DERT)

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These six domains constitute a conceptual mechanism that explains the interaction between epistemic beliefs and cognitive operations through discursive practices, which in turn generate particular profiles of epistemic reasoning and determine the achievement of scientific literacy. The recursive nature of this framework emphasizes that scientific reasoning profiles are neither static nor fixed, but instead provide opportunities for continuous transformation through appropriately designed pedagogical interventions.

Table 3. Six Domains of Discourse-Based Epistemic Reasoning Theory (DERT)

Domain	**Main Function**
Domain 1. Epistemic Structure (NOSK)	Foundational epistemic beliefs
Domain 2. Higher-Order Cognitive Operations (HOTS)	Cognitive processing mechanisms
Domain 3. Discursive Manifestation	Observable reasoning in discourse
Domain 4. Epistemic Reasoning Profiles	Configurations of epistemic reasoning
Domain 5. Scientific Literacy Outcomes	Educational consequences
Domain 6. Pedagogical Transformation	Developmental and instructional interventions

1) *DERT Theoretical Propositions*

To provide a framework that can be empirically tested in future research, DERT proposes six central theoretical propositions.

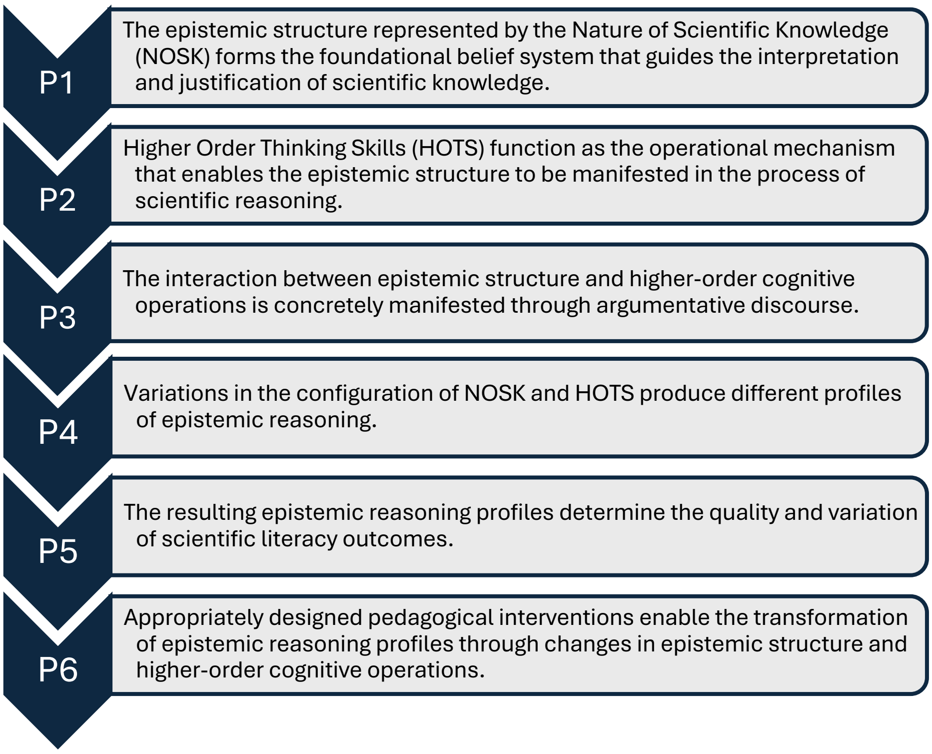

Figure 3. The Theoretical Propositions of Discourse-Based Epistemic Reasoning Theory (DERT)

2) *Explanation of the Theoretical Domains*

a) *Domain 1. Epistemic Structure (NOSK)*

Within the conceptual architecture of DERT, the Nature of Scientific Knowledge (NOSK) is positioned as the epistemic structure that provides the cognitive blueprint for how individuals understand the nature of scientific knowledge. This structure encompasses the empirical, tentative, theory and law, creativity, and sociocultural dimensions. Variations in the understanding of each dimension result in differences in how students interpret the validity of evidence, the evolution of knowledge, the explanatory function of science, the role of creativity, and the relationship between science and its social context. Through the lens of DERT, NOSK is not viewed merely as a collection of concepts about the nature of science. Rather, NOSK constitutes a system of epistemic beliefs that guides how individuals position scientific knowledge and determines the standards by which they accept, evaluate, or revise a claim.

b) Domain 2. Higher-Order Cognitive Operations (HOTS)

Within the DERT framework, Higher Order Thinking Skills (HOTS) are positioned as the higher-order cognitive operations that activate the epistemic structure during the process of scientific reasoning. Cognitive operations encompassing analysis, evaluation, and creation enable individuals to process, organize, and transform knowledge into argumentation, problem solving, and the construction of scientific explanations. Therefore, the quality of scientific reasoning depends not only on what individuals believe about scientific knowledge, but also on the cognitive capacities they employ to operationalize those beliefs across various scientific situations.

c) Domain 3. Discursive Manifestation

The interaction between epistemic structure and higher-order cognitive operations is manifested through argumentative discourse (discursive manifestation). From the DERT perspective, discussion and verbal interaction are regarded as authentic representations of the ongoing process of scientific thinking (thinking in action). Accordingly, the characteristics of claims, the use of evidence, the quality of justification, openness to revision, and the construction of alternative explanations can be used to empirically identify epistemic reasoning profiles. Thus, segment-based discourse analysis gains a methodological foundation that enables epistemic reasoning to be mapped more comprehensively than written instrument-based assessments, which tend to capture only the static products of thinking.

d) Domain 4. Epistemic Reasoning Profiles

The configuration resulting from the interaction between epistemic structure and higher-order cognitive operations produces various epistemic reasoning profiles. Based on the findings of this study, the dominance of the empirical dimension and analytical HOTS, accompanied by limitations in the tentative, sociocultural, evaluative, and creative dimensions, forms a specific pattern conceptualized as Verification-Oriented Epistemic Reasoning (VOER).

Definition of Verification-Oriented Epistemic Reasoning (VOER)

"Verification-Oriented Epistemic Reasoning (VOER) refers to an epistemic reasoning profile characterized by strong reliance on empirical evidence and analytical processing, accompanied by limited evaluative judgment, low epistemic flexibility, restricted sociocultural awareness, and weak creative knowledge production."

VOER represents the first profile successfully identified through this study. Nevertheless, DERT assumes that different configurations of NOSK and HOTS may generate other epistemic reasoning profiles, which remain open for exploration in future research.

e) Domain 5. Scientific Literacy Outcomes

The variations in epistemic reasoning profiles resulting from the convergence of epistemic structure and higher-order cognitive operations ultimately determine the quality of various scientific literacy outcomes. From the DERT perspective, scientific argumentation, scientific inquiry, socioscientific reasoning, biological investigation, and scientific literacy in general are understood as consequences of the epistemic reasoning configurations developed by individuals. Accordingly, scientific literacy is not viewed merely as conceptual mastery or the ability to answer test questions. Scientific literacy is the manifestation of the interaction among epistemic beliefs, cognitive activities, and argumentative practices occurring within the learning context.

f) Domain 6. Pedagogical Transformation

DERT views epistemic reasoning profiles as dynamic and capable of being reconstructed through appropriate pedagogical transformation. Argumentation-based learning, scientific inquiry, epistemic reflection, socioscientific issues, and scientific creativity training are positioned as mechanisms that enable changes in the configuration of NOSK and HOTS toward forms of reasoning that are more reflective, evaluative, adaptive, and productive. Therefore, DERT not only offers an explanatory framework for the formation of epistemic reasoning, but also provides a conceptual foundation for the development of instructional designs oriented toward transforming the quality of scientific literacy.

"As a middle-range theory, DERT offers a theoretically grounded explanation of how epistemic structures and higher-order cognitive operations converge through argumentative discourse to shape scientific literacy. Although developed within the context of biology teacher education, the theory remains open to empirical refinement and extension across diverse science education settings."

Accordingly, DERT shifts the focus of science education research from measuring isolated constructs toward understanding the configuration and interaction among constructs that shape epistemic reasoning. From this perspective, scientific literacy is not regarded as the direct outcome of conceptual mastery or higher-order thinking skills alone, but rather as the consequence of the convergence of epistemic structure, cognitive operations, and discursive practices that develop within learning contexts.

This conceptual shift opens opportunities for the emergence of new research agendas oriented toward mapping epistemic reasoning profiles, exploring the factors underlying Verification-Oriented Epistemic Reasoning (VOER), pedagogical transformation, and the development of epistemic reasoning-based instructional models in science education. Thus, DERT functions not only as an explanatory framework but also as a research programme that provides a conceptual foundation for the future development of science education theory and practice.

5. Conclusion

This study confirms that students' epistemic reasoning profiles are the result of the convergence between epistemic structures represented by the Nature of Scientific Knowledge (NOSK) and higher-order cognitive operations (Higher Order Thinking Skills/HOTS), which are manifested through argumentative discourse. The findings indicate the dominance of the empirical dimension and analytical HOTS, accompanied by the still limited tentative, sociocultural, evaluative, and creative dimensions, thereby forming the Verification-Oriented Epistemic Reasoning (VOER) profile. This configuration indicates that the relatively strong use of evidence and analytical ability has not automatically been accompanied by epistemic flexibility, critical evaluation of the quality of evidence, or the capacity to generate innovative scientific explanations. This study also confirms that the quality of scientific literacy is not determined by conceptual mastery or higher-order thinking skills independently, but rather by the interaction between the two within discursive practices. On this basis, this study proposes the Discourse-Based Epistemic Reasoning Theory (DERT) as a middle-range theoretical framework that explains the systematic relationships among epistemic structures, higher-order cognitive operations, discursive manifestations, epistemic reasoning profiles, and scientific literacy outcomes. Accordingly, strengthening scientific argumentation, epistemic reflection, authentic inquiry, socioscientific issues, and scientific creativity constitutes an urgent necessity for transforming students' reasoning toward forms that are more reflective, evaluative, adaptive, and productive.

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