Review

Reframing Questioning in Science Education for Sustainability: A Transformative Pedagogical and Epistemic Practice

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Reframing Questioning in Science Education for Sustainability: A Transformative Pedagogical and Epistemic Practice

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Abstract

Questioning is widely recognised as a key dimension of learning in science education, yet learner questioning has often been treated as a secondary aspect of classroom participation rather than as a central pedagogical and epistemic practice. This article offers a conceptual examination of questioning in relation to science education for sustainability, informed by a critical interpretive engagement with literature on questioning, participation, classroom dialogue, engagement, and science education. It argues that science education for sustainability requires more than the transmission of scientific knowledge, calling instead for pedagogical spaces in which learners can engage with complexity, uncertainty, interpretation, and the ethical and social dimensions of socio-scientific issues. The article's main contribution lies in repositioning learner questioning as a central condition of science education for sustainability and in showing that questioning is shaped not only by knowledge and motivation, but also by participation, hesitation, silence, and broader dynamics of voice, legitimacy, and power. In this perspective, fostering questioning becomes essential to more inclusive, dialogic, reflexive, and transformative approaches to science education for sustainability. The article further argues that fostering questioning in this way contributes directly to the educational ambitions embedded in SDG 4, SDG 13, and SDG 16 - making questioning-centred pedagogy not merely a methodological choice, but a condition for more democratic, just, and transformative science education for sustainable development.

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1. Introduction

Contemporary sustainability challenges such as climate change, biodiversity loss, environmental degradation, and socio-scientific controversy require forms of science education, and more broadly STEM (Science, Technology, Engineering, and Mathematics) education that go beyond the transmission of stable knowledge. If science education, and more broadly STEM education, is to contribute meaningfully to more sustainable futures and the achievement of the United Nations' Sustainable Development Goals (SDGs), they must support learners in engaging with complexity, uncertainty, ethical tension, and public debate [1,2]. This is particularly relevant in relation to three SDGs whose educational dimensions are directly implicated in the argument developed in this article: SDG 4 (Quality Education), which through Target 4.7 calls for inclusive and equitable learning environments that foster critical thinking, global citizenship, and education for sustainable development; SDG 13 (Climate Action), whose Target 13.3 mandates improving education and human institutional capacity on climate change mitigation, adaptation, and early warning; and SDG 16 (Peace, Justice and Strong Institutions), which through Target 16.7 links the cultivation of participatory, inclusive, and representative governance to the formation of critically engaged citizens.

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A science education that merely transmits scientific content without cultivating the capacity to interrogate, deliberate, and participate cannot adequately serve these interconnected ambitions.

Achieving such goals also requires helping learners develop the critical and questioning dispositions needed to navigate a digital environment saturated with misleading, partial, and sometimes false information. This is especially important given that children and adolescents are exposed from increasingly early ages to online content whose credibility cannot be taken for granted. In this sense, transformative education for sustainability involves not only scientific understanding, but also the capacity to interrogate claims, assess evidence, recognise uncertainty, and respond critically to information encountered in everyday life [2–4].

This broader educational orientation is reflected in work on education for sustainable development and on socio-scientific issues in science education. Recent literature shows that sustainability-related STEM education increasingly emphasises interdisciplinary thinking, real-world problem solving, argumentation, and critical engagement with socially relevant scientific issues, rather than the mere acquisition of decontextualised content [5–7]. From this perspective, learners are not simply expected to know more science, but to engage with STEM disciplines as fields of interpretation, judgement, and action in relation to complex sustainability questions. While sustainability is often framed within broader STEM agendas, this article focuses primarily on science education, where the pedagogical and epistemic significance of learner questioning has been more extensively developed in the literature. The argument advanced here nevertheless has broader relevance for sustainability-oriented STEM education.

Within such a framework, questioning becomes especially important. Questions make uncertainty visible, open conceptual spaces, invite dialogue, and create opportunities for critique, clarification, and participation. In science education, learner-generated questions have long been recognised as an important resource for meaningful learning and inquiry, helping to reveal prior understandings, misconceptions, interests, and emerging forms of reasoning [8,9]. In contemporary contexts, however, questioning matters not only because it supports learning, but also because it helps learners move beyond passive reception of information and develop a more critical relationship with knowledge claims, including those circulating beyond formal educational settings.

Yet, despite its importance, learner questioning has often been studied in fragmented ways. Much of the literature has focused either on teacher questioning or on learner participation more broadly, without fully integrating questions of voice, legitimacy, and power into analyses of who asks, who remains silent, and under what conditions questioning becomes possible. Even when research addresses participation, it frequently privileges observable behaviour, such as frequency of contributions or willingness to speak, over the relational and institutional conditions that shape whether learners feel entitled to intervene publicly. This fragmentation is particularly limiting in the context of science education for sustainability, where meaningful engagement depends not only on understanding scientific content but also on being able to interrogate complexity, ambiguity, and contested futures.

Moreover, research on classroom participation consistently suggests that learners are not equally positioned to ask questions. Confidence, fear of negative evaluation, classroom climate, teaching format, and broader social dynamics all shape participation patterns, including questioning and silence. Emerging research also points to gendered differences in in-class questioning and to the unequal distribution of discursive space in educational settings [10]. Critical perspectives on pedagogy and language further remind us that participation is never neutral: speaking in educational contexts is closely tied to recognition, authority, and symbolic power [11,12]. Seen in this light, questioning is not only about curiosity or cognition; it is also about whether learners are recognised as legitimate contributors to meaning-making.

This article addresses these issues by offering a critical review of learner questioning in relation to science education for sustainability, while considering its broader relevance for sustainability-oriented STEM education. It brings together literature on questioning, participation, silence, and classroom interaction, and re-examines these strands through a lens that foregrounds inquiry,

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legitimacy, and epistemic participation. Rather than treating questioning solely as an individual skill or a pedagogical technique, the article conceptualises it as a situated practice through which learners negotiate visibility, authority, and belonging in educational contexts shaped by sustainability concerns.

By synthesising and reinterpreting this literature, the article argues that fostering questioning in science education for sustainability requires more than encouraging participation or using interactive teaching methods. It also requires attention to the pedagogical and relational conditions under which learners feel able to ask, hesitate, challenge, and remain productively uncertain. This is particularly important in science education for sustainability, where transformative pedagogies must create space not only for answers, but also for doubt, controversy, and critical engagement.

This article is structured around the following questions:

1. How has learner questioning been conceptualised across research on science education and related educational contexts?
2. What does this literature suggest about the role of questioning in science education for sustainability?
3. What pedagogical and relational conditions shape whether learners can ask questions and engage critically with complex sustainability issues?
4. How might silence and non-questioning be reinterpreted beyond deficit-based accounts of participation?

The following sections address these questions through a critical synthesis of the literature.

2. Conceptual and Analytical Approach

This article is a conceptually oriented review paper grounded in a critical interpretive review of literature. Rather than mapping a delimited corpus of empirical studies through systematic review procedures, it engages selectively and argumentatively with existing scholarship in order to develop a conceptual contribution: the repositioning of learner questioning as a central epistemic and relational condition of science education for sustainability. This approach is appropriate when the aim is not to measure the prevalence of findings across studies, but to identify conceptual connections across bodies of literature that are rarely brought into dialogue with one another. As such, the article follows the logic of interpretive synthesis [13], in which the analytical movement is guided by the construction of an argument rather than by the exhaustive coverage of a field.

The literature informing this article was identified through structured exploratory searches conducted across Scopus, Web of Science, and ERIC (Education Resources Information Center). Search terms included combinations such as “learner questioning” AND “science education”, “classroom participation” AND “epistemic agency”, “student questioning” AND sustainability, “pedagogy of silence” AND “sustainability education”, and “socioscientific issues” AND “dialogic teaching”. The resulting corpus spans foundational theoretical works, including contributions from constructivist and sociocultural traditions, and contemporary empirical and conceptual research on science education, sustainability education, and classroom participation. The inclusion of foundational works [14,15] is deliberate: they provide the theoretical grounding without which the more recent literature on questioning and epistemic agency cannot be adequately contextualised. The inclusion of critical theoretical contributions on language, power, recognition, and epistemic injustice [11,12,16] is equally deliberate. These works were not included as generic background references, but because they provide conceptual resources for interpreting more recent research on questioning, participation, silence, and legitimacy in educational contexts. Rather than treating foundational and contemporary sources as separate bodies of literature, this review brings them into dialogue: the former offer the analytical vocabulary through which the pedagogical and epistemic significance of learner questioning can be understood, while the latter show how these dynamics emerge in current debates on science education for sustainability. The criterion guiding inclusion was conceptual relevance: sources were retained when they offered theoretical depth or empirical insight into the

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relational, epistemic, and pedagogical dynamics of questioning, silence, and participation in educational contexts. Consequently, the corpus should be read as analytically curated rather than comprehensive, with the aim of supporting conceptual development rather than mapping the full empirical landscape of research on questioning and participation. While the search strategy was not designed to be exhaustive in a systematic review sense, it prioritised conceptually rich contributions published mainly over the last two decades, complemented by earlier foundational works where these remained central to current debates.

The analytical orientation of this article is grounded in a sociocultural and critical perspective on learning and participation. From this standpoint, classroom interaction is never epistemically neutral: it is shaped by relations of power, recognition, and legitimacy that determine whose voices are heard, whose questions are taken seriously, and whose hesitations are interpreted as meaningful. This perspective draws on critical traditions in pedagogy [11,12,16] and on sociocultural theories of learning [14,17] to read the literature on questioning not merely as a record of individual cognitive behaviours, but as evidence of socially situated epistemic practices. It is further informed by the concept of epistemic injustice [16], which helps illuminate how credibility, recognition, and legitimacy are unevenly distributed within educational interaction. From this perspective, learner questioning cannot be understood solely as an individual cognitive or participatory act, but must also be examined in relation to the social conditions that enable some voices to be heard and taken seriously, while others are marginalised, dismissed, or silenced. It also reflects a transformative understanding of education for sustainability, in which the goal is not only the transmission of scientific knowledge, but the cultivation of learners capable of critical inquiry, ethical deliberation, and active participation in socio-ecological futures.

This orientation organises the argument developed across four interconnected analytical dimensions, each corresponding to one of the guiding questions introduced in the preceding section. The first examines how learner questioning has been conceptualised in science education research, and what this literature reveals about its pedagogical and epistemic functions (Section 3). The second addresses why questioning occupies a particularly central role in science education for sustainability, given the complexity, uncertainty, and ethical dimensions of the issues it engages (Section 4). The third analyses the pedagogical, relational, and social conditions that enable or constrain learner questioning in classroom contexts (Section 5). The fourth reinterprets silence and non-questioning beyond deficit-based accounts of participation, proposing a more interpretive and contextually sensitive reading (Sections 5 and 6). Taken together, these dimensions develop the central argument that questioning should be understood not as a peripheral classroom behaviour, but as a constitutive condition for more inclusive, dialogic, and transformative approaches to science education for sustainability.

3. Questioning as a Pedagogical and Epistemic Practice in Science Education for Sustainability

Questioning occupies a central place in science education because it supports inquiry, interpretation, and the active construction of knowledge. Within constructivist and sociocultural perspectives, questions are not merely requests for clarification, but forms of engagement through which learners identify uncertainty, test ideas, connect concepts, and participate in meaning-making. In this sense, questioning can be understood as an epistemic practice: it signals not only doubt, but also curiosity, interpretation, and the desire to extend, refine, or challenge understanding [9,14,15].

In science education, learner questioning has long been associated with meaningful learning. Questions can reveal prior conceptions, expose conceptual difficulties, and create opportunities for deeper cognitive engagement. They also provide teachers with insight into learners' thinking, making questioning relevant to formative processes of teaching and assessment [9,18]. However, the significance of questioning extends beyond its cognitive value. To ask a question is also to position oneself in relation to knowledge: to speak, to intervene, and to claim a degree of epistemic presence within the classroom [8,9].

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This broader understanding becomes especially important in science education for sustainability. Sustainability-related issues are rarely reducible to stable or uncontested facts. They often involve uncertainty, complexity, competing forms of evidence, ethical tensions, and disagreements about desirable futures. In such contexts, learning cannot be framed simply as acquiring correct answers. It also involves learning to engage with ambiguity, examine assumptions, assess claims critically, and participate in discussions where scientific, social, and moral dimensions intersect [2,3,5,19].

From this perspective, questioning is closely connected to scientific literacy understood in an expanded sense. It is part of learning how to interpret information, evaluate evidence, distinguish between stronger and weaker claims, and respond thoughtfully to knowledge circulating across educational, media, and everyday contexts. In science education for sustainability, questioning helps learners move beyond the passive reception of information and towards more critical forms of engagement with socioscientific issues. It is therefore not only a support for learning science, but also a condition for engaging with science as a field of interpretation, judgement, and public relevance [3,4,6].

Questioning is also significant because it contributes to participation. In sustainability-oriented science education, learners are expected not only to understand issues but also to deliberate, discuss, and imagine possible responses. Yet this requires more than content knowledge. It requires opportunities to speak, to hesitate, to explore uncertainty, and to formulate questions that may not yet be fully formed. A pedagogical environment that values questioning can therefore help create the conditions for more dialogic and participatory forms of science learning, particularly in relation to socioscientific issues and sustainability-related controversy [6,19,20].

At the same time, questioning should not be romanticised as if it emerged naturally whenever learners are interested. Research consistently suggests that questioning is shaped by pedagogical design, classroom norms, and learners' sense of confidence and legitimacy. Whether learners ask questions depends not only on what they know, but also on whether they feel authorised to speak, whether uncertainty is treated as intellectually productive, and whether their contributions are received as meaningful. This is particularly relevant in sustainability-related learning, where significant questions may be exploratory, uncomfortable, or disruptive of taken-for-granted assumptions.

Questioning should therefore be understood not simply as a technique for increasing engagement, but as a pedagogical and epistemic practice central to more inclusive, reflexive, and transformative forms of science education for sustainability. It is through questioning that learners can engage with complexity rather than avoid it, enter dialogue rather than merely receive information, and begin to see themselves as participants in the interpretation of sustainability-related issues rather than as passive recipients of established knowledge. The following section develops this argument further by examining why sustainability-oriented science education depends especially strongly on questioning-centred pedagogies.

4. Why Sustainability Requires Questioning-Centred Science Education

4.1. Complexity and Systems Thinking

Sustainability-related issues are characterised by complexity. Climate change, biodiversity loss, pollution, food insecurity, and energy transitions cannot be understood through linear cause-and-effect reasoning alone. They involve interconnected systems, feedback loops, multiple scales of analysis, and interactions between ecological, technological, social, economic, and political processes. For this reason, science education for sustainability requires pedagogical approaches that help learners move beyond simplified explanations and engage with relational and systemic forms of understanding [2,5,20].

Work on sustainability competencies has consistently highlighted systems thinking as a core dimension of education for sustainability, precisely because contemporary problems exceed

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disciplinary fragmentation and demand the capacity to understand interdependence, unintended consequences, and dynamic relationships across domains [3,5]. Questioning is central to this process because it enables learners to explore connections, identify tensions, and examine how different dimensions of a problem interact. Through questioning, learners can move from isolated facts to more systemic interpretations: what is connected to what, what consequences emerge across scales, and what assumptions underlie apparently straightforward solutions.

A questioning-centred approach is particularly important because complexity can easily become pedagogically paralysing. When learners are confronted with large-scale global problems, there is a risk that knowledge is presented as overwhelming, abstract, or fixed. Questioning creates openings within that complexity, allowing learners to enter difficult issues through exploratory reasoning and progressive refinement rather than through the expectation of immediate mastery. In this sense, questioning supports systems thinking not only by prompting inquiry, but also by helping learners resist reductive or fragmented understandings of sustainability challenges.

4.2. Uncertainty and Evidence

A second reason why sustainability requires questioning-centred science education is that sustainability issues are deeply entangled with uncertainty. Scientific knowledge is indispensable for understanding environmental and social challenges, yet many sustainability-related questions involve incomplete evidence, contested interpretations, probabilistic reasoning, and evolving forms of expertise. Learners therefore need more than access to information; they need opportunities to examine how knowledge claims are made, how evidence is evaluated, and where the limits of certainty lie.

Recent work in science education has increasingly emphasised that uncertainty is not a peripheral obstacle to learning, but a central epistemic feature of scientific practice and of sustainability-related inquiry [22,23]. Questioning plays a crucial role here because it helps learners distinguish between evidence and assertion, between more and less robust claims, and between scientific uncertainty and epistemic relativism. To ask questions about evidence is not to weaken science education, but to strengthen it. It allows learners to understand science as a dynamic, rigorous, and self-corrective practice rather than as a body of unquestionable facts.

This is especially relevant in contemporary informational environments, where children and young people encounter misinformation, oversimplified narratives, and persuasive but unreliable claims. In such contexts, science education for sustainability must help learners develop habits of critical interrogation: What is the source of this claim? What evidence supports it? What remains uncertain? What alternative interpretations exist? A questioning-centred pedagogy is therefore fundamental not only to scientific understanding, but also to informed judgement in everyday life [4].

4.3. Ethical and Political Dimensions

Sustainability issues are not only scientific; they are also ethical and political. Decisions about climate mitigation, resource use, biodiversity protection, consumption, food systems, or technological development are never purely technical. They involve conflicting values, uneven distributions of risk and responsibility, and disagreements about what should be prioritised, by whom, and for whose benefit. Science education for sustainability must therefore prepare learners not only to understand the scientific dimensions of these issues, but also to recognise their ethical and political complexity.

This argument has long been central to the literature on socioscientific issues, which shows that many science-related educational questions are inseparable from moral reasoning, public controversy, and civic judgement [19,24,25]. Questioning is essential in this domain because it makes room for interrogation beyond factual correctness. It invites learners to ask whose knowledge is being centred, whose interests are being served, what trade-offs are being normalised, and what visions of

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the future are being presented as desirable or inevitable. These are not peripheral questions; they are central to any serious engagement with sustainability.

A questioning-centred science education does not collapse science into opinion, nor does it treat all perspectives as equally valid. Rather, it helps learners understand that sustainability problems require the integration of scientific evidence with ethical reflection, social critique, and civic judgement. In this sense, questioning supports a more reflexive educational stance, one in which learners are encouraged not only to know, but also to examine the assumptions and implications of what is being proposed as knowledge, solution, or progress.

4.4. Dialogue, Deliberation, and Action

Finally, sustainability requires questioning-centred science education because sustainability is not only a matter of understanding problems; it is also a matter of discussing possible responses and imagining alternative futures. This requires forms of education that support dialogue, deliberation, and agency. Learners need opportunities to participate in shared inquiry, to listen to competing perspectives, to formulate positions, and to consider what action might be possible or desirable in response to complex issues.

Recent scholarship in science education and sustainability has increasingly highlighted the importance of agency, civic participation, and future-oriented engagement in relation to socio-ecological challenges [26,27]. Questioning is indispensable to such processes. Dialogue depends on questions that open rather than close discussion, that invite reflection rather than mere recall, and that allow learners to test ideas in relation to others. Deliberation depends on the capacity to ask not only what is true, but also what matters, what follows, and what should be done. Action, in turn, becomes more meaningful when it emerges from inquiry and critical engagement rather than from moral prescription alone.

For this reason, a questioning-centred science education for sustainability should not be understood simply as a strategy for increasing classroom participation. It is better understood as a pedagogical orientation that creates space for inquiry, critical engagement, and epistemic involvement. It enables learners to enter sustainability debates not as passive recipients of pre-formulated concerns, but as participants capable of examining evidence, confronting uncertainty, articulating values, and imagining responses. In this sense, questioning is not supplementary to sustainability education; it is one of the conditions that make transformative engagement possible.

Taken together, these arguments suggest that questioning should not be understood merely as an individual skill or classroom technique, but as a practice whose educational value depends on specific pedagogical and relational conditions. The next section therefore examines what enables or constrains questioning in educational contexts, particularly in relation to participation, silence, and legitimacy.

5. Participation, Silence, and Legitimacy in Sustainability-Oriented Classrooms

If science education for sustainability depends on questioning, dialogue, and critical engagement, it must also attend to the conditions under which learners are able - or unable - to enter the conversation. Participation cannot be assumed as a neutral or equally available possibility. In classroom contexts, the capacity to ask questions, express uncertainty, or contribute to discussion is shaped by pedagogical, affective, relational, and social factors that distribute discursive space unevenly across learners. Research on classroom participation and questioning has consistently shown that engagement is not simply a matter of individual willingness, but is mediated by learners' perceptions of classroom climate, their sense of safety in speaking publicly, and the ways in which participation is recognised and valued [9,28].

This issue becomes especially important in sustainability-oriented classrooms. Sustainability questions are often open-ended, controversial, ethically charged, and resistant to quick closure. They frequently require learners to speak tentatively, explore uncertainty, and engage with problems for which no single final answer can be easily established. Under such conditions, participation requires

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more than content knowledge. It also requires learners to feel that they can ask exploratory questions, articulate partial understandings, and test emerging ideas without being penalised for not already knowing the "right" response.

Silence, in this context, should not be interpreted too quickly as lack of engagement. In educational discourse, silence is often treated as absence: absence of participation, confidence, preparation, or interest. Yet a more critical reading suggests that silence may carry multiple meanings. It may reflect caution, uncertainty, strategic withdrawal, respect for perceived norms, fear of judgement, linguistic hesitation, or a sense of not being sufficiently entitled to speak. Especially in discussions involving complex sustainability issues, silence may signal not indifference, but difficulty in finding a legitimate way to enter the conversation. Rather than treating silence as a simple deficit to be corrected, it is more productive to understand it as a meaningful mode of positioning within classroom interaction.

This is why legitimacy matters. To participate in classroom dialogue is not simply to have something to say; it is also to perceive oneself as authorised to speak and to be recognised by others as a legitimate contributor. Legitimacy is shaped by subtle classroom norms: what counts as a "good" question, what forms of doubt are welcomed, whose contributions are taken up and expanded, and whose hesitations are overlooked or closed down. In this sense, participation is inseparable from recognition. Literature on epistemic injustice in education reinforces this point by showing how classroom and institutional cultures may privilege some voices while marginalising others, often through ordinary and normalised interactional patterns rather than explicit exclusion.

Such dynamics are not merely individual; they are also socially patterned. Research has shown that classroom participation may vary according to gender, linguistic confidence, cultural expectations, and prior educational experiences. In science and engineering contexts, recent evidence suggests that gendered differences remain relevant in relation to participation and in-class questioning, even when findings are not entirely uniform across settings [10]. These differences do not imply fixed deficits in particular groups, but they do point to the unequal distribution of confidence, visibility, and discursive legitimacy within educational spaces. From the perspective of epistemic injustice [16], such patterns can be understood not simply as differences in willingness to speak, but as uneven distributions of epistemic credibility: whose contributions are perceived as worthy of uptake, expansion, and serious engagement. Related work in feminist epistemology also highlights processes of self-silencing and what Dotson [29] terms testimonial smothering, through which speakers may preemptively withhold contributions in anticipation of dismissal or misunderstanding [30]. These dynamics, while most extensively documented in higher education and professional science, are conceptually continuous with the conditions that shape whether secondary and undergraduate science learners feel authorised to ask questions, challenge assumptions, or express uncertainty in public. Empirical work directly examining these dynamics in sustainability-oriented science classrooms remains limited, however, and much of the available evidence is drawn from broader STEM or higher education contexts. For science education for sustainability - a field that explicitly claims transformative and inclusive ambitions - attending to these gendered dimensions of epistemic participation is therefore not peripheral; it is part of ensuring coherence between stated aims and actual pedagogical practice.

Taken together, these dynamics - affective, relational, and gendered - suggest that a sustainability-oriented pedagogy requires a broader understanding of participation. It must move beyond equating engagement solely with visible verbal contribution, while also avoiding the romanticisation of silence. The challenge is not to force all learners to speak in the same way, but to create conditions in which a wider range of learners can enter dialogic space more securely and meaningfully. This may involve legitimising partial or emergent questions, reducing the performative risks of speaking, diversifying forms of participation, and recognising hesitation as part of inquiry rather than as failure. These implications are taken up in the following section.

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6. Pedagogical Implications for Questioning-Centred Science Education for Sustainability

If questioning is central to science education for sustainability, pedagogical practice must move beyond simply encouraging learners to "participate more". What is required is a more deliberate educational approach that creates the conditions under which questioning becomes possible, meaningful, and legitimate. The implications of the analysis developed in this article therefore extend beyond increasing the frequency of learner questions to the design of classroom environments in which uncertainty, dialogue, and diverse forms of participation can be productively sustained. Work in science education has long emphasised that learners' questions are a crucial resource for inquiry, meaning-making, and epistemic engagement [9], while more recent work in sustainability-oriented and dialogic education reinforces the importance of classroom spaces where learners can critically explore complex issues rather than merely respond to pre-structured prompts [31,32].

6.1. Normalising Uncertainty

A first implication is the need to normalise uncertainty as an ordinary and valuable dimension of learning. In science education for sustainability, learners are often confronted with issues that involve complexity, incomplete evidence, contested interpretations, and open futures. Under these conditions, pedagogical approaches that frame knowledge primarily in terms of certainty, correctness, and closure may inhibit questioning rather than support it. Learners may come to view uncertainty as a sign of failure, and questioning as evidence of insufficient understanding.

A questioning-centred pedagogy should instead treat uncertainty as intellectually productive. This means creating classroom cultures in which not knowing is not stigmatised, and where doubt, hesitation, and complexity are recognised as legitimate starting points for inquiry. Teachers can support this by modelling epistemic humility, acknowledging the provisional nature of some knowledge claims, and framing uncertainty not as weakness, but as part of scientific and civic engagement. Recent research has argued that uncertainty can function as a pedagogical resource rather than a barrier, and that learning in science is strengthened when teachers deliberately make space for learners to grapple with ambiguity rather than rushing toward closure [33].

6.2. Legitimising Exploratory Questions

A second implication is the importance of legitimising exploratory questions. In many classrooms, only certain kinds of questions are implicitly recognised as valuable: those that are clearly formulated, academically polished, or closely aligned with expected content. Yet some of the most important questions begin as partial, tentative, or unfinished attempts to make sense of complexity. If learners feel that only well-formed or already sophisticated questions are acceptable, many potentially meaningful contributions may never be voiced.

Teachers therefore need to widen what counts as a legitimate question. This includes recognising clarifying, speculative, ethical, and connecting questions as pedagogically valuable, not only those that display prior mastery. It also means responding in ways that preserve learners' willingness to inquire, rather than quickly evaluating or closing down their contributions. In this sense, legitimising exploratory questions is not merely a matter of inclusion; it also supports deeper engagement with issues that resist simple formulation. Foundational work on learner questions in science education has shown that such questions are powerful resources for teaching and learning [9,34].

To illustrate this distinction in practice, consider a science lesson on local biodiversity loss driven by climate change. An expected, pedagogically 'safe' question might be: "Which temperature increase causes coral bleaching?" This question seeks a predetermined factual answer, demonstrating basic cognitive engagement. In contrast, an exploratory, epistemic question might sound hesitant or unpolished: "If we engineer heat-resistant corals in the lab, aren't we just deciding which species survive, and is that even nature anymore?" This second question does not merely seek information; it grapples with ethical tension, technological intervention, and the unpredictable consequences of

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human agency. If a teacher only legitimises the first type of question - or dismisses the second because it lacks a clear scientific answer - the classroom ceases to be a space for transformative sustainability education. Legitimising exploratory questions means explicitly validating this kind of conceptual struggle as rigorous scientific thinking.

6.3. Diversifying Participation Formats

A third implication concerns the need to diversify participation formats. If questioning is treated exclusively as public oral intervention in whole-class settings, participation will likely remain unevenly distributed. Some learners may be ready to speak spontaneously in open discussion, while others may engage more comfortably through smaller groups, written prompts, anonymous questioning tools, asynchronous forums, or structured peer dialogue.

A questioning-centred pedagogy should therefore broaden the repertoire through which learners can enter inquiry. In contemporary science classrooms, this diversification can be facilitated by digital and structured tools. For instance, teachers can implement anonymous digital question boards (using platforms such as Mentimeter, Wooclap, or Padlet, among others) where students submit queries during a lesson without fear of peer judgement. Alternatively, asynchronous online forums or 'question boxes' (both physical and virtual) allow learners to process complex socio-scientific information after class and formulate their questions once they have had time to reflect. Structured peer dialogue, such as 'think-pair-share' routines, also provides a micro-level safe space where a question can be tested with a single classmate before being presented to the whole room. This is especially important because sustainability-related questions often require time for reflection, interpretation, and ethical positioning.

Diverse formats can reduce the performative pressure associated with immediate public speaking and make it easier for a wider range of learners to articulate questions in ways that feel manageable and legitimate. Diversifying participation is thus not simply a technique for inclusion, but a way of recognising that questioning itself may emerge through multiple pedagogical pathways. Research on participation-enhancing pedagogies and alternative questioning formats suggests that such approaches can reduce barriers to contribution and broaden engagement, especially for learners who are less comfortable with spontaneous public speaking [28,35].

6.4. Treating Silence Interpretively

A fourth implication is the need to treat silence interpretively rather than automatically as a deficit. As argued earlier, silence may reflect hesitation, uncertainty, strategic withdrawal, linguistic difficulty, fear of judgement, or the absence of discursive legitimacy. In classrooms engaging with complex and ethically charged issues, silence can also indicate the difficulty of responding meaningfully to questions that do not allow easy closure.

This does not mean that silence should be idealised or left entirely unquestioned. Rather, it suggests that teachers should resist reducing silence to disengagement and instead attend to its possible meanings in specific contexts. Pedagogically, this involves asking not simply why learners are not speaking, but under what conditions participation has become risky, narrow, or inaccessible. Such an interpretive stance may help teachers design more responsive environments in which silence is neither romanticised nor pathologised, but understood as part of the ecology of participation [36,37].

6.5. Supporting Dialogic Rather than Merely Responsive Classrooms

A final implication is the need to support dialogic rather than merely responsive classrooms. In many educational settings, learner participation remains organised around response rather than dialogue: learners answer teacher questions, provide expected contributions, or confirm understanding, but have limited opportunity to shape the direction of inquiry. A questioning-centred science education for sustainability requires something more dialogic. It requires classrooms in which

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learners can ask questions that genuinely influence discussion, open new lines of thought, and complicate rather than simply reinforce pre-structured knowledge.

This shift matters because sustainability education is not only about comprehension, but also about deliberation, interpretation, and the shared exploration of complex socio-ecological realities. Dialogic classrooms make room for disagreement, uncertainty, ethical reflection, and the co-construction of meaning. They also position questioning not as an occasional pedagogical add-on, but as a constitutive feature of learning itself. Supporting such classrooms requires pedagogical intentionality: not only encouraging learners to speak, but designing interactions in which their questions matter. Research on dialogic teaching and dialogic science education strongly supports this orientation [20,38–40].

Taken together, these implications suggest that questioning-centred science education for sustainability is not reducible to a set of participation techniques. It is better understood as a pedagogical orientation that reshapes how classroom engagement is conceived, supported, and recognised. To foster questioning in meaningful ways is to create conditions in which learners can approach sustainability issues not as passive recipients of already-settled knowledge, but as participants in inquiry, interpretation, and critical engagement.

To bring together the pedagogical argument developed in the previous sections, Figure 1 presents a conceptual framework for questioning-centred science education for sustainability. The figure visualises how the complexity, uncertainty, and ethical tension of sustainability challenges require educational environments grounded in discursive legitimacy and low-risk participation. Under such conditions, both learner questioning and meaningful silence can be understood as epistemic practices through which learners engage critically with sustainability-related issues. In this way, the figure highlights how questioning-centred pedagogy supports more transformative, inclusive, and dialogic forms of science education for sustainability.

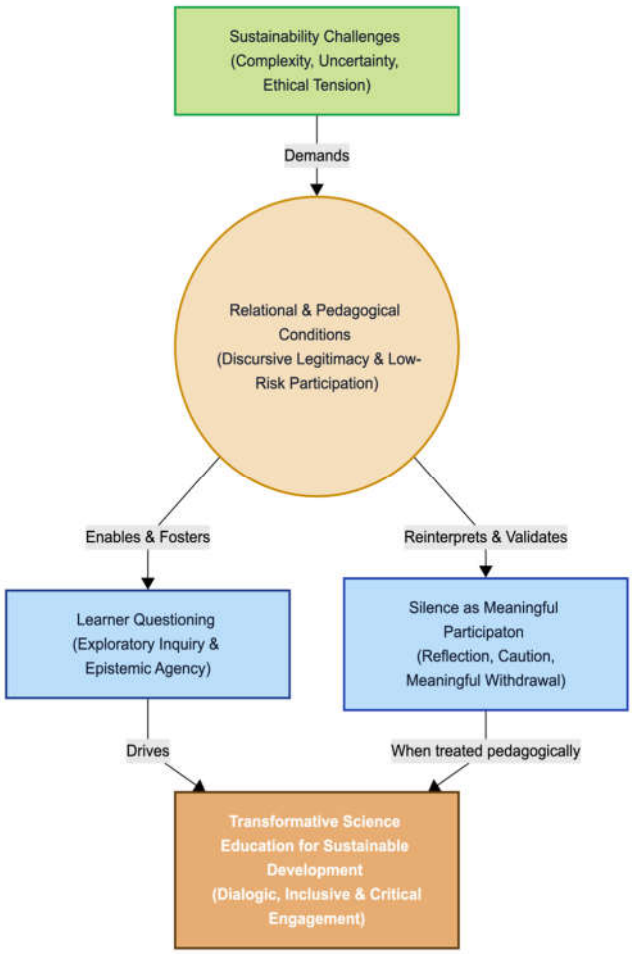

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Figure 1. Conceptual framework for questioning-centred science education for sustainability, illustrating the mediating role of discursive legitimacy between sustainability challenges and learners' epistemic practices - active questioning and meaningful silence - as conditions for transformative, inclusive, and dialogic learning.

7. Discussion and Conclusions

Within science education for sustainability, learner questioning is better understood as a central pedagogical and epistemic condition than as a secondary classroom behaviour or a supplementary participation technique. Bringing together literature on learner questioning, classroom participation, silence, legitimacy, and sustainability-oriented education makes it possible to see that questioning has often been conceptualised too narrowly: as a sign of engagement, an individual behaviour, or a pedagogical resource, but less often as a broader epistemic and relational practice. The significance of this reframing lies in shifting attention from whether learners ask questions to the conditions under which questioning becomes possible, meaningful, and educationally consequential.

This shift matters because sustainability-related issues place distinctive epistemic and pedagogical demands on education. Complexity, systems interdependence, uncertainty, ethical tension, and public deliberation require more than the acquisition of scientific content. They require learners to interrogate evidence, examine assumptions, navigate competing interpretations, and position themselves in relation to socio-ecological futures. From this perspective, questioning is not simply one possible classroom strategy among others; it is integral to the kind of engagement that science education for sustainability seeks to foster.

The analysis also suggests that questioning cannot be adequately understood through cognitive or pedagogical lenses alone. Whether learners ask questions depends not only on what they know, but also on whether they perceive themselves as entitled to speak, whether their contributions are likely to be taken seriously, and whether classroom environments allow uncertainty and partial understanding to be voiced without penalty. The issue, therefore, is not merely how to elicit more learner questions, but how to create educational conditions in which questioning is discursively legitimate and epistemically valued. This brings questioning into closer relation with broader concerns in dialogic pedagogy, participation research, and epistemic injustice.

Seen in this light, the argument of the article also redefines what counts as participation in sustainability-oriented classrooms. If transformative education is taken seriously, then participation cannot be reduced to visible verbal contribution alone. Silence and non-questioning cannot automatically be interpreted as disengagement, since they may also express uncertainty, caution, fear of judgement, limited legitimacy, or strategic withdrawal. The interpretive challenge is therefore not simply to increase talk, but to understand how classroom norms structure who can enter dialogue, in what ways, and at what discursive cost. This is especially important in sustainability education, where the issues at stake are often open-ended, controversial, and ethically charged.

The article further suggests that this pedagogical reframing has implications beyond classroom interaction narrowly understood. It also helps illuminate the educational dimensions of the SDGs invoked in the introduction. SDG 4, and especially Target 4.7, depends not only on access to knowledge but on pedagogies that cultivate critical inquiry, ethical reasoning, and meaningful participation. SDG 13 cannot be served by the passive reception of climate information alone; it requires the capacity to interrogate evidence, uncertainty, and competing frameworks of interpretation. SDG 16, in turn, highlights that inclusive and participatory institutions depend on citizens who have learned to speak, question, deliberate, and engage under conditions of recognition rather than exclusion. From this perspective, questioning-centred science education is not simply pedagogically desirable; it is relevant to the broader democratic and civic ambitions of sustainable development.

Taken together, these arguments suggest that a questioning-centred approach to science education for sustainability is not primarily about increasing interactional frequency. It is about cultivating pedagogical environments in which learners can engage uncertainty without penalty, formulate exploratory questions, participate through diverse modes, and encounter classroom

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dialogue as a space where their contributions are possible and meaningful. The article therefore invites a shift from viewing questioning as a technique to understanding it as part of the pedagogical architecture of inclusive, dialogic, and critically engaged science education for sustainability.

This article also has clear limitations. As a conceptually oriented paper informed by a critical interpretive review, it does not aim to provide an exhaustive or fully systematic mapping of literature on questioning, participation, and sustainability education. Its purpose is interpretive rather than comprehensive. In addition, although it draws on studies from different educational contexts, the available literature remains uneven in relation to age groups, disciplinary traditions, and intersectional analyses of participation. In addition, the literature base considered here is predominantly Anglophone and situated within education systems in the Global North, which constrains the extent to which the analysis can speak to sustainability education in other socio-educational contexts. The discussion of gendered dynamics in Section 5, while conceptually grounded, is constrained by the still limited empirical base specifically addressing questioning and epistemic participation in sustainability-oriented classrooms.

Future research could extend this agenda in several directions. One concerns how questioning is shaped by intersecting dimensions of identity, including gender, language, social background, and prior educational experience. Another concerns how pedagogical designs such as dialogic teaching, anonymous questioning tools, small-group inquiry, or socioscientific issue-based approaches affect not only the frequency of learner questions, but also their form, depth, legitimacy, and distribution. There is also scope for examining more explicitly the relationship between questioning, epistemic agency, and democratic participation in sustainability education.

Ultimately, the article argues that questioning should not be treated as an optional pedagogical add-on. It is one of the conditions through which science education for sustainability can move beyond the transmission of environmental facts and become more genuinely critical, participatory, and transformative.

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Abbreviations

The following abbreviations are used in this manuscript:

STEM	Science, Technology, Engineering, and Mathematics
SDG	Sustainable Development Goal

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