

BRIDGING SCIENTIFIC IDENTITY AND ESD THROUGH INQUIRY-BASED LEARNING: A SYSTEMATIC REVIEW OF SCIENCE EDUCATION PRACTICES IN HIGHER EDUCATION (2016-2025)

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ABSTRACT

Education for Sustainable Development (ESD) equips students with sustainability values, while science identity influences how they perceive their role in the world of science. This systematic literature review analyzes the potential of Inquiry-Based Learning (IBL) as a bridge between ESD and science identity. Following the PRISMA guidelines, this review searched Google Scholar, Science Direct and the Journal of Chemical Education, after the screening process, included 18 studies published between 2016 and 2025 that examined all three elements in the context of undergraduate science education. The analysis results indicate that IBL has the potential to develop students' science identity, and that integrating ESD contexts into IBL can strengthen that identity. Although the integration of these three elements remains limited, a synthesis of the findings suggests that IBL has the potential to serve as a bridge between ESD and the formation of science identity. Further research is needed to test the effectiveness of IBL that integrates ESD values in fostering students' science identity.

Keywords: Science identity; ESD; IBL; higher education; systematic review

INTRODUCTION

Science identity can be defined as a multidimensional and complex construct that reflects how an individual perceives, understands, and positions themselves in relation to science, whether as a learner, practitioner, or member of the scientific community (C. Chen et al., 2020). According to Carlone and Johnson, as cited in Chen & Wei, the construction of this science identity involves at least three interrelated dimensions: competence (knowledge and motivation to understand science), performance, and recognition (self-recognition and recognition by others as someone engaged in the field of science) (S. Chen et al., 2021). Furthermore, scientific identity is not static but is shaped and influenced by an individual's interests, competencies, experiences, and social context, including how they are recognized

by others as someone associated with the field of science (S. Chen & Wei, 2022).

Furthermore, science identity is not merely a theoretical concept, but a key construct that predicts individual success and provides a framework for creating a more inclusive and equitable science environment. First, science identity serves as the foundation for students' academic and psychological success, particularly for students from underrepresented groups. A study by Chen, et al. (2020) demonstrates that a strong science identity is not only associated with improved academic performance (such as grades) in college, but more crucially, it strengthens students' sense of belonging in the scientific community. By feeling like "science people," they feel more accepted and better able to persevere in the face of academic challenges. Second, a science identity

serves as a vital precursor to continuity and the future. Emphasizing that a science identity is not merely the result of success in science, but rather a precursor that motivates individuals to engage deeply, persevere, and ultimately choose a career in STEM (Chen & Wei, 2022) .

In the reviewed studies, science identity is predominantly operationalized through self-report instruments that measure three core dimensions: performance, competence and recognition. Meanwhile, ESD is defined as the integration of sustainability competencies into science learning activities, and is often measured through post-intervention assessments of students' sustainability attitudes, knowledge, or behaviors. Inquiry-Based Learning (IBL), in turn, is consistently characterized by the presence of five essential features: engaging in scientifically oriented questions, prioritizing evidence, formulating explanations, connecting explanations to scientific knowledge, and communicating and justifying findings.

Individuals who develop a strong scientific identity early on are more likely to continue pursuing a scientific path to higher levels, thereby ensuring the regeneration and resilience of the workforce in the science and technology sectors. Finally, a science identity provides a crucial analytical lens for understanding inequalities in science education. By employing a science identity that encompasses dimensions of competence, performance, and recognition, researchers and educators can analyze more holistically how social, cultural, and institutional factors shape an individual's path to being recognized as a legitimate "scientist." This is crucial for identifying and addressing systemic barriers that hinder the full

participation of diverse groups. This holistic approach to analyzing recognition as a scientist aligns with the essence of Education for Sustainable Development (ESD), which seeks to create an inclusive foundation for all learners to address complex global challenges. The integration of science identity, ESD, and IBL is empirically justified by a critical gap in current science education: while IBL has been shown to strengthen science identity, and ESD interventions have been shown to improve sustainability knowledge, few studies have examined how the synergy between the two can simultaneously cultivate a strong science identity and measurable sustainable behaviors. This gap is particularly significant given the rising global demand for a STEM workforce capable of driving the green transition, a demand that requires professionals who not only think like scientists but also act with sustainability principles at the core of their practice.

UNESCO defines Education for Sustainable Development (ESD) as an approach that bridges the needs of all learners by equipping them not only with knowledge and skills, but also with values and opportunities to actively address interrelated global challenges, including climate change, biodiversity loss, unsustainable resource use, and social inequality. Furthermore, ESD aims to empower communities to share responsibility for creating a sustainable future. Professionally, ESD aims to equip individuals with the competencies to: (1) assess the impact of their actions from local and global perspectives, (2) actively participate in building sustainable communities, and (3) develop the ability to face life's challenges in a healthy and responsible manner (UNESCO, 2015) .

In its implementation, ESD is an approach that combines three key elements: behavioral change, learning methods, and the sustainability of knowledge. The integration of these three elements creates an effective and transformative learning process, with the goal of empowering learners to make sound decisions and take responsible actions. The urgency of ESD's importance is driven by the Earth's alarming conditions, such as the increasing frequency of floods, landslides, storms, and global warming. To address these challenges, contributions from all parties are needed, including the education sector through the development of appropriate competencies. The potential of education as an effective means to address global issues can be realized if the education system is grounded in the principles of sustainable development (UNESCO, 2015).

One approach relevant to ESD is Inquiry-Based Learning (IBL), which is effective for developing 21st-century skills. As outlined by Chu et al., (2017), IBL engages students in the process of constructing knowledge through questioning, supported by a social constructivist framework. Their research shows that this approach not only promotes deep thinking and the application of knowledge but can also be enhanced through the integration of technology.

Empirically, the effectiveness of IBL has been extensively studied in various educational contexts, proving that IBL can improve academic achievement, learning motivation, and develop essential 21st-century skills such as collaboration, communication, and creativity (Wale & Bishaw, 2020). Nevertheless, the implementation of IBL faces several challenges, including the need for adequate instructional support, comprehensive

teacher training, and the creation of a conducive learning environment (Putri & Novita, 2024).

Although Science Identity, ESD, and IBL have each been extensively studied, systematic literature reviews that explicitly investigate the intersection of all three remain very limited. Existing research tends to be fragmented, for example, exploring IBL with Science Identity alone, or IBL with ESD separately. In fact, IBL has the potential to connect the process of building a science identity with the content and values of ESD. By mimicking the authentic work of scientists, IBL has the potential not only to develop aspects of identity performance but also to foster a sense of agency to contribute to solutions for sustainability issues. Therefore, this systematic review aims to map and synthesize empirical evidence on how IBL practices in science education seek to bridge these two domains.

Based on a review of these three key concepts, this study proposes a conceptual framework that positions IBL as a process variable bridging the relationship between the application of ESD principles in the science curriculum and the formation of students' Science Identity. Within this framework, an ESD-based learning context is implemented through the stages of IBL. Authentic inquiry processes are hypothesized to strengthen the three dimensions of Science Identity: competence through mastery of contextual science content, performance through engagement in scientific practices, and recognition by presenting findings to a broader community. This framework will serve as a guide for analyzing and synthesizing findings from the selected literature.

This systematic review is expected to make several significant contributions. For researchers, this synthesis will provide a comprehensive map of the existing research landscape and identify future research agendas at the intersection of Science Identity, ESD, and IBL. For education practitioners, particularly science teachers, this review will present practical models and pedagogical principles for designing inquiry-based learning experiences that simultaneously build scientific understanding, scientific identity, and a commitment to sustainability.

To achieve these objectives, this systematic review will address the following research questions:

1. What are the characteristics of IBL implementation reported in science education studies aimed at building Science Identity while integrating ESD principles?
2. What are the reported empirical findings regarding the impact of IBL

practices on strengthening the dimensions of students' Science Identity (competence, performance, recognition) in the context of ESD learning?

3. What supporting and inhibiting factors have been reported in efforts to bridge Science Identity and ESD through IBL?

To answer these research questions, this systematic literature review (SLR) was conducted following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) protocol. A literature search was performed in leading academic databases (such as Google Scholar and the Journal of Chemical Education) using keyword strings combining the three core concepts. Selected studies were rigorously screened based on predefined inclusion and exclusion criteria, then thematically analyzed to identify patterns and key findings.

METHOD

This study employed the Systematic Literature Review (SLR) method, a systematic research approach designed to collect, evaluate, integrate, and present findings from various prior studies related to the research question or topic of interest. The “systematic” nature of the SLR refers to the application of a consistent and widely recognized methodology, ensuring that the literature review process is conducted with rigor and transparency (Fay et al., 2019). The purpose of conducting an SLR is to provide a comprehensive and structured foundation for understanding research developments in a specific field, as well as to identify knowledge gaps that can be addressed through further research (Al-Zubidy & Carver, 2019).

The literature search was conducted using Publish or Perish (PoP) version 8 software to access and collect bibliometric data from the Google Scholar database. The use of PoP was deemed strategic to ensure a broad search scope, particularly in capturing publications indexed in Google Scholar that are not always accessible via conventional database search systems. The search string was designed by combining variations of keywords from the three core concepts: Science Identity, Education for Sustainable Development (ESD), and Inquiry-based Learning (IBL). The search was limited to publications from 2016 to 2025. The year 2016 was selected as the starting point because it coincides with the global adoption of the Sustainable Development Goals (SDGs), including

SDG 4 on quality education, which triggered a substantial worldwide increase in empirical ESD research and policy-relevant scholarship. The endpoint of 2025 was chosen to include the most current literature available up to the year this review was conducted. This ten-year window thus captures the core period during which ESD, science identity, and IBL have increasingly intersected in educational discourse and empirical investigation.

The reporting of this systematic review follows the PRISMA 2020 guidelines (Preferred Reporting Items for Systematic Reviews and Meta-Analyses), the latest reporting guidelines designed to ensure transparency and completeness of systematic review reports by providing a framework to clearly document the rationale, methods, and findings (Page, et al., 2021). The selection of these guidelines was based on several considerations, namely: (1) PRISMA 2020 has been widely adopted and recognized as a reporting standard in various leading scientific journals, thereby enhancing the credibility and ease of evaluation of this review; (2) this guideline offers a highly detailed structure, including a 27-item checklist and flowcharts, which are highly helpful in ensuring no critical steps in the process of identifying, selecting, and synthesizing studies are omitted from the report; (3) updates in the 2020 version allow for more comprehensive reporting.

Given the scarcity of literature addressing all three concepts—science identity, ESD, and IBL within the same context, the inclusion criteria were strategically designed. The primary criterion requires that published empirical or conceptual articles in journals address at least two of these three key concepts. The

articles must not only mention the terms but also examine or apply them within the framework of science education. An article may discuss how IBL shapes students' science identity, or how ESD themes are integrated through an inquiry-based approach. The publication timeframe is limited to the years 2016 through 2025. In addition to Google Scholar, structured searches were conducted in Science Direct to broaden the reach and include high-impact journals not fully indexed by Google Scholar. The Journal of Chemical Education was also searched directly as a specialized source for chemistry education scholarship. The entire selection process from identification, screening, and eligibility assessment to the final inclusion decision is visualized using the PRISMA 2020 flowchart. The mapping analysis procedure based on PRISMA guidelines is shown in Figure 1. The process of identifying and selecting studies for this systematic literature review (SLR) followed the PRISMA 2020 flowchart, as illustrated in Figure 1. An initial literature search conducted using the Publish or Perish software across various leading electronic databases successfully identified a total of 998 articles. After removing 11 duplicates, 987 articles remained, which then underwent a screening stage based on titles and abstracts. At this stage, 366 articles were excluded because their publication years did not meet the criteria. A total of 621 full-text articles were then obtained for eligibility assessment. Following a thorough examination of the full texts, 19 studies were excluded because they were not articles; the remaining 602 reports were excluded primarily for the following reasons: the articles did not discuss the interaction of at least two of the three concepts (science identity, ESD, and

IBL) in depth and merely mentioned the terms (n=556), and the articles were Systematic Literature Reviews (n=28). Finally, 18 studies met all the established inclusion criteria and were included in this systematic review. Although none of the

articles directly addressed all three conceptual pillars simultaneously, the selected articles provided a foundation and valuable insights into the dynamic relationships between at least two concepts, thereby enabling an integrative analysis.

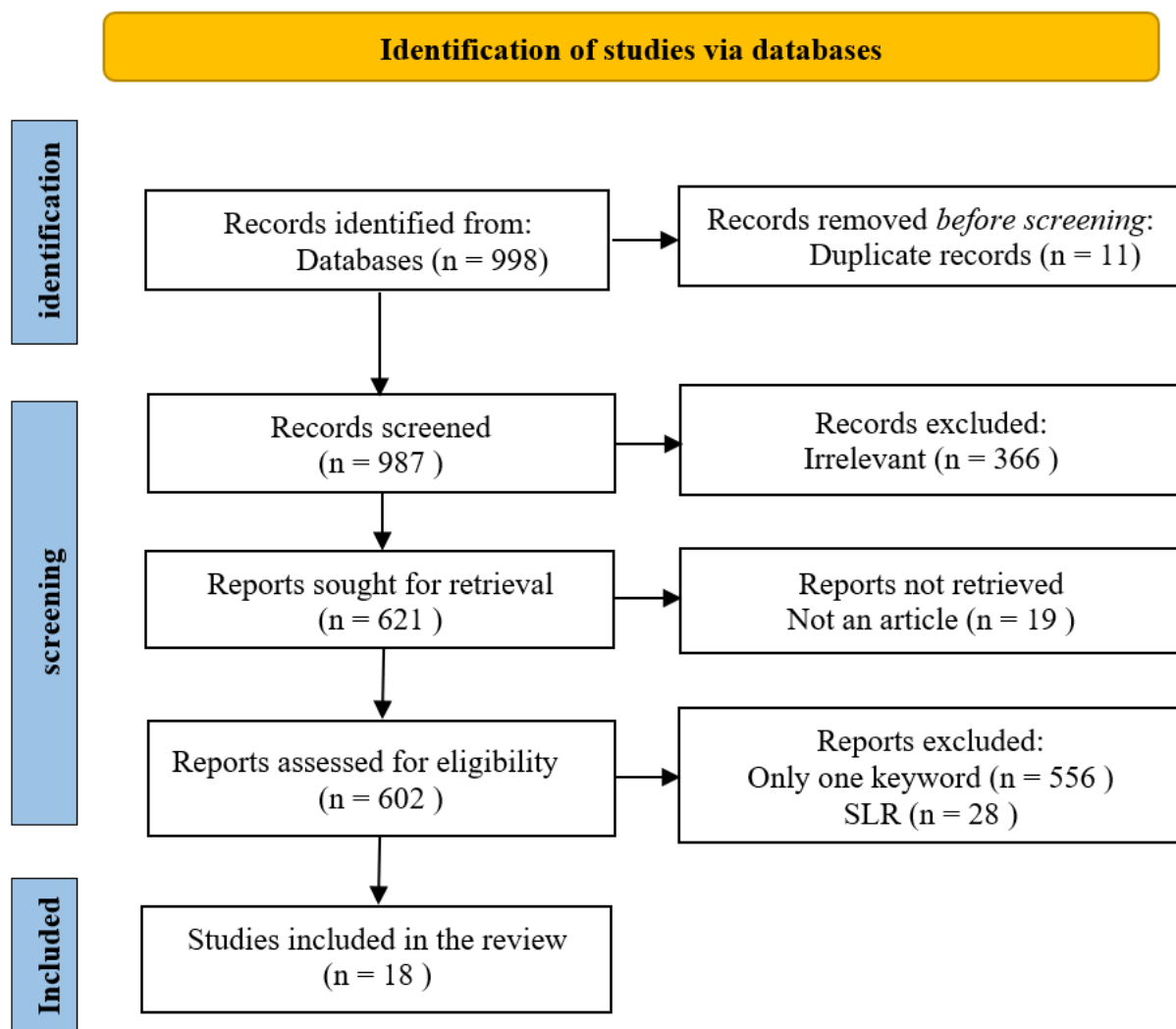


Figure 1. PRISMA flow diagram of this study (Page et al., 2021)

RESULTS AND DISCUSSION

Inquiry-based learning in science education has long been recognized as an effective pedagogical approach for deep conceptual understanding. However, in the context of 21st-century global challenges, the role of inquiry is increasingly challenged to foster students' scientific

identity and empower them with the values and capabilities to act toward a sustainable future. A systematic review of recent research reveals that Inquiry-Based Learning (IBL) emerges as a pedagogical framework with the potential to bridge the gap between Science Identity and ESD. A

synthesis of empirical findings from various educational contexts, ranging from elementary school to higher education, reveals characteristic patterns of IBL implementation that integrate the principles of Education for Sustainable Development (ESD) and create space for strengthening the dimensions of science identity: competence, performance, and recognition. This discussion will explore three key questions: first, to outline the characteristics of IBL implementation reported in the research; second, to substantiate with empirical findings regarding its impact on each dimension of science identity; and third, to identify supporting and inhibiting factors in this integration effort. It is hoped that these findings will provide a roadmap for the development of future practice and research at the intersection of IBL, science identity, and ESD.

In response to the first research question, Table 1 compares various characteristics of IBL implementation that integrate ESD principles reported in the literature to build Science Identity. Based on a synthesis of several studies, effective IBL implementation to build *Science Identity* while integrating ESD principles is characterized by the contextualization of authentic problems, collaborative design emphasizing scientific performance, and a focus on action and meaningful reflection. The first prominent characteristic is the use of relevant and complex sustainability issues as entry points, such as placing students in the role of researchers investigating real-world problems like

climate change and sustainable oil palm cultivation (Fitriyana et al., 2025; Matthiesen et al., 2025). This approach, as observed in training for urban water practitioners (Ison et al., 2021), not only engages participants cognitively but also fosters *the recognition* that science is a powerful tool for understanding and addressing the challenges of their world—a foundation of *Science Identity*.

Equally important are the action- and reflection-oriented characteristics of IBL, which serve as a bridge between scientific understanding and social responsibility. The principle of action-oriented learning in ESD is realized when inquiry does not end with conclusions on paper but is followed by concrete action. As demonstrated by Baptista et al., students created and distributed leaflets and campaign videos about the impacts of mining (Baptista et al., 2025). Similarly, Frank & Stanszus,(2019) and Sulistina et al.,(2021), document how pre-service teachers transform their consumption behaviors and reduce plastic use (Frank & Stanszus, 2019; Sulistina et al., 2021). These actions represent the culmination of applied science performance. Accompanied by reflection, as reflected in reflective journals and sustainability awareness questionnaires, this process enables participants to reconstruct their identities not only as science learners but as agents of change who possess the agency to apply scientific knowledge in building a more sustainable future (Frank & Stanszus, 2019; Matthiesen et al., 2025; Sulistina et al., 2021).

Table 1. ESD-IBL Implementation

IBL Phases (Synthesis of Various Models)	Implementation Characteristics for Building Science Identity	Strategies for Integrating ESD Principles	References
<i>Engagement with a Relevant Problem</i> (Orientation, Problem Formulation, Ask)	Using authentic, locally relevant, and socially meaningful issues (<i>socio-scientific issues</i>)	Linking the problem to the SDGs	(Baptista et al., 2025); (Fitriyana et al., 2025); (Igboanugo & Naiho, 2024); (Ison et al., 2021); (Matthiesen et al., 2025)
<i>Scientific Investigation & Exploration</i> (Exploration, <i>Find Out</i> , Investigation)	Providing <i>hands-on inquiry</i> experiences	Investigations focus on understanding the causes and effects of sustainability issues.	(Boaventura et al., 2020) ; (Hardianti & Wusqo, 2020) ; (Huang & Pei, 2024) ; (Sulistina et al., 2021) ; (Wilczek et al., 2022)
<i>Explanation & Communication</i> (Discussion, Generalization, Communication, <i>Reflection</i>)	An opportunity to communicate findings to a wider audience	Communication not only explains findings but also aligns with action-oriented principles.	(Baptista et al., 2025); (Matthiesen et al., 2025); (Sulistina et al., 2021) ; (Wang & Guo, 2021)
<i>Action & Reflection</i> (Elaboration, Action, Reflecting on Impact, Act)	Seeing the impact of their knowledge by transforming it into concrete action	Immediately linking learning to sustainable action	(Baptista et al., 2025); (Murphy et al., 2020) ; (Frank & Stanszus, 2019) ; (Sulistina et al., 2021) ;

Based on the Science Identity theoretical framework by Carlone and Johnson (as cited in Chen & Wei,(2022) , an individual's identity in the field of science is constructed through three interrelated and mutually reinforcing dimensions. First, the competence dimension, which refers to mastery of scientific content knowledge. Second, the performance dimension, reflected in an individual's ability to practice scientific behavior. Third, the recognition dimension, which encompasses both internal self-recognition and external recognition from others that the individual is capable of understanding and contributing to the world of science.

The empirical findings regarding the impact of IBL practices on the dimensions

of students' Science Identity, as summarized in Table 2, demonstrate a clear and identifiable contribution from each phase of learning. Based on a synthesis of various empirical findings, the consistent integration of ESD contexts into science learning has the potential to develop students' *science identity* through synergistic interactions among its three main dimensions: competence, performance, and recognition. For instance, Wilczek et al. (2022) redesigned an undergraduate organic chemistry course into an entirely inquiry-based, remote format focused on transferable skills such as data analysis and science communication. Survey responses showed that all students experienced gains in both self-efficacy (closely tied to the

competence dimension) and science identity (encompassing recognition and performance), and notably, the pre-existing gaps between students from underrepresented groups and their peers closed entirely within a single semester. The mechanism suggested is that an inquiry-based environment, by emphasizing skill development and collaborative presentations, provides equitable opportunities for students to

demonstrate competence, perform scientific practices authentically, and receive peer/instructor recognition. However, this study employed a single-group pre-post survey design without a control condition; thus the evidence remains correlational and cannot establish a definitive causal link between IBL and the observed gains in science identity dimensions.

Table 2. Analysis of the Impact of ESD-IBL on *Science Identity*

Competency	Performance	Recognition
Process Skills & Critical Thinking	1. Conducting systematic investigations (Sulistina et al., 2021) 2. Arguing based on evidence (Fitriyana et al., 2025) 3. Analyzing data (Hardianti & Wusqo, 2020)	Internal: Increased self-efficacy and confidence in science abilities (Nafakoti & Sri Atun, 2025; Wilczek et al., 2022) External: Recognition from peers/teachers during collaboration and presentations (Sulistina et al., 2021)
Understanding of Science Content & Sustainability	1. Engaging in authentic science practices to investigate issues (pollution observation, energy experiments) (Boonyod et al., 2025; Huang & Pei, 2024) 2. Designing action plans or solutions (Wilczek et al., 2022)	Internal: Self-confidence as an “expert” on the topic (Huang & Pei, 2024) External: Self-recognition as an informed agent of change (Boonyod et al., 2025)
Communication & Collaboration Skills	1. Creating media & presenting findings to the public (Baptista et al., 2025; Matthiesen et al., 2025) 2. Engaging in socio-scientific debates (Murphy et al., 2020) 3. Working in multidisciplinary teams (Ison et al., 2021)	Internal: Sense of ownership and leadership over the project (Murphy et al., 2020) External: Feedback from the audience (community, faculty, experts) (Baptista et al., 2025; Ison et al., 2021; Matthiesen et al., 2025)
Holistic Perspective & Interdisciplinary Collaboration	1. Mapping complex systems (Ison et al., 2021) 2. Designing solutions that consider various stakeholders (Wilczek et al., 2022) 3. Analyzing interconnected environmental impacts (Baptista et al., 2025)	Internal: Confidence to bring sustainability messages into the professional world (Igboanugo & Naiho, 2024) External: Strengthening networks with communities of practitioners (Ison et al., 2021)

First, mastery of process skills and critical thinking enables students to engage

in authentic scientific performance. They conduct systematic investigations,

construct arguments based on evidence, and analyze complex data (Hardianti & Wusqo, 2020; Setiyaningsih et al., 2024) . Success in assuming this scientist-like role then yields significant forms of recognition. Internally, self-confidence and self-efficacy regarding their scientific abilities grow (Nafakoti & Sri Atun, 2025; Wilczek et al., 2022) . Externally, recognition is gained through collaborative interactions and presentations in front of peers and teachers, which further validates their competencies (Setiyaningsih et al., 2024).

Second, a deep understanding of science and sustainability encourages students to engage in activities that have a direct impact. They not only understand the theory but also apply it in authentic scientific practices, such as investigating pollution or experimenting with renewable energy, and even designing concrete action plans. This kind of direct engagement fosters a strong sense of internal recognition. Students develop a sense of confidence as individuals who master the subject matter and, more importantly, begin to identify themselves as agents of change (Boonyod et al., 2025; Huang & Pei, 2024)

Third, communication and collaboration skills enable students to demonstrate scientific performance in a broader context. They create communication media, present findings to the public, debate socio-scientific issues, and work in multidisciplinary teams (Baptista et al., 2025; Ison et al., 2021; Matthiesen et al., 2025; Murphy et al., 2020) . This performance yields dual recognition. Internally, they foster a sense of ownership and leadership over the resulting project (Murphy et al., 2020) . Externally, constructive feedback from the audience, including the public and experts, provides social validation of their scientific

contributions (Baptista et al., 2025; Ison et al., 2021; Matthiesen et al., 2025) .

Fourth, a holistic perspective and interdisciplinary collaboration skills are high-level competencies manifested in performance such as mapping complex systems, analyzing interconnected environmental impacts, and designing solutions by engaging stakeholders (Baptista et al., 2025; Ison et al., 2021) . Mastery of this complexity fosters strategic and future-oriented recognition. Internally, they feel confident in integrating sustainability missions into their professional careers (Wilczek et al., 2022) . Externally, the networks built with communities of practitioners strengthen their position as part of the sustainability problem-solving ecosystem.

Overall, this underscores that the ESD context serves as a catalyst linking enhanced scientific competencies with opportunities to perform authentically. It is this process that ultimately fosters recognition both from within and from the community, thereby shaping students' science identity not only as science learners but as capable and confident individuals who can contribute to solving real-world sustainability challenges.

Based on a synthesis of various studies, efforts to bridge Science Identity and Education for Sustainable Development (ESD) through Inquiry-Based Learning (IBL) are supported by several key factors. First, the role of educators as effective facilitators—who guide and motivate students—has proven crucial in creating a self-directed learning environment that supports the development of a science identity (Baptista et al., 2025; Nafakoti & Sri Atun, 2025) . Second, relevant and authentic learning contexts, such as the integration of socio-scientific

issues, local wisdom, and everyday phenomena, significantly enhance student engagement and understanding of science and sustainability (Boonyod et al., 2025; Matthiesen et al., 2025; Sulistina et al., 2021). Third, a clear IBL learning structure and a collaborative learning environment play a crucial role in guiding students to develop critical thinking and collaboration skills (Nafakoti & Sri Atun, 2025). Technological support and resources, as well as flexible institutional policies, also serve as key drivers by providing tools and opportunities for authentic inquiry (Matthiesen et al., 2025; Wang & Guo, 2021). Finally, strong partnerships between schools, researchers, and the community provide authentic learning experiences and enrich students' perspectives (Boaventura et al., 2020).

On the other hand, several barriers have been reported. Resource and time constraints, such as short-term interventions and a dense curriculum, often limit the depth of inquiry and long-term developmental observations (Boonyod et al., 2025; Matthiesen et al., 2025). The readiness of educators and students also poses a challenge; the dominance of the teacher's role in conventional approaches and the lack of teacher training in IBL can limit student autonomy, while students' passive tendencies and variations in intrinsic motivation hinder their adaptation to active learning models (Igboanugo & Naiho, 2024; Konieczny, 2024; Sulistina et al., 2021). The complexity of IBL-ESD skills themselves, such as planning experiments and engaging in critical reflection, is often difficult for students to

master (Boaventura et al., 2020; Hardianti & Wusqo, 2020; Wilczek et al., 2022). Broader systemic challenges, such as a rigid education system with an excessive emphasis on written exams and a culture of rote memorization, often conflict with the philosophy of inquiry and sustainable development (Huang & Pei, 2024; Ison et al., 2021; Konieczny, 2024). Furthermore, limitations in research design and assessment, such as small sample sizes and an evaluation focus limited to cognitive aspects, restrict a holistic understanding of the impact of IBL on scientific identity and ESD competencies (Boonyod et al., 2025; Huang & Pei, 2024).

These findings carry four practical implications. First, short-term IBL interventions prove insufficient; curriculum designers should embed IBL-ESD modules longitudinally across semesters to allow iterative identity development. Second, teacher training must move beyond one-off workshops toward sustained, practice-based programs that explicitly develop skills in facilitating open inquiry and integrating ESD themes. Third, assessment systems need reform: conventional written exams should be complemented by authentic tools such as inquiry rubrics, reflective journals, and validated science identity scales capable of capturing competence, performance, and recognition growth. Fourth, partnerships with local communities and sustainability organizations can provide authentic inquiry contexts that simultaneously strengthen students' recognition as legitimate science actors and advance tangible ESD outcomes.

CONCLUSION

This systematic literature review confirms that Inquiry-Based Learning (IBL) serves as an effective bridge between Science Identity and Education for Sustainable Development (ESD). Although studies on enhancing science identity through the IBL-ESD approach remain limited, the synthesis of the collected empirical evidence consistently reveals the distinctive characteristics of IBL-ESD implementation as well as its positive impact on the three dimensions of Science Identity (competence, performance, and recognition). These findings simultaneously highlight key enabling and

inhibiting factors, and open opportunities for further research to explore the specific mechanisms and most effective IBL-ESD implementation strategies for building science identity. Institutionally, this calls for integrating IBL-ESD modules into core curricula, funding sustained lecturer training in inquiry-based pedagogies, and formalizing community partnerships to provide authentic contexts for inquiry and identity recognition. Thus, this SLR not only maps existing evidence but, more importantly, serves as a solid foundation for designing more focused and context-specific follow-up studies.

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