

Systematic Review

Integrating GreenComp and UNESCO ESD Learning Objectives in Science Teacher Education: A Scoping Review Design with a Critical-Conceptual Analytical Approach

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Abstract

The growing acceleration of socio-ecological crises has increased demands for higher education to move beyond disciplinary teaching toward competence-based sustainability education. In science teacher education, this shift requires not only aligning curricula with the Sustainable Development Goals (SDGs) but also developing transformative sustainability competencies. This review analyzes the relationship between UNESCO's Education for Sustainable Development (ESD) learning objectives and the European GreenComp framework, exploring their integration into science education programs. Based on a qualitative thematic review of 65 publications published between 2015 and 2025, the study identifies a strong emphasis on normative and methodological aspects of sustainability education, while critical-political perspectives and futures literacy remain less represented. The paper proposes an integrative model built around three interconnected dimensions: SDG-oriented learning objectives, sustainability competences, and a critical socio-ecological perspective. The findings indicate that effective curriculum design in science teacher education must combine content-oriented and competence-oriented approaches. UNESCO's ESD objectives provide socio-environmental relevance and normative guidance, whereas GreenComp contributes systems thinking, anticipatory competences, and action-oriented learning. However, the review warns that sustainability education risks remaining functional rather than transformative unless issues of power, inequality, and socio-ecological justice are explicitly addressed.

Keywords: sustainability competences; GreenComp; science teacher education; transformative sustainability education; education for sustainable development; sustainability in higher education



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1. Introduction

The intensification of contemporary socio-ecological crises has called into question the epistemological, ethical and pedagogical foundations of higher education. In recent years, a broad body of literature has converged in arguing that these crises should be understood as complex and interdependent phenomena, characteristic of complex adaptive systems in which environmental, social and economic dimensions interact [1]. This dynamic not only exhausts biophysical resources; it is also often framed through a technical narrative

of efficiency that shifts debate toward material management, encouraging a depoliticization of sustainability that obscures the power structures responsible for the crisis. In this context, the planetary boundaries framework developed in [2] warns that human activity has crossed several critical biophysical thresholds, compromising the stability of the Earth system.

This reality has multiple manifestations: climate change, accelerated biodiversity loss, disruption of biogeochemical cycles, soil degradation and increasing pressure on freshwater. These dynamics are closely linked to a linear economic model based on extraction, production, consumption and disposal, characterized by massive waste generation and limited material circularity. However, their effects are not distributed equally: the most vulnerable populations experience their consequences most intensely, deepening structural inequalities and reinforcing dynamics of climate injustice.

This gives rise to an ecological and economic crisis to which a frequently underestimated social and cultural dimension must be added. In this sense, the current crisis challenges not only productive systems but also forms of social relationship and community building. The weakening of community ties and the decline in participation in traditional support networks, such as neighborhood associations or collective spaces, have direct implications for social cohesion, emotional well-being and the capacity for collective responses to contemporary challenges.

Different studies distinguish between education as a mechanism for reproducing the existing order and education as a tool for social transformation. The former tends to reproduce epistemological frameworks and socio-economic structures that have contributed to the current crisis. The latter seeks to generate critical, ethical and practical capacities oriented toward the construction of sustainable futures [3,4]. As Sterling [5] argues, the issue is not simply what to teach, but whether education is helping to maintain unsustainable systems or to transform them.

In the field of science teacher education, this tension is particularly relevant. Traditionally, science teaching has been oriented toward the transmission of decontextualized disciplinary knowledge. In contrast, sustainability-oriented science education must integrate scientific knowledge with an epistemological dimension that replaces reductionism with the language of complexity [6]. This involves addressing contemporary problems through an understanding of self-organized, far-from-equilibrium systems, where concepts such as entropy and uncertainty become structuring axes for critical reflection and ecosocial transformation.

In this context, two reference frameworks have gained prominence on the international educational agenda: Education for Sustainable Development (ESD), promoted in [7], and the GreenComp framework [8]. While ESD articulates learning objectives aligned with the Sustainable Development Goals (SDGs), providing a normative and thematic basis, GreenComp proposes a set of action-oriented competences for contexts of complexity and uncertainty through four areas: embodying sustainability values, embracing complexity, envisioning sustainable futures and acting for sustainability.

This review article starts from the hypothesis that, although the literature warns of the risk that certain processes of curricular integration may reproduce adaptive rather than transformative approaches, both frameworks, when approached critically, can help move education from a reproductive logic toward a transformative one. In particular, we argue that the SDG-related learning objectives operate as a framework for problem definition (what to learn), whereas GreenComp competences function as a framework for response capacity (how to act). In addition, the explicit integration of critical perspectives such as climate justice or the analysis of power structures prevents this articulation from resulting in superficial approaches or even in merely declarative forms of sustainability.

Based on this conceptual framework, this study is structured around the following research question:

To what extent can the integration of the Education for Sustainable Development learning objectives (ESD-UNESCO) and the competences of the GreenComp framework reconfigure science teacher education toward a transformative approach?

To answer this question, the article develops a critical review of the literature published between 2015 and 2025 in the field of sustainability education and science education. This approach makes it possible to integrate theoretical contributions, empirical studies and pedagogical proposals in order to identify patterns, tensions, gaps and emerging trends in recent research. Beyond a descriptive synthesis, the review adopts an analytical and interpretive orientation aimed at problematizing the epistemological and pedagogical assumptions underlying the ESD and GreenComp frameworks, as well as assessing their real potential to promote meaningful educational transformations.

The analysis is organized around three main axes: (1) the conceptual relationship between SDG-oriented learning objectives and sustainability competences; (2) the tensions and limitations associated with their implementation, including risks of superficiality, depoliticization or merely declarative integration of sustainability; and (3) emerging practices in higher education that seek to operationalize this integration through critical, systemic and transformative pedagogical approaches.

On this basis, the article not only synthesizes the current state of knowledge but also proposes avenues for research and educational practice, contributing to the debate on the role of science education in the transition toward sustainable societies and on the limits and possibilities of education as a tool for ecosocial transformation.

1.1. SDG-Oriented Learning Objectives: Scope, Contributions and Limitations

UNESCO's Education for Sustainable Development learning objectives [8] have had a global impact on the curricular reorientation toward sustainability. Their main strengths are, first, connecting scientific knowledge with concrete socio-environmental challenges and, second, providing internationally comparable cognitive, socio-emotional and behavioral objectives.

Nevertheless, several authors have pointed out that the SDGs, on which the ESD guide is based, tend to operate as a broad but conceptually ambiguous normative framework in which potentially contradictory objectives coexist, such as economic growth and ecological sustainability. This ambiguity may result in superficial implementation in educational contexts, where the SDGs are incorporated as labels rather than as critical frameworks of analysis [9].

Therefore, although the ESD learning objectives represent progress in curricular specification, they require the support of robust competence frameworks in order to avoid superficial implementation [10]. Knowing the specific SDG targets is not enough; systems thinking is needed to understand geopolitical variables, and futures literacy is required to design resilience scenarios. The integration of these elements provides a solid values framework for addressing controversial issues in the education of future teachers [11].

1.2. GreenComp: Transformative Potential and Internal Tensions

To overcome the aforementioned normative and sometimes static nature of the SDGs, the GreenComp framework emerges. According to Bianchi [6], it introduces an important pedagogical shift by moving the axis of science education from the mere accumulation of biophysical data toward the acquisition of competences that enable students to act as critical and systemic thinkers in the face of the current planetary emergency. Its four dimensions—values, complexity, futures and action—form a competence-based model

oriented toward transformation. Recent research shows that GreenComp facilitates the transition toward more participatory and future-oriented pedagogies in teacher education [11,12].

The integration of sustainability into science teacher education should not be understood as the mere addition of content, but as a transition toward an Epistemological Dimension (ED) grounded in complexity [6]. In this sense, adopting the language of complexity makes it possible to move beyond individualistic solutionism by situating environmental problems as emergent properties of interconnected socio-ecological systems, where transformative action depends not only on personal behavioral changes but also on understanding structural interdependencies. Following Preiser [1], an approach based on complex adaptive systems is proposed, one that recognizes the interdependencies and self-organization of living systems; this is essential if pre-service teachers are to understand biophysical limits and the dynamic nature of contemporary society.

Nevertheless, the implementation of GreenComp in Faculties of Education raises important epistemological and pedagogical tensions. As Vargas and Kong [13] note, this educational reorientation requires moving beyond a traditional scientific literacy focused exclusively on disciplinary content and advancing toward transdisciplinary approaches capable of connecting scientific knowledge with socio-environmental responsibility. However, part of the critical literature warns that GreenComp may lead to forms of ‘psychologization’ of the climate crisis, reinterpreting structural problems such as individual deficits in behavior, skills or attitudes.

From this perspective, there is a risk that the education of future teachers may overemphasize individual responsibility to the detriment of analyzing the economic, political and corporate structures that sustain the ecosocial crisis. This individualization may generate feelings of frustration or eco-anxiety [14]. In addition, the GreenComp framework has only a limited presence of categories explicitly linked to climate justice, degrowth or political economy, often placing it within an institutional neutrality compatible with green modernization agendas [15].

Consequently, the literature identifies three main tensions around GreenComp: (1) the risk of individualistic solutionism, which shifts the focus from structural transformations to personal changes; (2) the limited presence of critical categories linked to power, climate justice and ecosocial inequalities; and (3) a degree of institutional neutrality that makes it difficult to address socio-scientific controversies from explicitly critical perspectives. These limitations suggest that the acquisition of sustainability competences cannot be reduced to training in ‘correct’ behaviors, but must incorporate processes of ethical reflection, political analysis and systemic understanding of the relationships between science, society and nature.

In this regard, several authors argue that the transformative potential of GreenComp depends on its articulation with critical pedagogical approaches capable of moving beyond superficial or merely declarative curricular integration. Laherto et al. [12] emphasize that sustainability competences only acquire meaning when they are linked to educational practices oriented toward collective action and democratic deliberation. Similarly, Wolff et al. [16] warn that many educational policies oscillate ambiguously between behaviorist objectives and transformative goals, hindering the consolidation of truly critical educational models. The challenge, therefore, does not lie only in incorporating sustainability transversally, but in constructing formative processes that enable students to interpret and act upon complex and uncertain problems from an ecosocial perspective [7].

This curricular transformation requires a profound rethinking of the role of science teachers. Beyond transmitting technical content, teachers must integrate cognitive, procedural, ethical and emotional dimensions that foster a relational understanding of the Earth

system and of the interdependencies among ecological, social and economic processes [17]. From this viewpoint, science education becomes a potential space for promoting transformative learning aimed at reconstructing relationships between human beings and nature, overcoming fragmented educational models that are insufficient in the face of contemporary climate uncertainty [17]. In line with this, Woiwode et al. [18] underline the need to incorporate processes of inner transformation as a leverage point for sustainability, recognizing that teachers not only teach science but also mediate forms of ethical relationship with the biosphere and positions toward contemporary crises.

1.3. Bridging the Gap: Towards an Integrated Model of Content and Competence

The literature suggests that neither approaches based exclusively on content (SDGs) nor those focused solely on competences (GreenComp) are sufficient on their own to address the complexity of sustainability. In this context, there is a prevailing need for educational approaches that address sustainability as a problem characterized by high levels of uncertainty, conflicting values and urgent decisions.

Nevertheless, despite the growing institutional consensus on the need to incorporate sustainability into higher education, several studies reveal a persistent gap between normative discourses and their effective implementation in university curricula [19]. In many cases, sustainability continues to be integrated in a fragmented way, through isolated content or decontextualized competences, without deeply transforming educational purposes or teaching practices [5].

In this scenario, hybrid proposals are beginning to emerge that attempt to articulate SDG-oriented learning objectives with competence frameworks for sustainability. Within Education degrees, science education occupies a strategic place in this process, since it constitutes the space of didactic transposition in which scientific knowledge acquires social, ethical and political meaning [20].

1.4. Science Education as an Opportunity for the Critical Integration of Sustainability

The incorporation of sustainability into science education has gradually evolved from approaches centered on environmental literacy toward more complex perspectives that integrate social, ethical, political and cultural dimensions. This shift reflects a significant epistemological change in the understanding of science as a social practice, rather than as neutral knowledge detached from power dynamics and contemporary conflicts [5]. However, despite the growing normative and discursive development around Education for Sustainable Development (ESD), several studies show that its implementation in higher education remains fragmented, superficial and, in many cases, disconnected from robust theoretical frameworks capable of promoting deep transformations in educational processes.

In Education degrees, this disconnection is often manifested in the persistence of approaches centered on isolated content, the limited incorporation of critical methodologies and the presence of reductionist conceptions of socio-environmental problems among future teachers. In this context, Environmental Education for Sustainability (EES) from a critical perspective becomes especially relevant. It conceives sustainability not as a set of desirable individual behaviors, but as a socio-political process aimed at questioning and transforming power relations, development models and the structures that reproduce socio-ecological inequalities and injustices [5].

From an epistemological perspective, critical EES is grounded in frameworks such as political ecology, critical pedagogy and complexity theory [21], which make it possible to understand the socio-environmental crisis as a multidimensional phenomenon shaped by historical inequalities, distributive conflicts and hegemonic models of production and consumption. From this perspective, it is essential to move toward the paradigm of complex

adaptive systems, which allows pre-service teachers to overcome determinism through the understanding of self-organized phenomena and non-equilibrium processes [6]. These approaches challenge technocratic views that reduce sustainability to problems of efficiency or individual adaptation, proposing instead educational models oriented toward social and ecological justice, an ethics of care and transformative collective action [22]. Consequently, teacher education must promote multiple literacies—scientific, ethical, political, ecological and emotional—that enable a critical interpretation of the complexity of contemporary problems.

Within this framework, active methodologies linked to science education acquire a particularly relevant role. Strategies such as socio-scientific controversies, learning based on socio-environmental problems, collaborative inquiry and community-oriented service learning have shown significant potential for developing critical and transformative competences among university students [20]. These methodologies foster connections between scientific concepts and real contexts, make visible the ethical and political dimensions of science and promote reflective processes oriented toward informed and socially responsible decision-making, that is, an “authentic learning”. Likewise, recent research highlights that the incorporation of emotions, narratives and decolonial perspectives contributes to building more complex, situated and relational understandings of socio-environmental problems [14].

However, the possibilities for educational transformation do not depend exclusively on classroom practices but also on institutional and structural factors (which are not being analyzed, so it is a possible limitation of this study). The literature recurrently identifies obstacles such as insufficient specific training for university teachers, the absence of binding criteria for curricular sustainability and the rigidity of study plans [23,24]. Despite advances in international and national sustainability agendas, a considerable distance persists between institutional discourses and effective teaching practices, which highlights the need for comprehensive approaches capable of overcoming merely declarative or performative sustainability [5].

In this scenario, science education is configured as a strategic space for articulating critical and ecosocial science education. Drawing on contemporary approaches linked to systems thinking, socio-scientific controversies and critical scientific literacy, this field makes it possible to problematize the production of scientific knowledge, its socio-political dimension and its role in understanding current socio-environmental conflicts [20]. Several studies show that situated work with real problems, project-based learning, scientific inquiry and service learning can promote significant transformations in the conceptions of pre-service primary teachers, strengthening both their capacity for critical analysis and their perceived educational efficacy for addressing sustainability in diverse school contexts [25]. This methodological approach is essential for fostering scientific literacy oriented toward action and transformative agency in the face of the climate crisis.

From this perspective, it is essential to examine how sustainability can be integrated through critical approaches in initial teacher education, while simultaneously considering the epistemological, pedagogical and institutional dimensions that condition such integration. This analysis is particularly relevant for advancing toward educational models oriented not only to the development of sustainability competences but also to the promotion of social and ecological justice, democratic participation [26] and the transformation of educational practices in a context marked by climate uncertainty and contemporary ecosocial complexity [17].

2. Materials and Methods

2.1. Review Design

This study adopts a scoping review design with a critical-conceptual analytical approach. The review is guided primarily by the PRISMA extension for scoping reviews (PRISMA-ScR) [27], which provides a structured framework for the identification, screening, eligibility, and inclusion of studies, and transparent reporting of evidence in exploratory reviews.

The main objective is to analyze, in an integrated manner, the relationship between the Education for Sustainable Development (ESD) learning objectives promoted by UNESCO and the European GreenComp sustainability competence framework, situating this articulation in the specific context of initial science teacher education.

Unlike traditional systematic reviews aimed at evaluating the effectiveness of interventions or synthesizing homogeneous quantitative results, this research adopts a scoping review design which is particularly appropriate for mapping emerging, heterogeneous, and conceptually complex fields. This methodological design responds to an increasingly consolidated line of research in education and sustainability, which recognizes the limitations of traditional systematic reviews for addressing questions of a conceptual, normative and critical nature.

In this sense, the PRISMA-ScR protocol ensures transparency, traceability and reproducibility in the bibliographic search and selection process, while the critical-conceptual approach makes it possible to identify emerging patterns, epistemological tensions, structural gaps and contradictions in the recent literature on sustainability and science teacher education. This scoping review followed the PRISMA-ScR stages of identification, screening, eligibility, and inclusion of studies, together with systematic data charting for subsequent qualitative synthesis.

In line with recent reviews in the field of sustainability and higher education [9,10], the study integrates two complementary dimensions. On the one hand, a systematic component aimed at ensuring the transparency and traceability of the process of identifying, screening and selecting relevant documents through replicable bibliographic search procedures and the application of inclusion and exclusion criteria; on the other, a critical-interpretive component intended to examine the epistemological, pedagogical and political assumptions underlying the sustainability frameworks analyzed, as well as the tensions derived from their implementation in science education and teacher education.

This approach is especially pertinent because of the conceptual and normative nature of the frameworks analyzed. Both GreenComp and UNESCO's learning objectives go beyond the strictly technical or curricular level, incorporating specific visions of the role of education in the transition toward sustainable societies. Therefore, in addition to describing research trends, the review aims to critically problematize how sustainability competences are conceptualized, which educational dimensions are prioritized and which remain marginal or insufficiently developed.

The review is situated in the field of Higher Education for Sustainability (HESD) and addresses the convergence among different areas of research: sustainability competences, science education, teacher education, transformative learning, systems thinking and critical perspectives on ecosocial education. From this perspective, the study is not limited to identifying emerging practices or pedagogical approaches; rather, it seeks to understand the discursive logics and educational models that currently guide the integration of sustainability into science education.

The review process followed the main phases established by the PRISMA 2020 statement: identification of records through systematic searches in academic databases, removal of duplicate documents, initial screening through review of titles and abstracts, full-text

assessment according to previously defined inclusion and exclusion criteria and final selection of the studies included in the qualitative synthesis and critical analysis.

The adoption of this methodological design made it possible to combine procedural consistency and analytical depth, favoring a comprehensive understanding of the potentialities and limitations of integrating ESD and GreenComp in science teacher education.

2.2. Databases and Search Strategy

The bibliographic search was carried out using two databases widely recognized in educational and sustainability research: Scopus and Web of Science (WoS), the two most widely used databases in these fields.

The period covered publications between 2015 and 2025, coinciding with the consolidation of the Sustainable Development Goals (SDGs), the international expansion of Education for Sustainable Development (ESD) and the creation of the GreenComp competence framework. Only peer-reviewed journal articles published in English or Spanish between 2015 and 2025 were considered eligible for inclusion.

The search criteria were based on combinations of keywords in English and Spanish and the use of Boolean operators (AND/OR) to refine thematic relevance. The complete search strategy (example for Scopus) was reconstructed as an advanced query and is included in the manuscript as Figure 1. The authors have decided not to include the category of science education as a criterion, which is going to be analyzed in depth in future works.

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TITLE-ABS-KEY ( ( "Education for Sustainable Development" OR "EDS")
OR ( GreenComp OR "sustainability competenc*") AND ( "teacher
education" OR "pre-service teacher*") AND ( LIMIT-TO (DOCTYPE, "ar")
OR LIMIT-TO (DOCTYPE, "re") ) AND LIMIT-TO ( LANGUAGE, "English")
OR LIMIT-TO ( LANGUAGE, "Spanish") )
```

Figure 1. Advanced search query in SCOPUS. The asterisk (*) indicates a truncation operator used to retrieve multiple word ending.

2.3. PRISMA Process: Identification, Screening, Eligibility and Selection

The process followed the four PRISMA phases, as shown in Figure 2. The bibliographic search in Scopus ($n = 46$) and Web of Science ($n = 50$) identified a total of 96 records. After removing 22 duplicates, 74 unique records remained for screening.

All 74 records were screened based on titles and abstracts, and none were excluded at this stage. The full texts of the 74 remaining studies were assessed for eligibility. Nine studies were excluded for not meeting the inclusion criteria, including lack of ESD/GreenComp competence focus, no connection with teacher education, superficial integration of sustainability, or exclusive technical-industrial orientation without educational relevance.

The final sample consisted of 65 studies, which were subjected to thematic and conceptual analysis. For each included study, information regarding publication year, study type, educational context, sustainability framework(s), and thematic focus was extracted prior to the coding process.

The analytical categories were developed through an iterative coding process combining deductive and inductive approaches. An initial coding framework was established based on the objectives of the review and the conceptual dimensions of GreenComp and UNESCO's ESD learning objectives. This framework was progressively refined during the analysis of the selected studies to incorporate emerging themes, resulting in the six analytical categories presented in this review. Coding decisions were discussed among the authors

until consensus was reached, ensuring consistency in the classification and interpretation of the studies.

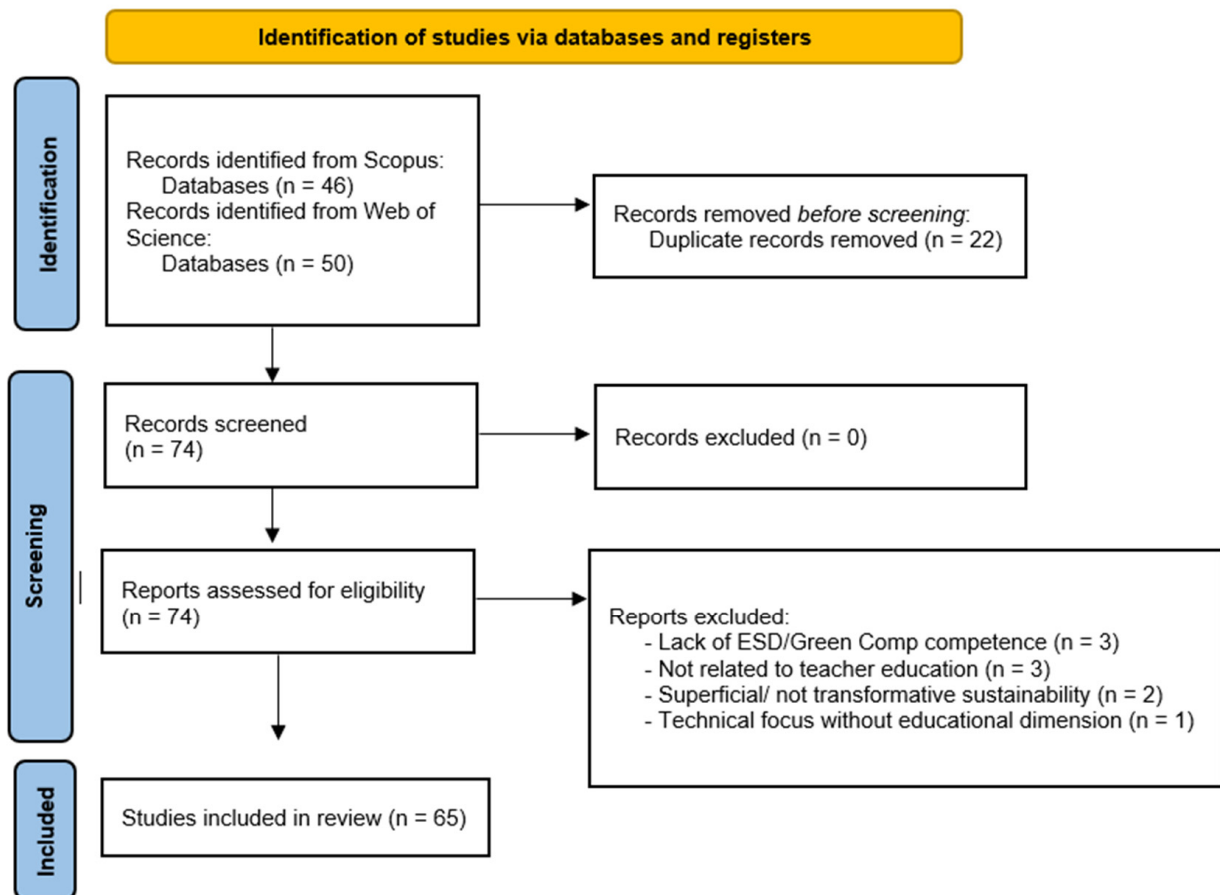


Figure 2. PRISMA 2020 flow diagram for new systematic reviews, which included searches of databases and registers only.

The included references covered normative (SDG-UNESCO), competence-based (GreenComp), epistemological, pedagogical and critical approaches, allowing a comprehensive analysis of the integration of sustainability frameworks into science teacher education.

No formal critical appraisal of methodological quality was undertaken because the purpose of this scoping review was to map and critically synthesize the existing literature rather than evaluate the effectiveness or risk of bias of individual studies.

2.4. Use of Generative AI Tools

Artificial Intelligence (AI) was used exclusively for the graphical preparation of Figure 3. Specifically, OpenAI's ChatGPT image generation tool was employed to transform an author-developed conceptual framework into a graphical representation. The conceptual model, scientific content, structure, and interpretation of the figure were entirely designed, reviewed, and validated by the authors. The AI tool was not used for literature searching, study selection, data extraction, coding, data analysis, interpretation of results, or manuscript writing. The authors assume full responsibility for the accuracy and integrity of all scientific content presented in the manuscript.

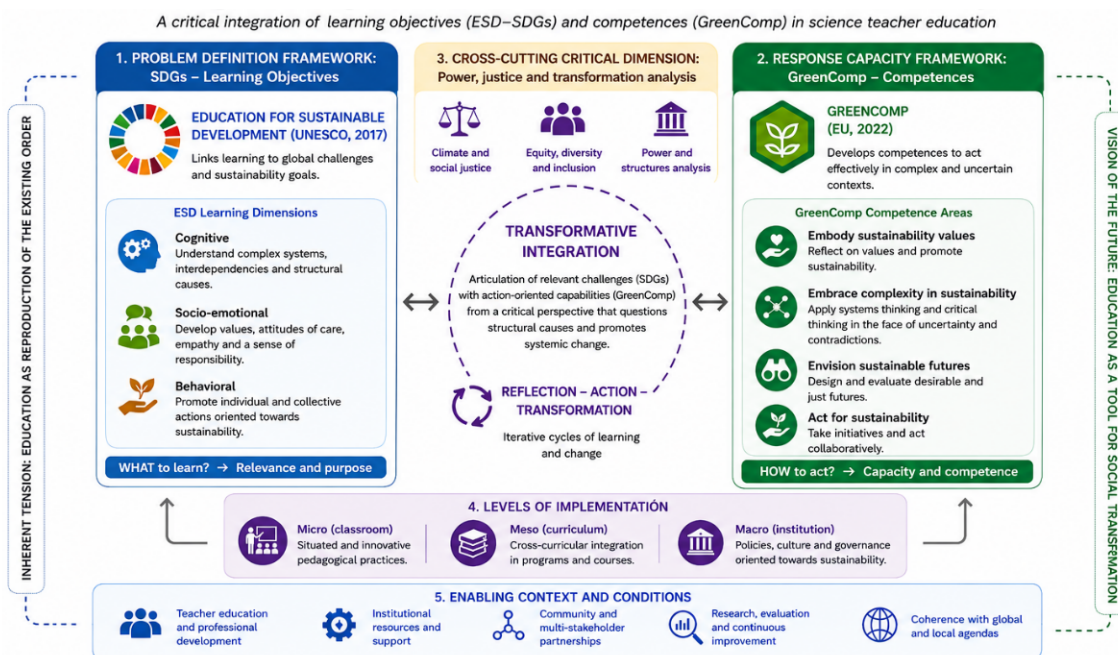


Figure 3. An integrative framework for transformative science education for sustainability. Source: authors' own elaboration using OpenAI's ChatGPT image generation tool.

3. Results

The thematic analysis of the 65 selected studies made it possible to build a system of six analytical categories aimed at systematically examining the integration between the Education for Sustainable Development learning objectives (ESD-UNESCO) and the GreenComp competence framework in science teacher education. These categories were defined through a deductive–inductive coding process and were articulated through analytical questions that guided the interpretation of the reviewed literature. The analysis also incorporated the epistemological dimension proposed in this study, understood as the need to problematize the forms of production, validation and application of scientific knowledge in sustainability contexts.

The six categories were organized around two complementary analytical axes. The first, descriptive–diagnostic in nature (Categories 1–3), examined the predominant conceptual frameworks, the treatment of complexity and the incorporation of ethical and emotional dimensions. The second, critical–propositive in nature (Categories 4–6), analyzed anticipatory capacities, the critical depth of educational proposals and the pedagogical strategies used to promote educational transformation processes oriented toward sustainability. The findings are presented below by category.

- Category 1. Reference frameworks and operationalization of ESD competences (Normative predominance)

This category, articulated around the analytical question ‘which normative and conceptual frameworks structure initial science teacher education and which dimensions of learning do they prioritize?’, examines the conceptual and normative frameworks that support sustainability education in teacher education, including GreenComp, the 2030 Agenda and the SDGs. The analysis focused on identifying how sustainability competences are conceptualized and the extent to which studies integrate in a balanced way the cognitive, socio-emotional and behavioral dimensions proposed by UNESCO, as well as the degree of curricular operationalization of these competences.

The results indicate that this is the most densely populated category in the review. Most studies focus on translating international frameworks (SDG-UNESCO and, more

recently, GreenComp) into assessable competences in the university setting. A transition is observed from basic ‘environmental literacy’ toward more complex competence models that attempt to cover cognitive, socio-emotional and behavioral dimensions. Authors such as Cebrián et al. [23] and Vargas and Kong [13] highlight how international policy acts as the main driver of curricular change, although with the risk of superficial or merely declarative implementation.

- Category 2. Systems thinking and complexity in science education (The disciplinary approach)

Under the analytical question ‘how is complexity addressed in scientific disciplinary contexts and to what extent is a reductionist view of knowledge overcome?’, this category analyzes the incorporation of systems thinking and complexity theory into science education. It examined whether the studies maintain technocratic approaches focused on the efficient management of environmental problems or whether they integrate perspectives based on complex adaptive systems, interdependence and non-linearity, as well as concepts linked to uncertainty, self-organization, non-equilibrium processes and relationships among ecological, social and economic dimensions [6].

The analysis indicates that systems thinking appears as a natural strength of science education, given its connection with biophysical and ecological concepts. The studies in this category [28,29] show that scientific training facilitates the understanding of complex systems such as the carbon cycle or the water–energy–food nexus. However, the risk of ‘scientism’ persists: a tendency to reduce sustainability to a problem of technical management or material efficiency, while ignoring the socio-political roots of the crisis.

- Category 3. Socio-emotional dimension, values and ecological citizenship

This category responds to the analytical question ‘what role do emotions, values and teacher identity play in education for sustainability?’ and is especially linked to the ‘embodying sustainability values’ area of the GreenComp framework. The analysis aimed to identify how studies incorporate affective, ethical and value-based dimensions into teacher education, including ecocritical approaches, emotional literacy, ecological empathy and active citizenship, as well as the role of narratives, reflective experiences and participatory methodologies in constructing teacher identities committed to sustainability.

The results show that, despite being recognized by UNESCO as essential, this category is less represented in the tradition of science teaching than cognitive categories. Studies such as those by Goga and Pujol-Valls [30] or Mróz et al. [31] explore the use of narratives, emotions and teacher identity as pathways for fostering genuine ecological citizenship. ‘Teacher identity for sustainability’ is identified as a critical factor: teachers must not only know science but also develop an ethics of care toward the biosphere.

- Category 4. Futures competences and anticipatory literacy

The analytical question guiding this category is ‘how is the capacity to imagine alternative futures, face uncertainty and design resilient responses promoted?’ The analysis focused on proposals aimed at encouraging the imagination of sustainable scenarios, decision-making in uncertain contexts and the construction of educational responses to complex socio-environmental problems, acting as a bridge between systemic knowledge and transformative action.

The analyses show that this category has a minority representation in the corpus compared with C1 and C6. The identified studies incorporate tools for prospective thinking, future scenarios and anticipatory literacy, although often peripherally with respect to the central aim of each work. Only a subset of articles explicitly addresses the development of anticipatory competence as a formative axis. Represented by authors such as

Livrini et al. [17] and Ratinen and Linnanen [32], this category focuses on the capacity of future teachers to imagine possible, desirable and just scenarios. ‘Futures Literacy’ is identified as the ‘hinge’ that enables a shift from knowledge of disaster (past/present) to transformative action (future).

- Category 5. Critical dimension and socio-ecological justice (The structural gap)

Under the analytical question ‘to what extent do the studies incorporate structural analyses of inequality, power and climate justice?’, this category examines the degree to which the reviewed literature integrates critical perspectives related to socio-ecological justice, inequality, models of intensive resource exploitation and the political economy of sustainability. The objective was to identify whether the combination of ESD and GreenComp is limited to functional approaches or whether it promotes transformative pedagogies capable of questioning the structures that sustain the contemporary ecosocial crisis.

According to the review conducted, this is the least represented category in the analyzed corpus. Studies that explicitly address justice, the structural causes of the ecological crisis or political ecology frameworks in science teacher education represent a minority [33,34]. Most of the works classified in C5 do so tangentially, incorporating elements of critical analysis as a secondary dimension of studies mainly oriented toward C1 or C6. The existing literature concentrates on systems thinking from a predominantly technical perspective, with limited attention to the socio-economic and political determinants of the ecosocial crisis.

- Category 6. Pedagogical design and teacher-education strategies (The ‘how’)

This transversal category, articulated around the analytical question ‘which didactic strategies are used to develop sustainability competences and what evidence exists regarding their educational potential?’, focused on the methodologies and pedagogical devices employed in teacher education. Strategies such as project-based learning, inquiry-based science education (IBSE), service learning, socio-scientific controversies and other active methodologies oriented toward sustainability were coded, relating them to the competences they foster and to the reported evidence on their formative impact.

The results indicate that, together with C1, this is the category with the greatest production, centered on practical operationalization. The most effective strategies identified are Project-Based Learning (PBL), Socio-Scientific Controversies (SSC) and Service Learning (SL). These active methodologies are shown to be the main vehicle for attempting to close the ‘knowledge-action gap’ in Faculties of Education.

Table 1 presents the complete classification of references according to the categories. The screening results reveal that the final corpus ($n = 65$) makes it possible to identify predominant trends and critical gaps in the literature on the integration of sustainability into science teacher education. The characteristics of the 65 studies included in the review, including publication type, educational context, sustainability framework, main contribution, and analytical category, are summarized in Supplementary Table S1.

It is important to emphasize that the proposed IFET model represents a theoretical interpretation derived from the review rather than an empirical outcome; the distinction between review findings and conceptual propositions should be clear.

Overall, the distribution of the literature reflects a field of research with a solid normative and methodological basis, but with important fractures in the integration of socio-ecological justice and futures literacy. This limited presence of climate justice approaches suggests a tendency to operationalize sustainability from predominantly technocratic and individualized perspectives. The following section discusses how the proposed articulation model between UNESCO and GreenComp can act as a catalyst for overcoming these tensions and moving toward transformative ecosocial science.

Table 1. Complete classification of references according to categories.

Reference	C1	C2	C3	C4	C5	C6
Aguirregoitia et al. (2025) [35]			X			X
Ammonet et al. (2022) [36]	X					X
Aragon et al. (2025) [37]	X		X			
Asikainen & Tapani (2021) [38]	X					X
Baena-Morales et al. (2023) [39]		X				X
Baptista et al. (2025) [25]		X				X
Blasco-Magraner et al. (2025) [40]	X		X			
Bowden (2025) [41]	X		X			
Bozkurt & Bozkurt (2024) [42]	X	X				
Brandt et al. (2021) [43]	X		X			
Bürgener & Barth (2018) [33]	X				X	
Buseth et al. (2025) [44]	X					X
Calero et al. (2025) [34]	X				X	
Campagnaro & Goga (2022) [45]			X		X	
Castaño et al. (2025) [46]	X					X
Cebrián et al. (2019) [23]	X					
Ceulemans & Severijns (2019) [47]	X					X
Chuliá-Jordán et al. (2022) [48]	X					X
Fuertes-Camacho et al. (2021) [49]	X				X	X
Gavinolla et al. (2022) [50]	X					
Goga & Pujol-Valls (2020) [30]			X		X	
Goller & Markert (2025) [51]	X					
Guo et al. (2024) [52]	X	X				
Haim & Aschauer (2024) [53]	X		X			X
Hay & Simamane (2025) [54]		X			X	X
Hogan & O’Flaherty (2021) [26]	X					X
Imara & Altinay (2021) [55]	X					
Kadji-Beltrán (2024) [56]	X					X
Karvonen & Ratinen (2025) [57]	X					
Karvonen et al. (2023) [58]	X					X
Lasen, Tomas & Hill (2015) [59]	X				X	X
Lautensach et al. (2025) [60]	X	X			X	
León et al. (2025) [61]			X		X	
Levrini et al. (2023) [17]	X	X		X		
Lorente-Echeverría et al. (2022a) [19]	X					
Lorente-Echeverría et al. (2022b) [62]	X					
Miani et al. (2025) [63]		X		X		X
Motzfeldt & Häggström (2025) [64]				X		X
Mróz et al. (2025) [31]			X			X
Muñoz-Losa et al. (2025) [65]	X		X			
Murphy et al. (2020) [66]	X					X
Padial-Ruz et al. (2025) [67]	X					X
Pérez-Martín & Esquivel-Martín (2024) [68]	X				X	X
Ratinen & Linnanen (2022) [32]	X			X		
Reed et al. (2025) [29]	X	X				
Riuttanen et al. (2021) [69]	X	X				
Sá et al. (2022) [70]	X					
Saseendran & Thomas (2025) [71]	X	X				X
Shpak & Vasques (2023) [72]			X		X	X
Singh & Sharma (2025) [73]	X					
Singh-Pillay (2023) [74]	X					X
Singh-Pillay (2025) [75]	X					X
Solís-Espallargas & Morón-Monge (2020) [76]	X					X

Table 1. *Cont.*

Reference	C1	C2	C3	C4	C5	C6
Stouthart et al. (2025) [77]	X					
Su et al. (2024) [78]	X					X
Suh et al. (2020) [79]	X					X
Tabassum et al. (2025) [80]		X				X
van Harskamp et al. (2024) [81]	X					X
van Herten & Perez (2022) [82]			X		X	
Vargas & Kong (2022) [13]	X				X	X
Vergara-Arteaga et al. (2025) [24]	X					
Villena-Martínez et al. (2024) [83]	X		X			
Vuorio et al. (2024) [28]		X				X
Vuorio et al. (2025) [84]		X				X
Yli-Panula et al. (2025) [85]	X					
Total number of references per category	50	14	14	4	13	34

Authors own elaboration. The X indicates the category to which the research refers.

4. Discussion and Conclusions

The cross-category analysis shows that the reviewed literature has produced more work on normative frameworks (C1) and pedagogical strategies (C6), while the critical dimension (C5) remains significantly underrepresented. Regarding what the reviewed literature shows, the results reveal a central tension in initial science teacher education: there is a consolidated corpus on ‘what’ to teach (UNESCO objectives) and on ‘how’ to organize competences (GreenComp), but a notable gap persists around the structural dimensions of the ecosocial crisis.

The analysis of the literature suggests that UNESCO’s objectives function as thematic guidance, providing the necessary socio-environmental content (e.g., climate change, biodiversity loss). However, as observed in Category C1, these objectives tend to become an enumeration of topics if they are not supported by the procedural and systemic dimension contributed by GreenComp. In this sense, the reviewed studies suggest that the integration of both frameworks generates a synergy in which the SDGs provide thematic relevance and GreenComp provides an orientation toward action.

One of the most relevant findings of the review is the limited representation of the dimensions of ‘Critical Thinking’ and ‘Socio-ecological Justice’ (Category C5). Most of the literature in science education remains within a paradigm of functional sustainability, centered on technical solutions or individual behavioral changes (such as recycling or energy saving).

Based on these findings, and as the conceptual contribution of the present study, the Integrative Framework for Ecosocial Transformation (IFET) is proposed. It is important to underline that this model is not derived directly from the review data as if it were an empirical result; rather, it is a theoretical proposal by the authors, constructed from the trends, tensions and gaps identified in the analyzed literature. Its function is to offer an interpretive scheme that coherently articulates the UNESCO and GreenComp frameworks with the underrepresented critical dimension, with a view to guiding future research and curriculum design. Unlike approaches that treat both frameworks in parallel, IFET articulates them in three complementary dimensions:

4.1. Problem-Definition Framework (SDG-UNESCO)

This provides thematic relevance and normative orientation. The UNESCO guide [8] translates the SDGs into learning objectives that make it possible to contextualize scientific knowledge within real-world problems. In our model, this dimension is reinforced through

an Epistemological Dimension (ED) that incorporates the language of complexity to avoid reductionist views of natural phenomena [6].

4.2. Response-Capacity Framework (GreenComp)

This provides action-oriented competences for contexts of uncertainty. Its dimensions make it possible to move beyond the mere acquisition of information, favoring the development of the critical capacities needed to interact with complex adaptive systems [1]. This dimension fosters resilience and agency in the face of the climate crisis, moving students from inaction toward active participation.

4.3. Structural Critical Framework (Climate and Socio-Ecological Justice)

This incorporates a dimension frequently absent from institutional discourses. This perspective makes it possible to analyze the structural causes of the crisis, including global inequalities, power relations and extractives' models. Without this critical dimension, the articulation between the SDGs and GreenComp risks becoming a 'declarative form of sustainability' centered on individual changes and lacking commitment to social justice.

The integration of these three dimensions (Figure 3) forms a pedagogical model oriented toward transformative science education, capable of avoiding technocratic reductionism or merely declarative forms of sustainability integration. It also favors transdisciplinary approaches that make it possible to understand sustainability not only as a technical problem but also as an ethical, political and cultural challenge that requires rethinking the relationships between science, society and nature. In this sense, science education can play a fundamental role in constructing formative practices oriented toward critical thinking, democratic participation and ecosocial transformation.

Figure 3 visualizes this transformative flow. Although the base of the model is grounded in the SDGs, it gains depth through the ESD. Here, relevant scientific knowledge includes the understanding of recursive loops, homeostasis and carrying capacity. As Levrini et al. [17] suggest, this scientific basis not only explains the present; it is also what enables futures literacy (C4), transforming uncertainty into a tool for action. This epistemological solidity is what gives the apex of the critical dimension a real foundation, allowing teachers to act not only as instructors but also as guides in the face of systemic complexity [5].

The incorporation of the critical dimension into the proposed model aims to prevent the science curriculum from drifting toward the superficial integration of sustainability content. By integrating political economy, power structures and the recovery of traditional knowledge, science education ceases to be merely conservative and becomes transformative.

The limited representation of futures literacy (C4) in the literature indicates that teacher education remains predominantly reactive. In line with Sterling [5] and Levrini et al. [17], the present analysis suggests that the integration of the anticipatory area of GreenComp constitutes a relevant direction for research, insofar as the capacity to imagine future scenarios can counteract the paralyzing effects of eco-anxiety and foster agency among future teachers.

The predominance of Category C6 (Pedagogical Strategies) in the reviewed literature shows that the 'how' is well documented, although frequently disconnected from the analysis of the structural causes of the crisis. Consistently with the proposed model, the review suggests that methodologies such as Inquiry-Based Science Education or Socio-Scientific Controversies have greater formative potential when they are explicitly articulated with the critical dimension of the framework.

Finally, there is another possible limitation we should consider: the absence of science education as a criterion, perhaps, made it difficult to identify articles that connect the

categories formed with science education (with the exception of category 2). This affects the documentation of how categories 1 and 3–6 are connected and can influence science education; potential limitations associated with excluding other databases and gray literature sources (only WOS and SCOPUS are considered in this paper) exist, particularly given the interdisciplinary nature of sustainability education research; the review period (2015–2025) or the publication and/or language biases resulting from the search strategy could be a potential limitation of this study. Finally, due to the critical nature of this paper, we assume the necessity of a future validation of these results.

5. Future Directions

The roadmap for future research following this study should focus on the empirical validation and expansion of the proposed integrative model. The following priority lines are suggested:

- Empirical validation in university classrooms: It is necessary to develop case studies and action-research designs that implement the tripartite model in Faculties of Education. This would make it possible to assess how the articulation between GreenComp and UNESCO objectives actually affects the development of the professional identity of pre-service science teachers.
- Assessment instruments for the critical dimension: Given the scarcity of the literature in category C5 (socio-ecological justice), the development and validation of instruments is suggested to measure not only technical knowledge of sustainability but also the capacity for critical analysis of power structures and the ecosocial commitment of future teachers.
- Managing eco-anxiety and futures literacy: A crucial emerging line of inquiry concerns how GreenComp's 'anticipatory competence' can act as a mechanism of resilience in the face of eco-anxiety. Investigating the balance between the rigor of scientific diagnosis and the construction of narratives of active hope is vital for transformative science education.
- Integration of traditional and local knowledge: Future research should explore how the proposed model can effectively integrate traditional knowledge and connections with place (bioregionalism), hybridizing scientific knowledge with community wisdom in order to incorporate epistemically diverse perspectives into sustainability teaching.
- Impact of digital technologies: It is recommended to analyze how the use of tools for visualizing complex systems and digital twins can facilitate understanding of the systemic interdependencies proposed by GreenComp in initial teacher education contexts.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/su18147002/s1>, Table S1: Characteristics of the studies included in the critical scoping review; Table S2: Scoping Reviews (PRISMA-ScR) Checklist.

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Abbreviations

The following abbreviations are used in this manuscript:

SDGs	Sustainable Development Goals
ESD	Education for Sustainable Development

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