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## A Systematic Review on Teaching Natural Sciences for Sustainable Learning: Challenges and Opportunities Experienced by South African Preservice Teachers

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**Abstract.** Sustainable Learning (SL) emphasises contextual relevance, deep knowledge retention, and heutagogical approaches aligned with Education for Sustainable Development (ESD). This systematic literature review synthesises evidence on the challenges and opportunities of applying Problem-Solving Teaching and Learning (PSTL) approaches in Natural Sciences education to prepare Preservice Teachers (PSTs) for SL in South Africa. Guided by PRISMA protocols, 36 peer-reviewed studies (2014–2024) were analysed using ATLAS.ti for thematic coding. Ben-Eliyahu’s five pillars of Sustainable Learning in Education (SLE) provided the theoretical lens for categorising findings. Results indicate that PSTL strategies such as project-based and inquiry-based learning enhance critical thinking, collaboration, and adaptive expertise, essential for sustainability-oriented teaching. However, persistent challenges include inadequate reflective practice, workload stress, limited contextual adaptation, and digital inequities. The review highlights tensions between policy aspirations for democratic, inquiry-driven pedagogies and systemic constraints such as assessment-driven cultures and resource limitations. It concludes that teacher education programs require structural redesign to embed PSTL strategies, strengthen reflective practice, and integrate digital tools responsibly. Recommendations include new approaches to realising curriculum aims, institutional support, and targeted professional development to bridge the theory-practice gap, cultivating teacher competences for SL aligned with multiple developmental plans.

**Keywords:** Sustainable Learning in Education; SLE Framework; Problem-Solving Teaching and Learning; Preservice Teachers; Natural Science; Opportunities; Challenges

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## 1. Introduction

The concept of Sustainable Learning (SL) has gained prominence. SL is active learning that lasts beyond the classroom. It promotes students' autonomy and assumption of responsibility for their learning and the practical application of their information in real-life scenarios (Ben-Eliyahu, 2021; Hays & Reinders, 2020). Accordingly, sustainable pedagogies that encourage preservice teachers (PSTs) to adopt and adapt heutagogical methods that empower learners to engage in critical thinking, community involvement, problem-solving, and other higher-order cognitive skills (Mwinkaar & Lonibe, 2024) (DBE, 2012). By embedding SL principles (Hays and Reinders 2020) in their teaching of Natural Sciences (NS), PSTs can help prepare learners for the future.

In this sense, PSTs would equip learners with the knowledge, skills and values necessary to solve real-world problems and cultivate responsible citizenship (Batista et al., 2024; Singha & Singha, 2024). These notions are consistent with mandatory requirements for teaching NS in South Africa, where PSTs are being prepared to teach in this case. According to the South African NS Curriculum and Assessment Policy Statement (CAPS), PSTs are obliged to select NS content, use variety of teaching approaches to promote among other vital aspects, "the contribution of Science to social justice and societal development" as well as, "the need for using scientific knowledge responsibly in the interest of ourselves, of society and the environment" (DBE, 2012, p. 9). The alignment among SL, NS and the teaching of NS which implicates PSTs in this context, is therefore prominent.

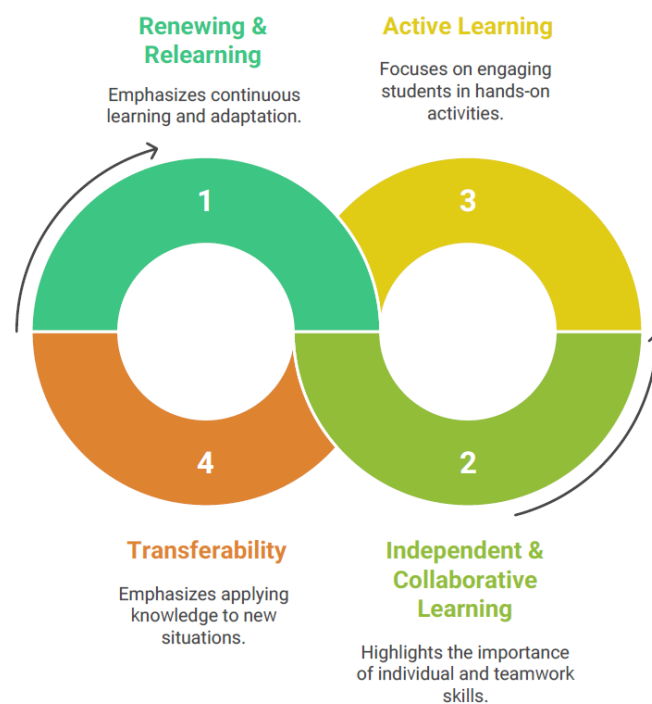
As society, the economy, and the environment continue evolving and knowledge is being developed and updated, it is increasingly critical that pedagogical approaches are also sustainable to unshackle and cultivate students' potential. As such, there has been a demand for transformative educational approaches to enable students to navigate socio-scientific issues, contribute to sustainable development, and respond to socio-economic gaps (Bossér, 2024); herewithin lies the backdrop of this study. The outpouring evolution of global challenges, akin to climate change, resource depletion, and socio-political inequalities, requires educational systems to adapt, preparing students for the present and a future where they can actively engage with and resolve these pressing issues.

The concept of development is inherently tied to transformation, which is reflected in the global agenda set by the Sustainable Development Goals (SDGs) for 2030 (Leal Filho et al. 2018). Sprouting from the earlier Millennium Development Goals, the SDGs called for nations to collaborate to formulate country-specific development plans (Jayasooria & Yi, 2023; Sachs et al., 2022; UNESCO, 2017). For South Africa (SA), this meant the rollout of the National Developmental Plan (NDP), which advocates for the "promotion of sustainable livelihoods" through "quality education" (NPC, 2013).

Subsequently, remanence of this advocacy can be noted in the NS CAPS, Minimum Requirements for Teacher Education Qualifications (MRTEQ), and other education policy documents (DBE, 2012; DHET, 2015). NS is referred to in this case as a scientific literacy compulsory school subject, and these policies highlight and

motivate the importance of NS education in addressing diverse socio-scientific issues and the development of higher-order thinking skills necessary for students to thrive in a rapidly changing world.

We adopt Ben-Eliyahu's (2021) SLE as an analytic lens to couch how NS education can deliver on these policy ambitions. SLE comprises four core aspects: (1) Renewing & Relearning (reflective cycles that sustain learning over time), (2) Independent & Collaborative Learning (balanced learner agency and social learning), (3) Active Learning (inquiry and hands-on engagement), and (4) Transferability (application of knowledge across domains and contexts). These aspects within the SA policy emphasise applied learning and responsible use of scientific knowledge (Schudel et al. 2021). Figure 1 outlines the unending fluid path the centred learning travels through.



**Figure 1: Sustainable Learning in Education Lens**

As changes are being assumed in the educational environment to support learners build the basic proficiencies required to navigate contemporary societal complexities, attention increasingly turns to PSTs, who are central to driving scientific inquiry and sustainability efforts.

For SA, this is particularly significant where communities grapple with significant disparities such as water scarcity and pollution, energy crises and renewable alternatives, climate change and biodiversity loss, food security ills, and widespread social inequality (de Beer et al., 2022). Therefore, integrating SL principles into NS facilitation enhances academic performance and cultivates adaptable individuals capable of making meaningful contributions to society. Under this perspective, institutions would provide the much-desired good quality

education that directly addresses and responds to the specific issues, challenges, and contexts affecting the recipients of that education (Chand, 2024; Zajda, 2023).

A primary objective of the CAPS curriculum is to enhance problem-solving competencies in NS education, especially among PSTs. Nabila et al. (2024) highlight Problem-Solving Teaching and Learning (PSTL) approaches as a diverse set of strategies that illustrate scientific concepts and foster critical thinking and sustainable learning habits. PSTL strategies encourage students to identify, analyse, and address real-world problems through active participation. Whether implemented within SL frameworks or as stand-alone strategies, these approaches promote deeper learning by engaging students as active participants in their educational process, rather than passive recipients of information (Arora & Kaur, 2024). As students confront practical challenges, they develop essential skills such as critical thinking, collaboration, decision-making, and adaptive coping, integral to lifelong learning and sustainable development.

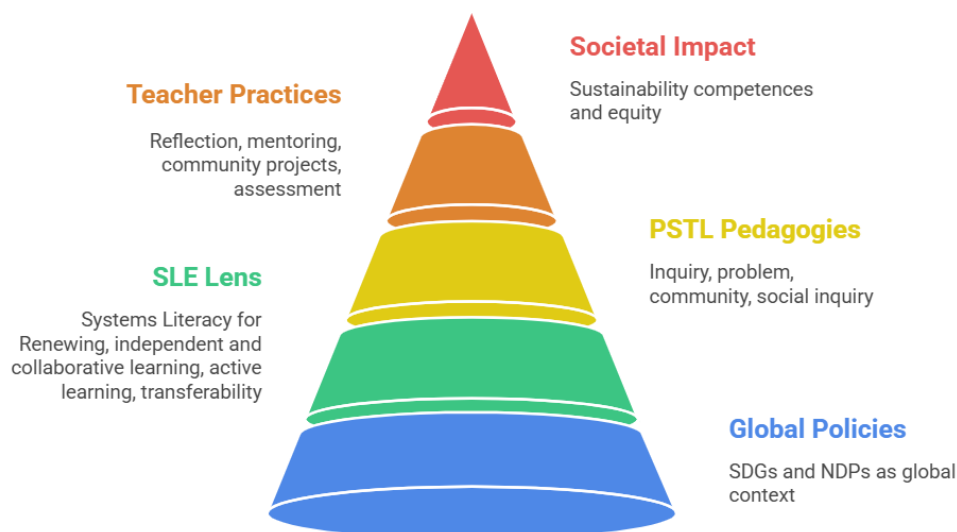
In NS education, PSTL emphasises applying scientific principles to address environmental, societal, and technological issues. These methodologies, such as Project-Based Learning (PBL), problem-based learning (PBL), Inquiry-Based Learning (IBL), and Case-Based Learning (CBL), align with the goals of CAPS, which stress the importance of applying classroom knowledge to address real-world challenges. Despite these progressive goals, implementing PSTL approaches faces obstacles; little to no work is being done to produce solutions from classroom content; this is regardless of the provision of the appropriate knowledge strands in the NS subjects' guidelines (Mnguni & Gasa, 2024).

Amplifying these assertions, Holubnycha et al. (2024) report that there is a need for PSTs to possess competencies in collaborative learning, IBL, PBL, and other innovative pedagogies that align with sustainable learning practices. Accordingly, there is a growing consensus that teacher development programs must better equip PSTs with the skills necessary to implement these approaches effectively, creating NS classrooms that enable deep learning and help students develop the competencies needed to live sustainably (Altassan, 2023; Koculu et al., 2022; Mebert et al., 2020; Ngwenya & Mavuru, 2021; Ryan, 2021).

This study aims to contribute to the growing discourse on SL and NS education by examining teaching and learning strategies within the context of SL, particularly in developing countries such as South Africa. There is a paucity of systematic literature reviews specifically addressing these practices in such contexts (d'Escoffier et al., 2024; Stam et al., 2023). Recognition of the existence of this gap stems from the appreciation of PST as a lever for transformation in NS classrooms.

The contrast between international studies and the context of SA revealed a wealth of insights into pedagogical practices, manifesting as a need for transformation in the under-resourced schools in SA. By applying the principles of SLE, this study seeks to fill an essential gap in the literature on educational practices that promote sustainable development through sustainable pedagogical frameworks (Ben-Eliyahu, 2021). Figure 2 provides a clear conceptualisation and emphasis of

sustainable pedagogies that encourage PSTs' development and advocate for IBL/PBL/PBL that enact Active Learning and Transferability; while structured group roles, peer assessment, and lesson study advance Independent & Collaborative Learning; and on the other hand e-e-portfolios with guided prompts cultivate Renewing & Relearning by embedding cycles of reflection and feedback. All of this leads and builds to the tip of accomplishment that sees to answering the societal issues.



**Figure 2: Conceptual alignment of policy, SLE, and PSTL in NS teacher education**

The outcomes of this research will provide valuable insights for educational scholars and inform policymakers and practitioners seeking to improve NS education. The attainment of these provisions rests on the insights into the gaps between transcontinental practices and the trends in the approaches undertaken by researchers and other stakeholders. Moreover, this study will serve as a reference point for future empirical investigations, aiming to assess the alignment between professional practices and research findings in the field of sustainable education (Booth et al., 2021).

The review offers an alignment between international pedagogical insights and the realities of SA education, and in turn points out the gaps in context-sensitive research and proposes directions for future localised teacher training and curriculum development. Through this contribution, the study seeks to enrich educational development's academic and practical dimensions.

**RQ1:** What challenges hinder preservice teachers' teaching of natural sciences for sustainable learning?

**RQ2:** What opportunities are available for preservice teachers' teaching of natural sciences for sustainable learning?

**RQ3:** How can the opportunities available for preservice teachers circumvent the challenges that hinder their teaching of Natural Sciences for Sustainable Learning?

A systematic literature review (SLR) identifies, evaluates, and interprets all relevant research of a specific research question, topic, or phenomenon. Its primary goals are to locate pertinent studies, assess their accuracy in predicting outcomes, and summarise findings while minimising biases and subjectivity typical of traditional literature reviews.

SLRs serve to evaluate the current state of a research domain, identify knowledge gaps, and assess the impacts of specific activities or events. They highlight deficiencies in existing research, guide future investigations, and enhance understanding of trends and transformations within a field. SLRs are instrumental across industries, laying a foundation for scientific endeavours, steering future research, and advancing disciplines by evaluating methodologies and addressing key issues in ongoing debates. They also prevent redundant research by leveraging established data, improving research quality (Chong et al., 2022).

## 2. Method

### 2.1 Procedure and Data Collection

Mengist et al. (2020) state that the SLR method involves multiple stages. This study was conducted in April 2025 using the following Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Page et al. 2021):

1. Defining eligibility criteria
2. Defining information sources
3. Selection for Study
4. Procedure for data collection
5. Data component selection
6. Eligibility criteria

The systematic literature review guidelines established the following Inclusion Criteria (IC) and Exclusion Criteria (EC):

IC1: Articles that address the concepts of sustainable learning (SL) or problem-solving teaching and learning (PSTL) approaches

IC2: Preservice or in-service teachers are the focus of research in the field of teacher education.

IC3: Given the rapidly evolving nature of educational practices and sustainability-related frameworks, only studies published within the last 10 years (from 2014 to 2024) will be considered.

IC4: Literature published in English.

EC1: The review primarily focused on empirical research that involved data collection and analysis.

EC2: Books, government reports, and inaccessible literature to the authors.

#### 2.1.1 Information source

This study primarily sourced its literature review from EBSCOhost, an internet research database renowned for its extensive coverage of academic literature in the field of education and its wide range of database access. We performed

deduplication using both EBSCOhost and manual methods. EBSCOhost was used as a platform to access multiple databases, see the list in Figure 1.

### *2.1.2 Screening and selection for study*

We took multiple steps to address potential bias to increase the review's credibility. We employed predetermined inclusion and exclusion criteria, dual-independent screening in blind mode on Rayyan, and a third reviewer to settle disputes to lessen selection bias. To reduce database bias, we used citation chasing in addition to EBSCOhost searches to find studies that might have gone unnoticed. We concentrated on English peer-reviewed studies, acknowledging potential language and publication bias, although we pointed out that this might underrepresent non-English contexts and unpublished findings. Lastly, we piloted the screening form, performed calibration rounds, maintained an audit trail in Rayyan and ATLAS.ti, and used reflexive memos to state our assumptions during coding to reduce researcher bias explicitly.

The selection process for this study took place in the following phases:

Using the following search keywords aligned with the study's objectives: (sustainable learning and education) AND preservice teacher\*).

Reviewing and choosing titles for articles, abstracts, and keywords according to the predetermined criteria for acceptance.

Conducting an in-depth review of all studies that advanced beyond the preliminary selection, ensuring thorough reading while rigorously complying with the eligibility requirements. To increase transparency and lessen bias, Rayyan was used for a two-stage screening process (Ouzzani et al., 2016). Title/abstract screening: Using blind mode and pre-established IC/EC labels, three reviewers independently screened records in Rayyan. Rayyan identified conflicts, which were hidden from other reviewers until unblinding.

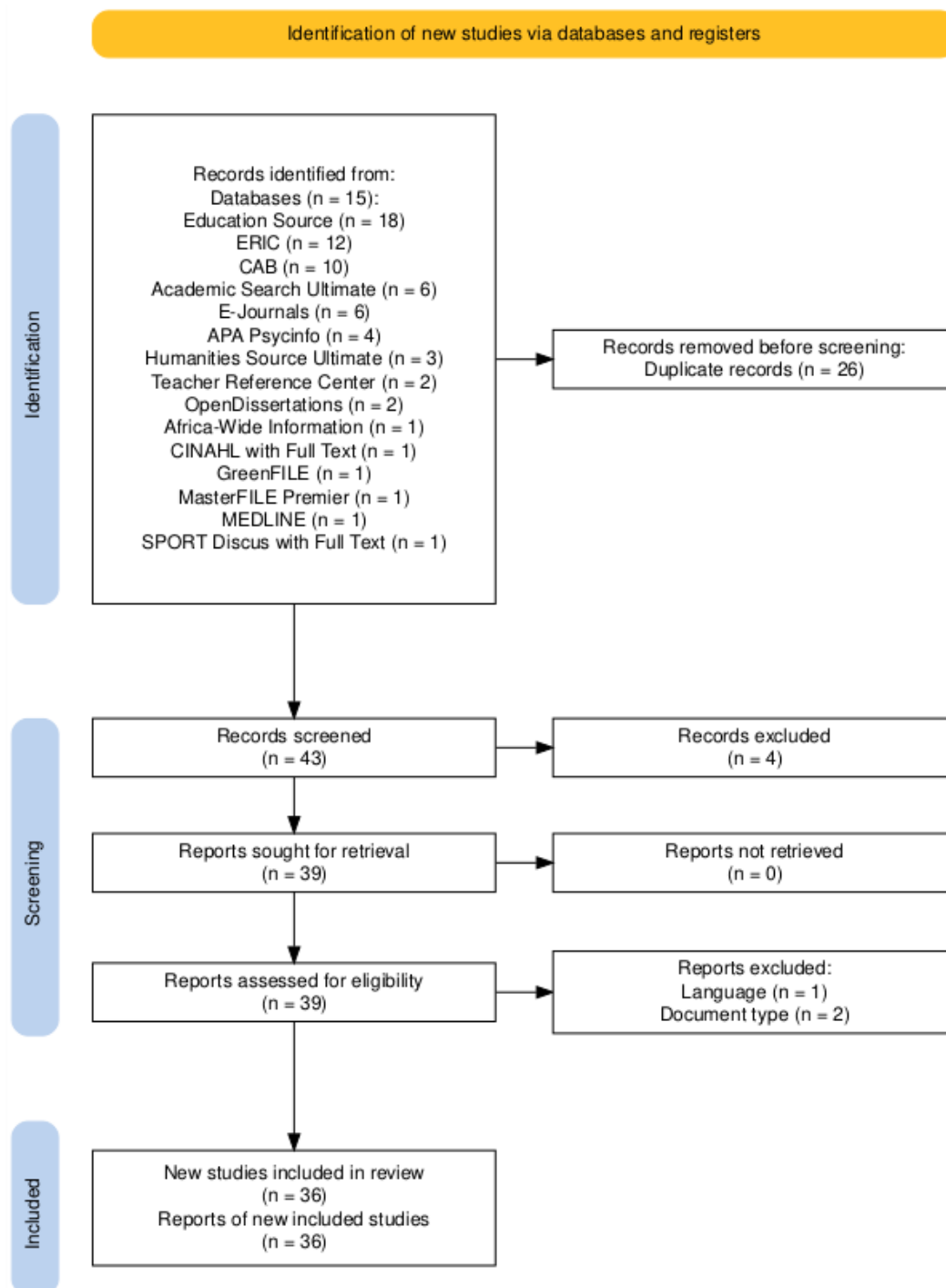
Full-text screening: The eligibility of the shortlisted articles was evaluated independently by the same three reviewers. Initially, disagreements were settled through dialogue; recurring disputes were decided by a third reviewer's vote, with justifications recorded in Rayyan. Figure 1 summarises the recorded reasons for exclusion at full text. We measured agreement during title/abstract screening, calculated inter-rater agreement, and had a third reviewer settle disagreements to assess inter-rater reliability.

### *2.1.3 Data collection procedure*

The procedure to analyse data was conducted through a Computer-Assisted Qualitative Data Analysis Software (CAQDAS), ATLAS.ti (Kibiswa 2019). The initial data extraction consisted of the type of source, name of the source, publication year, title, methodology, country, and purpose. A thorough data extraction included exploring the opportunities and challenges for PSTs teaching NS for SL.

### 2.1.4 Data components selection

The data components retrieved from all publications were outlined as follows: year of publication, authors, country, sample, research objectives, research outputs, and research findings. Moreover, Figure 3 completely presents the stages of the SLR through a PRISMA flow diagram (Haddaway et al., 2022).



**Figure 3: PRISMA flow diagram**

The search yielded 69 records from various databases, with duplicates and ineligible records removed, resulting in 43 records, which we further screened. Of

these, 39 reports were sought for retrieval and assessed for eligibility. Three reports were excluded due to IC4 and EC2. Ultimately, 36 new studies were included, providing the researchers with a refined set of research for the review.

#### 2.1.5 Data extraction and analysis

We extracted participant information, focal constructs (SL, PSTL), bibliographic and methodological details, and variables for descriptive synthesis using a structured Excel form that was improved through piloting. Ben-Eliyahu's SLE was the foundation for the hybrid deductive-inductive coding approach used in ATLAS.ti. The qualitative analysis was extended through open coding to capture contextual mechanisms and outcomes. Intercoder reliability was maintained while coding was done cooperatively. Descriptive statistics and comparative analyses across geographic subsets were part of the quantitative synthesis, and thematic prevalence and intersections were visualised in Figures 2-3 and Table 2 using code frequencies and co-occurrence matrices.

### 3. Results

#### 3.1 Initial Overview

The study's findings provide an insight into the environment surrounding the training of PSTs, their development in practice, and their impact in and out of class.

The word cloud in *Figure 2* provides a visual representation of primary ideas derived from the initial overview of the literature, emphasising concepts and recurrent subjects within the academic dialogue. There authors' overview: (a) *Education, learning, teachers, students, and teaching*: These bring into perspective the main focal point in the articles being analysed, which is educational structures, teaching methods, and the roles of teachers and learners, further indicating a significant emphasis on literature concerning the involvement of various stakeholders, such as teachers, parents, community members, and policymakers, in the teaching and learning process. (b) *Sustainability, sustainable, environmental, and development*: Stresses the evolving attention directed to Education for Sustainable Development (ESD), especially with SDG 2030 looming.

As a result, this corresponds with current global issues and socio-scientific issues, exhibiting the need for more research directed towards unearthing approaches that will enable the use of education as a vehicle to promote economic, social, and environmental responsibility, better preparing students for social and scientific challenges (DBE, 2012; UNESCO, 2020).



notable, with growth in local and continental articles in recent years, reflecting that other corners of the world recognise and understand the relevance of these fields (Pandey, 2024).

From the analysis of the temporal trends, a steady rise indicates the field's importance even though the growth is gradual rather than exponential. Crucially, the thematic emphasis has also changed. While more recent publications highlight practice-based innovations like problem-solving pedagogies, digital integration, and teacher resilience, earlier studies focused more on conceptual underpinnings like sustainability awareness. The three primary geographic categories covered by the reviewed literature are international, continental, and national. The field is dominated by international studies, especially in Europe and Asia, which account for roughly 60% of the sample.

With a strong emphasis on technological innovation, collaborative pedagogies, and teacher resilience, these contributions demonstrate a strong international academic engagement with SL. Studies from continental Africa make up around 25% of the sample and have grown significantly in recent years. They frequently draw attention to issues unique to a given area, like scarce resources, big class sizes, and the significance of community involvement as crucial facilitators of sustainability in education. About 15% of the reviewed literature is from South Africa, and documents such as DBE (2012) and DHET (2015) strongly align with national policy priorities.

Equity, inclusivity, and the structural difficulties of integrating sustainability into teacher preparation programs are frequently highlighted in these works. South African and broader African studies emphasise social justice, contextual relevance, and resource adaptability more than international literature, which usually examines innovative technologies like virtual reality and online collaborative platforms. This illustrates both a shared dedication to sustainability across contexts and a difference in focus, with local realities influencing the specific strategies used. Such can be advocated for by Ndlovu (2025) in honour of Professor Mahlomaholo.

To elaborate further on the analysis of the regional variations in approaches to SL, as shown in Table 1, we provide a comparison table of findings across geographical contexts from the data synthesised from the reviewed studies.

**Table 1: Regional Variations in Approaches to Sustainable Learning**

<b>Region</b>	<b>Number of Studies</b>	<b>Narrative Summary of Findings</b>
<b>Africa</b>	2	Studies emphasised Life and Earth Sciences teachers' engagement with sustainability concepts, highlighting challenges in integrating problem-solving approaches into natural sciences. Findings also pointed to gaps in teacher preparation and resource access.
<b>Local South Africa</b>	7	Research underscored the importance of reflective practices, portfolio development, and contextual teaching strategies for sustainable learning. Studies showed that preservice teachers benefit from locally relevant content and experiential approaches, though systemic barriers (e.g., curriculum alignment, training resources) remain.
<b>International</b>	27	Findings covered a wide range of approaches, including inquiry-based learning, self-regulated learning, and integration of ICT in sustainable education. Studies frequently focused on preservice teacher motivation, socio-scientific issues, and knowledge modelling. Themes emphasised collaborative learning, critical thinking, and global competencies, though limitations included small sample sizes and cultural specificity.

#### **4. Discussion**

At its core, this study explores the challenges and opportunities in preparing PSTs to teach NS for SL. Perceived through Ben-Eliyahu's (2021) five pillars of the SLE lens, this study presents findings that ought to provide robust support for the applicability of the employed lens in the comprehension of the multifaceted landscape of NS education for SL, while also extending its nuances within this specific context.

##### **4.1 Opportunities for leveraging and challenges hindering the teaching of natural sciences for sustainable learning**

Our analysis suggests a dynamic relationship between challenges and opportunities in PSTs towards nurturing SL in NS. As the summary presented through *Table 1* informs us of the numerous alleged challenges, they transform into valuable opportunities for PSTs' growth in both their profession and practice when approached reflectively and strategically.

**Table 2: Challenges reported in literature, also found to be opportunities in other categories**

<b>Challenges</b>	<b>Potential as Opportunity</b>	<b>Authors</b>	<b>Category</b>
<b>Unequal participation and group conflict</b>	<i>Encourages the development of facilitation, conflict resolution, and peer accountability skills.</i>	Legrain et al., 2021	International
<b>Managing teacher workload and stress</b>	<i>Prompt the development of more efficient systems, delegation, and self-care routines.</i>	Granlund and Pastuhov, 2024; Manasia et al., 2019; Putri, 2021	International
<b>Overcoming feelings of inadequacy and a self-doubt mindset</b>	<i>Builds resilience, self-awareness, and a growth mindset when addressed reflectively.</i>	Akyol et al., 2018; Amos & Levinson, 2019; Barends et al., 2023; Brandt et al., 2023; Granlund, 2022; Pastuhov, 2024; Manasia et al., 2019	International, South Africa
<b>Developing supportive relationships</b>	<i>Lays the foundation for collaborative networks and emotional intelligence.</i>	Granlund & Pastuhov, 2024; Legrain et al., 2021	International
<b>Meaningful feedback and reflection</b>	<i>Strengthens metacognition, learner agency, and continuous improvement.</i>	Barends et al., 2023; Brandt et al., 2022; Granlund & Pastuhov, 2024; Legrain et al., 2021; Rodriguez-Gomez et al, 2024	International, SADC, South Africa
<b>Understanding student motivation and learning</b>	<i>Enhance responsive teaching practices and curriculum relevance.</i>	Christodoulou & Papanikolaou, 2023; Gumbi et al., 2024; Jeong et al., 2020; Legrain et al., 2021; Lekhu, 2023; Manasia et al., 2019	International, African, South Africa
<b>Creating engaging and meaningful learning experiences</b>	<i>Sparks innovation and the use of contextually relevant pedagogies.</i>	Akyol et al., 2018; Amos & Levinson, 2019; Brandt et al., 2022; Christodoulou & Papanikolaou, 2023; Legrain et al., 2021	International, African, South Africa
<b>Democratic Engagement</b>	<i>Fosters inclusion, shared ownership,</i>	Chang et al., 2020; De Lange et al., 2014; Egan et al.,	International

	<i>and critical citizenship.</i>	2024; Ho et al., 2016; Inwood & Kennedy, 2020; Putri, 2021; Tusoy et al. 2024;	
<b>Promoting continuous professional development</b>	<i>Cultivates lifelong learning and adaptability among educators</i>	Alkhalaf, 2021; Brandt et al., 2022; Granlund & Pastuhov, 2024; Manasia et al., 2019	International
<b>Lack of continuity and sustainability in cooperative learning</b>	<i>Highlights the need for institutional support and systemic embedding of practices.</i>	Legrain et al., 2021	International

The prevalent issues of unequal participation and group conflict initially present barriers to effective collaborative learning, potentially stifling the rich discourse necessary for addressing complex socio-scientific issues in NS (Karisan & Zeidler, 2016). However, through attempts by PSTs to address these dynamics, the development of desired skills such as facilitation and conflict resolution skills becomes a compulsory possession. The recognisable need for these is in managing diverse classroom environments and guiding future learners through integrated problem-solving regarding sustainability challenges, in turn breeding responsible citizens.

Similarly, managing teacher workload and stress is a significant impediment that leads to a superficial engagement with complex SL topics or reliance on traditional and/or less effective teaching methods. Nevertheless, by prompting the development of efficient systems and self-care routines, the cultivation of personal sustainability practices by PSTs becomes relevant. This enhances their professional durability and models a holistic approach to sustainability, emphasising well-being alongside environmental and social concerns, which they can then impart to their learners in NS (Dube et al., 2023).

The pervasive feelings of inadequacy and self-doubt among PSTs, which can be traced to the interdisciplinary nature of SL and a perceived lack of expertise in socio-scientific issues, can result in the direct impediment of their willingness to experiment with innovative pedagogies for SL. However, through reflective practice, resilience and a growth mindset can be cultivated by addressing these feelings. This empowers PSTs to confidently engage democratically with controversial topics, lead community-based projects, and embrace the iterative nature of sustainable solutions within NS. Furthermore, disregarding the need for meaningful feedback and reflection hinders PSTs' refinement of their pedagogical content knowledge for sustainability and connecting their teaching practices to the real-world SL outcomes.

Conversely, PSTs can enhance their capacity to critically analyse their NS teaching practices for SL, resulting in continuous improvement and more effective

sustainability education by strengthening metacognition through structured feedback. Lastly, the challenge of cultivating and visualising democratic engagement can limit learner agency in exploring sustainability issues and prevent the development of attributes such as critical thinking, short-circuiting the loop for informed decision-making. However, if this is viewed/undertaken as an opportunity, PSTs would be enabled to cultivate classroom environments where learners actively participate and interact with content that speaks to socio-scientific issues, develop shared ownership of learning, and become active and engaged citizens, which is a core tenet of NS for SL.

## **4.2 Ben-Eliyahu's Pillars Applied to NS Education for SL**

Our findings consistently demonstrate the relevance of Ben-Eliyahu's (2021) pillars for understanding SL in NS education, and in many instances, extend their application by highlighting specific contexts and mechanisms.

### *4.2.1 Renewal and lifelong learning*

A strong emphasis has been placed on the continuous evolution of knowledge and practice essential for sustainable education. The literature highlights PSTs' engagement in experiential learning, such as school partnerships and service learning, as central for promoting self-reflection and adaptability, directly aligning with Ben-Eliyahu's (2021) concept of learning that is ongoing growth and renewable.

Furthermore, integrating innovative pedagogical strategies and connecting PSTs with real-world teaching cases simulates sustainable practices and builds resilient learning communities. The benefits of the mentioned approaches enable PSTs to apply theoretical knowledge and continually construct their knowledge and understanding, reflecting the dynamic nature of NS and SL. The call for quality PSTs is disseminated worldwide, and the emphasis on teaching practice programmes has increased over time, further highlighting the importance of continuous learning beyond comfort zones.

Our findings extend this pillar by crucially highlighting the centrality of reflective practice, specifically in the context of NS for SL. Through analysis, we find demonstrations on how reflective practice, particularly through portfolios, allows PSTs to critically analyse their experiences, question beliefs, and acquire a view of renewal resources. This advances environmental awareness and prepares PSTs to create responsible, engaged, and critical-thinking citizens who appreciate the cohesion of the economy, society, and environment.

This pillar is further strengthened by the growing importance of Self-Regulated Learning (SRL) and technology integration, such as Virtual Reality (VR), which offer resources for continuous learning and adaptation to challenging socio-scientific issues. Socio-Scientific Inquiry-Based Learning (SSIBL) and Responsible Research and Innovation (RRI) provide PSTs with a concrete way to actively contribute to updating practices and knowledge in line with sustainability goals.

#### 4.2.2 *Independent and collaborative learning*

The recognition of the importance of self-directed and cooperative skills in PSTs is consistently emphasised by literature, where they reflect on their epistemology, axiology, and ontology of teaching and learning. Independent engagement's significance can also be tracked in its importance for continuous professional growth, akin to PSTs developing adaptive expertise by letting them respond to different teaching situations in NS for SL in a flexible and creative way.

Simultaneously, our results support the collaborative dimension by showing a shift toward more purposeful and structured forms of group work. Such things as open-ended discussion forums for learning together and building a sense of belonging to a community of practice. The explicit acknowledgment of technology's role in making collaborative learning possible through online platforms adds to this pillar by offering new ways for people to build knowledge together in NS for SL.

A holistic approach to preparing PSTs is shown by the mixing of independent and collaborative learning, which is emphasised by studies that stress the use of knowledge in real-world situations through case studies, simulations, and field-based experiences. This synergy helps PSTs realise more confidence in their abilities and creates a supportive community, leading to better, longer-lasting teaching practices in NS. Hence, we find relevance in the independent and collaborative learning, which also places its focal point on learner agency.

#### 4.2.3 *Dynamics of Active Learning in Education*

Ben-Eliyahu's pillar on the Dynamics of Active Learning in Education is unquestionably affirmed by literature, emphasising how crucial it is for preparing PSTs for the challenges of teaching NS for SL. Per the DBE (2012) and other official frameworks, experiential learning is continuously promoted in the literature, where PSTs apply NS content to real-world contexts, encouraging active and meaningful participation. This improves Pedagogical Content Knowledge (PCK) and makes it possible for PSTs to respond to sustainability-related societal demands successfully.

Our findings highlight active learning strategies essential for NS for SL. For example, simulation and Project-Based Learning (PBL) provide safe environments where PSTs can try out PSTL strategies, get feedback, and gain confidence in managing behaviour among learners, especially when it comes to socio-scientific issues. The reason behind this is the development of inquiry skills and the equipping of PSTs to integrate research-informed practices into their teaching of sustainability-related content and research engagement, particularly RRI and SSIBL.

The metaverse and VR are also said to play a crucial role in technology integration, highlighting how immersive environments can give PSTs the advanced skills needed for NS classrooms in the twenty-first century. This crucial role expands on the understanding that the dynamic element of active learning and shows how immersive learning environments can give PSTs the cutting-edge skills they need for NS classrooms. Furthermore, there are arguments that the focus on student-

centred pedagogies, particularly PSTL approaches and SSIBL, directly challenge traditional rote learning methods by promoting active engagement that cultivates critical thinking, self-awareness, and deep understanding of sustainability issues in NS. To create similar environments and develop a flexible and resilient teaching workforce capable of handling challenging educational issues, PSTs are said to be prepared by this shift towards dynamic and engaging learning experiences.

#### *4.2.4 Transferable attributes for multiple context application*

Findings from the literature assert that PSTs must apply their knowledge and abilities in various dynamic educational and social contexts, and this finding resonates with the pillar of transferable attributes for real-world application. Over this, significant emphasis is placed on bridging the theory-practice gap through fieldwork, role-playing, simulations, and experiential learning. It seeks to encourage all collaborators to transfer NS learnt content to transform and sustain their contexts. PSTs are further enabled to meet a variety of student needs while tackling particular social and scientific issues by emphasising flexible pedagogical tools, such as student-centred strategies like project-based learning and inquiry-based learning. This process directly nurtures self-regulating learners who can continuously improve their methods.

Our findings further this pillar by emphasising the role of technology and sustainability principles in improving transferability within NS for SL. The combination of VR content production and metaverse platforms presents a significant opportunity for developing flexible learning environments that facilitate the transfer of knowledge and skills and improve technological readiness. Similarly, PSTs can reposition from theoretical knowledge to workable solutions for challenges when sustainability principles are explicitly applied to real-world issues. Conjointly, PSTs participating in sustainability-focused community-based projects promote a deeper understanding of the connections between social, economic, and environmental issues by facilitating the application of theoretical NS knowledge to real-world solutions.

#### *4.2.5 Motivation and caring relationships*

Our review firmly backs the pillar of motivation and caring relationships in establishing an environment that is learning supported for PSTs and enabling them to create similar environments in their future classrooms for NS for SL. This is encouraged and emphasised repeatedly in the literature by building supportive relationships between teacher educators, mentor teachers, and PSTs. To support PST motivation and well-being and enhance their ability to teach NS for SL with empathy and confidence, it is critical to establish a safe space to ask questions, share experiences, and get constructive criticism.

Our findings gravitate towards adding to the integrity of this pillar by emphasising the value of collegiality, human capital, and group learning as sources of inspiration and assistance. Our results also strengthen this pillar by emphasising the value of collegiality and group learning as sources of inspiration and assistance. PSTs develop a strong sense of belonging that increases their intrinsic motivation when they collaborate, learn from one another, exchange ideas, and support one another. Giving PSTs constructive criticism and chances

for introspection is essential because it enables them to pinpoint their areas of weakness, hone their teaching strategies, and boost their drive to keep learning and developing.

The literature also highlights the obligation (DBE, 2012) for PSTs to develop mutually and nation-building relationships and motivation with their learners. PSTs must have a thorough understanding of the elements influencing learning and student motivation, reflection of which can also be traced in government policy documents (DBE, 2012; DHET, 2015). This entails investigating different innovative learning theories and motivational techniques that PSTs can employ, such as social media use.

It is believed that compelling and captivating educational experiences in NS for SL depend on developing positive relationships with learners, which are typified by empathy, active listening, and inclusive learning environments. By planning lessons relevant to learners' experiences and interests in sustainability, active learning, and PSTL approaches have also been demonstrated to make learning enjoyable and meaningful for learning, encouraging motivation and curiosity.

The reviewed literature revealed limitations of the SLE regarding this specific context. At a micro-level, privilege tends to be pinned to the learner and classroom dynamics while placing at the periphery insights into meso- and macro-level constraints akin to policy churn, labour relations, funding, and infrastructure, which are particularly influential in developing contexts like this. Furthermore, SLE's normative universalism risks understating local epistemologies, linguistic diversity, and socio-political histories that shape feasibility and legitimacy in the Global South. For these gaps to be attended to, proposed extensions include a sixth pillar on Structural and Policy Alignment, and a fidelity gradient across pillars to capture variability in real-world implementation.

Although rooted in South Africa's policy environment, the opportunities-intension pattern is common throughout the Global South, especially in areas where ambitious pedagogical reforms clash with resource limitations, assessment logics, and infrastructure disparities. We argue that SLE is still a valuable organising framework as long as it is expanded and contextualised to include digital governance and structural determinants. In practice, this means investing in mentor development and digital equity, integrating reflective structures (e-portfolios, coaching), and matching funding and standards with SL placements. Theoretically, adding equity-data and policy-structure lenses to SLE can help clarify why and when SL persists and fails.

## **5. Synthesis of Findings**

The findings reveal the interconnected ecosystem across the five pillars and the preparation of PSTs to teach NS for SL. There is a clear interaction between various elements, and this can be seen from the emphasis on robust reflective practices attached to the renewal and lifelong learning pillar's direct contribution to independent learning by cultivating awareness and critical analysis. Further,

extending the influence to strengthen the transferable attributes by enabling and exposing PSTs to adapting practices across diverse contexts.

Moreover, cultivating caring relationships is not merely an isolated pillar but the foundational layer that fortifies collaborative learning by creating a safe space for PSTs to engage in an open dialogue and share vulnerabilities. Because motivated PSTs are more likely to try project-based learning and SSIBL, these encouraging settings also increase the efficacy of "Active Learning" strategies by encouraging deeper engagement and the development of "transferable attributes." Its widespread and increasingly important role in contemporary NS for SL education is demonstrated by integrating technology across several pillars, from enabling immersive active learning experiences to facilitating collaborative learning.

Despite the overwhelming evidence of these interrelated practices' beneficial effects, there are some issues with their actual application, especially regarding teacher workload and the possibility of "uni-dimensionality exposure." The full realisation of "transferable attributes" may be threatened if school partnerships are overly dependent on one kind of context (such as underprivileged schools) without wider exposure, even though they present countless opportunities for real-world application and renewal.

This draws attention to a conflict between broad contextual adaptability and deep, situated learning, indicating the need for thoughtful curriculum design that strikes a balance between the two. As noted by Legrain et al. (2021), systemic embedding is necessary, and the evidence pertaining to the long-term sustainability of cooperative learning initiatives also presents an area that warrants additional empirical investigation.

Therefore, a comprehensive situational analysis is essential in understanding these dynamics, as it provides a structured view of the internal capabilities, limitations, and external conditions shaping NS classrooms for SL. Systematically mapping strengths, weaknesses, opportunities, and threats to the SLE pillars, teachers and policymakers gain valuable insights into how best to support learners in developing the skills, attributes, and mindsets needed for effective and contextually responsive learning and teaching. Such an analysis highlights the most needed interventions and guides strategic decisions to create balanced, resilient, and future-focused NS education environments.

With all attended to, the literature also surfaced contradictions. Barends et al. (2023) speak to reflective practice being widely recognised as critical for professional growth. Meanwhile, de Lange et al. (2014) noted that heavy curricular demands and assessment-driven cultures often reduce reflection to a superficial/cosmetic exercise. Subsequently, Approaches such as SSIBL align with ESD goals (Amos & Levinson, 2019), yet standardised assessments and rigid pacing guides frequently limit their implementation (Manasia et al., 2020). We note the praises for service-learning for linking theory and practice (Egan et al., 2024; Singh-Pillay, 2015), yet under-resourced schools often bear coordination

costs without proportional benefits. Implications, therefore, become clear that they are not to be traced or situated under an individual stakeholder.

## **6. Implications**

The implications of these findings are systematically addressed at different levels from individual (PST-level), institutional (programme level), policy (system-level) and theoretical implications.

### **6.1 Individual (PST-level)**

Firstly, a safe space created by caring relationships allows vulnerability and risk-taking, and this motivates PSTs to lean towards attempting SSIBL and other sustainable pedagogies. The implication, therefore, is that a sustainable attempt at developing good-quality PSTs does not lie in the techniques and methodologies. Still, affective safety and belonging are preconditions for method uptake. Secondly, the overwhelming emphasis on reflective practices indicates the need for routinised, evidence-based reflective cycles. This explicitly connects adaptable practices to experiences across assorted realities, enacting “transferable attributes”. Thirdly, the rise of techno-pedagogical ideals enables immersive active learning and collaboration, which implies that there is importance in the abilities of the PSTs to select tools in inquiry, collaboration, and reflection instead of adopting them as an add-on.

### **6.2 Institutional (programme level)**

Firstly, the pillars' interdependency and the aligned call for systematic embedding pointed out by Legrain et al. (2021) imply that teacher training programmes should integrate pillar practices vertically (year-year) and horizontally (across modules), with assessed artefacts that evidence reflective growth, collaboration and tech-enabled inquiry. Secondly, the prevalence of fragile collaborative initiatives implies a need for durable collaboration infrastructures such as shared digital workspaces and basic education - higher education communities of practice.

### **6.3 Policy/System-level**

Implications of these findings tell us that there must be transformation within the accreditation and quality assurance systems towards demonstrable, systemic integration of reflective practice, caring relationships, collaborative and active learning, technology use, and school partnerships, moving beyond superficial compliance. Furthermore, with constraints akin to teacher workload, system-level innovation needs legitimised time for reflection and collaboration through mechanisms like micro-credentialed components or credit-bearing offsets, which will enable the design and enactment of socially sensitive, inquiry-based learning.

### **6.4 Theoretical Implications**

Theoretically, these findings imply that fostering inquiry-based pedagogies like SSIBL requires attention to affective-social foundations, where caring relationships and motivation project the relational safety and encouragement necessary for active and collaborative learning. Subsequently, reflective practice emerges as a neo-critical transfer mechanism, enabling teachers to bridge situated experiences with adaptable, cross-contextual competences through structured,

critical analysis. Taken together, these implications support an ecosystemic view of professional learning, where growth is driven by the alignment of sociocultural (communities of practice), cognitive (active inquiry), metacognitive (reflection), affective (care), and technological dimensions, necessitating systemic embedding to sustain the much-desired meaningful change.

## **7. Limitations**

While this study has been comprehensively conducted, it is also subject to several limitations that should be considered when delving into this paper. Firstly, publication bias could affect the review; studies with significant or positive results have a higher chance of being published than those with null or negative results. Preparing PSTs for NS for SL could result in underestimating difficulties or less successful methods and overrepresenting successful interventions. Secondly and lastly, the review offers a general overview of the opportunities, challenges, and practices associated with Ben-Eliyahu's pillars; however, the scope of a systematic review limited the depth of analysis for each intervention or context. More thorough qualitative or quantitative research would be needed to properly examine the subtleties of specific interventions or the long-term effects of preparatory approaches on PSTs' capacity to teach.

## **8. Recommendations**

Based on the findings of this study, in the table, we recommend the following concrete actions for various stakeholders:

The reforms of the curriculum must be implemented by teacher education programs to improve PST preparation for teaching significantly. To nurture broad adaptability, they should first incorporate required service-learning elements and real-world fieldwork into NS methods courses, emphasising regional socio-scientific issues and guaranteeing placements in various educational environments. Second, it is necessary to set up strong frameworks for reflective practice, like organised e-portfolios or journals with guided questions for analysing one's own beliefs and experiences teaching SL. Thirdly, it is crucial to have specialised modules on pedagogical content knowledge for SL that cover the frameworks such as RRI and SSIBL.

Policymakers must act decisively and play a crucial enabling role. A substantial investment is needed to guarantee high-quality, diverse placements, particularly in the form of more funds allotted to strengthen and maintain university-school partnerships. These funds should cover mentor incentives, transportation, and resources. For programs to be consistent and high-quality, it is also necessary to establish explicit national guidelines and professional standards that incorporate ESD competencies into teacher education and development frameworks.

Understanding the human component, policies and resources must also support professional development for teachers in digital literacy, artificial intelligence in education, effective classroom management, and self-care techniques to reduce stress and facilitate successful SL integration. Lastly, adding to Mhlanga et al.'s (2022) findings and recommendations, encouraging digital equity is essential to

developing collaborative learning by guaranteeing that all educational institutions have fair access to safe online environments, digital materials, and reflective practice essential for SL.

For NS/SL education to be effective, PSTs must also actively participate in their own professional development. This speaks to the ability to situationally analyse the NS environment for the three units of analysis: *learner, teacher, and learning and teaching aids and resources*. To exchange ideas and obtain valuable insights, this entails actively seeking mentorship from seasoned NS teachers who integrate SL and embracing opportunities for collaborative learning with peers.

PSTs should participate in community-based sustainability projects outside the classroom to expand their knowledge of real-world socio-scientific issues and obtain real-world experience. Responding to changing challenges requires developing adaptive expertise, which includes being willing to try various teaching philosophies, looking for answers on your own, and improving tactics in response to feedback and reflection. In the end, active listening is a top priority for developing sympathetic, encouraging relationships with students and coworkers.

Table 2 below synthesises the core recommendations for stakeholders, alongside the mentioned challenges to implementation and corresponding mitigation strategies. This structured summary highlights the interdependence of systemic support and individual agency in advancing SL integration within NS education. Provided is an explicit linking of each recommendation to challenges and further recommendations of practical considerations necessary for successful enactment to overcome the mentioned challenges.

**Table 2: Summary of Recommendations, Challenges, and Mitigation Strategies**

Stakeholder	Recommendation	Challenge	Mitigation Strategy
Teacher Education Programs	Integrate SL and authentic fieldwork	Limited placement capacity	Strengthen school-university partnerships; allocate transport funds
	Institutionalise structured reflection	Digital fluency gaps	Provide templates and short training sessions
Policymakers & Leaders	Offer PCK-for-SL modules	Curriculum overload	Use modular, stackable formats
	Fund and sustain partnerships	Fiscal constraints	Pooled district funding; performance-based compacts
	Establish national standards	Policy adoption lag	Phased rollouts; stakeholder consultations
	Promote digital equity	Infrastructure gaps	Public-private partnerships; device loan schemes
	Support targeted professional development	Time constraints	Micro-PD; asynchronous modules

<b>Preservice Teachers</b>	Engage in mentorship and peer collaboration	Mentor availability	Virtual mentoring; peer triads
	Participate in community-based projects	Time/logistics	Align projects with coursework; short, high-yield tasks
	Develop adaptive expertise	Risk aversion	Low-stakes microteaching; rapid feedback cycles

Methodologically, we recommend prioritising longitudinal, mixed-methods, and design-based research (DBR) to trace and track the development of PSTs' ESD competences and PCK-for-SL. Simultaneously, we recommend the adoption of realist, contextualised, and implementation science approaches to determine what works, for whom, and under what conditions. To strengthen measurement rigour, we suggest developing validated tools knitted for assessing quality reflective practice, mentor support, and the authenticity of SSI activities, while harnessing learning analytics from e-portfolios.

## 9. Conclusion

The offering of this study is a distinctive contribution, as it conceptualises the preparation of PSTs to teach NS for SL couched on Ben-Eliyahu's SLE. Contrary to fragmented approaches that treat reflective practice, collaboration, and technology integration as isolated strategies or add-ons, this review demonstrates their interdependence within a systemic and holistic framework. Central to this preparation is the creation of safe, caring, sustainable and reflective spaces that foster vulnerability, democratic dialogue/engagements, and experimentation. These are conditions essential for inquiry-based pedagogies such as SSIBL to sprout and grow. These interconnected practices enable PSTs to develop adaptive expertise and transferable attributes necessary for addressing the complexities of contemporary science education as aimed for by CAPS.

The implications extend beyond individual teacher preparation to institutional and policy levels. Teacher education programmes must embed reflective practice, collaborative learning, and vertically and horizontally technology integration. Institutions should prioritise structured mentorship, partnerships with diverse schools, and opportunities for PSTs to engage in community-based projects. Policymakers play a critical role by legitimising time for reflection and collaboration through supportive standards, resources, and accountability frameworks.

Preparing PSTs for NS for SL is not a technical exercise but a systemic endeavour requiring collaboration among all stakeholders, with learning being the centre. Cultivation and encouragement of socio-emotional, cognitive, metacognitive, and technological dimensions in concert, teacher education can cultivate reflective, resilient, and socially responsive teachers capable of driving sustainable transformation in science education.

## 10. Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this article and that no external funding or specific acknowledgements are applicable for this study.

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