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Integrated STEM for sustainability in school and early teacher education: a systematic review (2019–2025)

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This systematic review synthesizes research on school-focused initiatives that integrate science, technology, engineering, and mathematics (STEM) with sustainability goals, published between 2019 and 2025. Searches of Scopus, Web of Science, and SpringerLink, along with reference checks, identified 49 studies. We coded approaches, topics, technology use, outcomes, and implementation features. Of these 19 studies, 42 empirical interventions were mapped by topic and subject, while seven conceptual or non-anchored pieces were excluded from topic counts but were used for informed interpretation. Publications accelerated after 2020 and clustered in North America and Southeast/East Asia. Climate dominated the topic distributions, followed by water and circularity; biodiversity and energy were at moderate levels, while smaller clusters addressed disaster, built environment, and justice/policy. Technology integration was most prevalent in water and circularity units, moderate in disaster and built environment, and comparatively limited in climate; energy and justice/policy showed minimal technology integration. Outcome synthesis indicated broad gains from project-based and inquiry-oriented designs and from context/place-based approaches; socio-scientific argumentation most consistently advanced agency and values; modeling and engineering design excelled on skills and, with coherence supports, also improved concepts. A synthesized framework addresses key implementation challenges—curriculum fit, teacher capacity, cognitive load, assessment alignment, and equity logistics. The review offers design-ready guidance for selecting approaches that match desired learning and participation outcomes.

KEYWORDS

project-based pedagogy, socio-scientific reasoning, systems modeling, learner agency, computational thinking, assessment alignment

1 Introduction

Across school systems, there is growing pressure to integrate disciplinary science, technology, engineering, and mathematics (STEM) learning with education for sustainable development (ESD), enabling youngsters to reason about—and act on—pressing socio-ecological issues. Over the past decade, classroom innovation has encompassed project-based learning (PjBL), inquiry-based learning (IBL), socio-scientific issues (SSI) and argumentation,

modeling and systems thinking, engineering design, game-based learning, and context/place-based education. When these approaches are associated with authentic problems, students tend to demonstrate stronger conceptual understanding, motivation, and capacity to participate in solutions (Birney and McNamara, 2021; Cole et al., 2024; Ellington and Prado, 2024; Restaino et al., 2024).

Evidence suggests that approach matters for outcome. SSI and structured argumentation consistently strengthen scientific/chemical literacy and civic willingness to act—especially when designs include deliberation and action-taking phases such as “Ask–Find out–Act” or collaborative argument cycles (Zhu and He, 2022; Georgiou and Kyza, 2023). Modeling activities that scaffold connections and mechanisms improve students’ systems reasoning and the coherence of their explanations (Sezen-Barrie et al., 2023; Cole et al., 2024). Engineering design projects—e.g., salinity sensors and circular bioeconomy labs—develop problem-solving and conceptual application (Jefferson et al., 2020; McCance et al., 2021; Dung et al., 2023). Although game-based designs consistently increase attention and perceived relevance, they require careful scaffolding to yield cognitive gains (Kim et al., 2023; Besalti and Smith, 2024).

The “where” and “for whom” of learning are equally important. Place- and community-based designs that associate lessons to local infrastructures, partners, and audiences have demonstrated benefits for relevance, preparedness, and stewardship, provided equity barriers—such as transport, fees, and language—are addressed (Birney and McNamara, 2021; Spencer et al., 2022; Ellington and Prado, 2024). Culturally situated approaches, including Ethno-STEM and Indigenous partnerships, help learners see science as connected to community practices and identities (Spencer et al., 2022; Izzah et al., 2023). These moves align with calls to reframe science education around justice, power, and historical context rather than treat technologies and “solutions” as neutral (Gandolfi, 2024; Lowan-Trudeau and Fowler, 2025).

Delivering on this vision depends on effective teacher learning. Studies show that structured tools, e.g., content representation, (CoRe), paired with video-based reflection can make teachers’ pedagogical reasoning about sustainability explicit and improvable. In addition, co-teaching arrangements help integrate disciplinary perspectives around sustainability anchors (Forsler et al., 2024; Wang et al., 2025). Professional development that connects mathematics and science with citizenship through modeling, SSI, and inquiry shifts teacher beliefs and practices at scale (Maass et al., 2022).

Technology is a double-edged lever. Low-cost, “green” kits and simple calculators increase access while surfacing core concepts (Sharif et al., 2021; Nurramadhani et al., 2024). On the contrary, building information modeling (BIM)-linked simulations and energy games can enhance energy literacy and systems thinking, but they pose cognitive-load and integration challenges if not supported by stepwise scaffolds (Kim et al., 2023). Place-based data platforms and citizen science initiatives foster computational thinking and broaden pathways for participation (Birney and McNamara, 2021).

Despite growing momentum, the evidence base remains fragmented. Reporting varies across subjects, outcome domains, and measures; certain topics (e.g., justice/policy and built environment) are underrepresented; and risk-of-bias features (e.g., comparators, fidelity, and validated outcomes) are uneven. A consolidated map is needed to show who is studying what, with

which approaches, employing which technologies, and to what effect—and to identify actionable remedies for recurring implementation challenges.

1.1 Aim and research questions

This systematic review synthesizes integrated STEM studies that explicitly target sustainability/ESD between 2019 and 2025 and answers:

- 1 How have publications and geographies evolved over time?
- 2 How are subject anchors distributed across STEM integration approaches?
- 3 Which sustainability topics are addressed, and how is technology employed within these studies?
- 4 For each approach, what cognitive, affective, skills, and agency/behavior outcomes are most consistently improved?
- 5 What thematic design patterns link approaches, sustainability topics, and outcome gains?
- 6 What challenges and remedies recur across implementations?

1.2 Contribution

We presented a trend and geography visuals; a subject × approach map; a sustainability topics × subject table showing the percent of studies using technology; an outcome-by-approach synthesis that clarifies “what works for what;” and an actionable challenge–remedy table. Together, these outputs offer a design-ready evidence map for curriculum developers, teacher educators, and policymakers planning integrated STEM for sustainability.

2 Methodology

2.1 Protocol and reporting

We followed the PRISMA 2020 reporting guidance (Page et al., 2021) for a systematic review of integrated STEM associated with sustainability/ESD, covering the period between January 1, 2019 and July 15, 2025. The PRISMA flow diagram (Figure 1) details identification, deduplication, screening, eligibility assessment, and inclusion, with full-text exclusions tallied by reason. The final database search was conducted on July 15, 2025.

2.2 Databases, time window, and search strategy

We searched Scopus, Web of Science Core Collection (WoS Core), and SpringerLink for records published between January 1, 2019 and July 15, 2025. Searches were limited to English-language journal articles and conference proceedings. We combined three concept blocks with AND:

1. Integration terms: “integrated STEM” OR STEM OR STEAM OR “engineering design” OR modeling OR inquiry OR PjBL

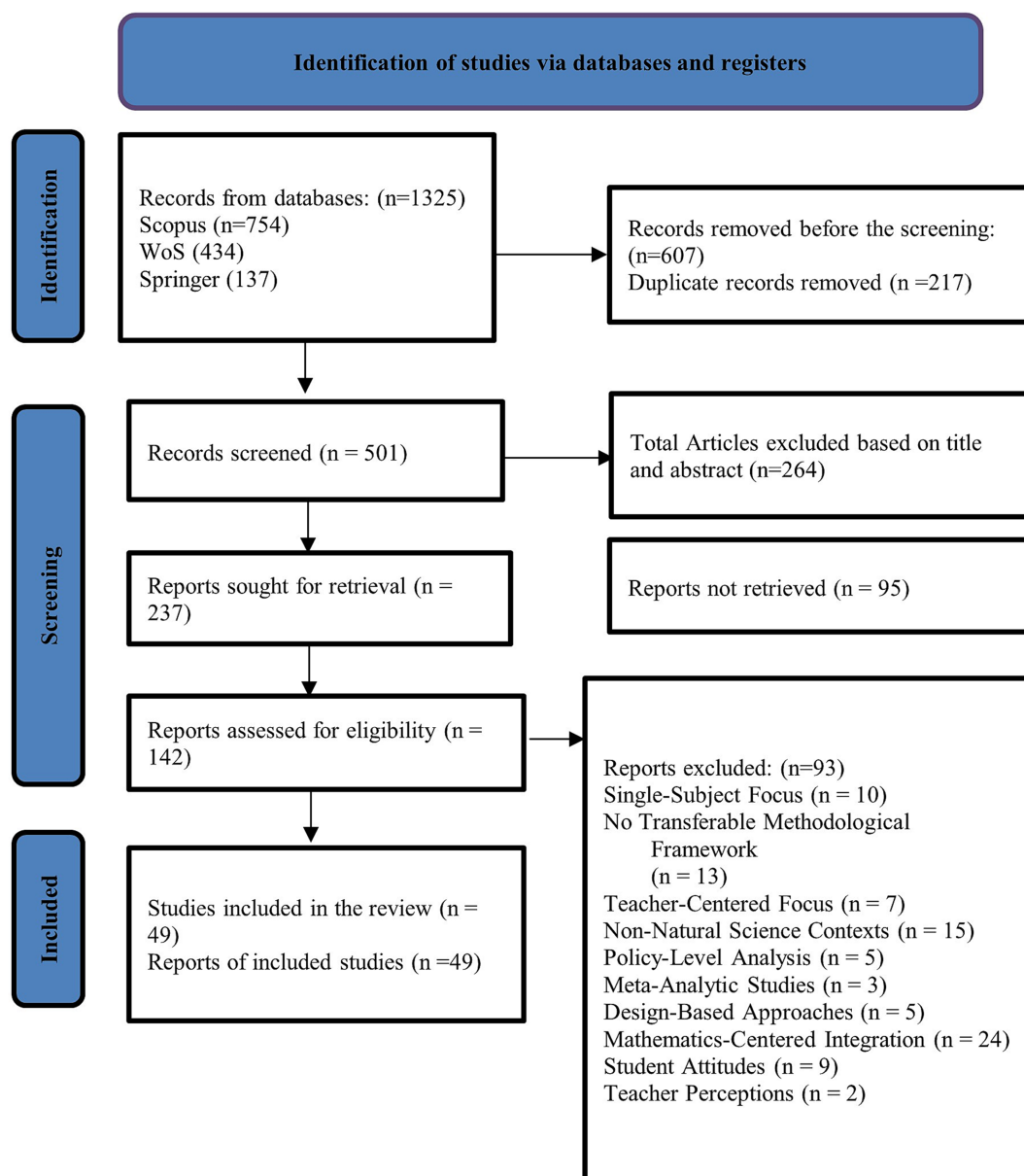


FIGURE 1
PRISMA guideline flowchart.

- OR IBL OR SSI OR argumentation OR “game-based” OR simulation OR “computational thinking”
2. Sustainability terms: sustainable OR ESD OR “climate change” OR energy OR water OR biodivers* OR “waste” OR circular OR “disaster” OR hazard* OR “built environment” OR “green building” OR justice OR policy*
 3. Education/context terms: school OR K–12 OR elementary OR middle OR secondary OR high school OR teacher OR preservice OR pre-service OR undergraduate*

Database-specific, runnable Boolean strings (with field limits and filters) are provided in [Supplementary material](#). Reference lists of included papers were also scanned to identify additional records.

2.3 Eligibility criteria

Studies were eligible if they:

- Focused on STEM or science education with an explicit sustainability/ESD aim (e.g., climate, energy, water, biodiversity, circular economy, disasters, built environment, and justice/policy).
- Were situated in formal or co-curricular school (primary/secondary) settings or early teacher education (preservice or introductory undergraduate courses) settings.
- Reported empirical data (quantitative, qualitative, or mixed). Conceptual and methods papers that directly operationalized ESD-linked STEM designs (e.g., transferable lab protocols and

justice-oriented frameworks) were retained for thematic mapping but were excluded from risk-of-bias appraisal.

- Were published between 2019 and 2025 in English.

We excluded higher education studies focused strictly on advanced disciplinary training, papers with no identifiable ESD link, and commentaries lacking actionable design/measurement implications.

Population: school (primary/secondary) learners and preservice/introductory undergraduate teachers.

Intervention: integrated STEM designs explicitly linked to ESD.

Comparator: recorded when present; not required.

Primary outcome: cognitive, skills, and agency/behavior; secondary outcome: affective.

Study designs: quantitative, qualitative, or mixed methods empirical studies.

2.4 Screening and study selection

Search results were exported to a spreadsheet for de-duplication and screening. Titles/abstracts were screened against the criteria ($n = 232$ retained for full-text retrieval). We obtained 142 full texts; studies were excluded when they lacked an ESD focus, did not involve STEM integration or school/teacher/introductory UG contexts, or provided insufficient methodological detail. The final included set comprised 49 studies. Reasons and counts at each step are documented in [Figure 1](#).

2.5 Data extraction

A structured codebook (piloted on a subset and refined iteratively) guided extraction into a master sheet (see [Supplementary material](#) for a snapshot of study characteristics). Variables captured:

- Bibliographic: authors, year, country/region.
- Subject focus (Environmental Science, Biology, Chemistry, Physics, and Mixed).
- STEM integration approach (PjBL, IBL, SSI/argumentation, modeling, engineering design, game-based, STEAM, context/place-based; “Lab-based” flagged as a delivery mode).
- Sustainability/ESD focus (climate, energy, water, biodiversity, waste/circular, disaster, built environment, and justice/policy).
- Technology use (any/none, type: sensors/probes, apps/web platforms, BIM/simulation/game, imaging/thermal, and data platforms).
- Education level (elementary, middle school, high school, preservice, and introductory undergraduate).
- Outcomes reported with instruments/indicators.
- Teacher professional development (PD) (yes/no, format).
- Design (quant/qual/mixed, quasi-experimental, case, R&D, and methods).
- Notes (contextual features and implementation details).
- Equity/culture: population, approach, partnership level, supports, outcomes, and justice orientation.

2.6 Coding rules

2.6.1 Approach and subject

When multiple approaches were used, we assigned a primary approach (based on central learning cycle and analysis focus) and marked secondaries for sensitivity checks. Subject focus was the dominant disciplinary anchor evidenced by tasks and assessments.

2.6.2 Outcomes

We grouped outcomes into four domains: cognitive (knowledge/ tests and literacy scales), affective (attitudes, motivation, values, and nature-relatedness), skills (modeling, design/problem solving, data/CT, and argumentation), and agency/behavior (willingness to act, participation, and preparedness). Effects were coded positive (+) when authors reported statistically significant gains vs. baseline/comparison or convergent qualitative evidence of improvement; mixed/neutral otherwise. These outcome codes inform [Table 1](#), which presents the synthesis by instructional approach in the Results section.

2.6.3 Technology

We coded whether technology was used (yes/no) and identified the dominant type. The percentage of studies using technology within each sustainability topic is reported in [Table 2](#) (sustainability topics $\times$ subject with % tech) in the Results section.

2.6.4 Cultural equity coding

We operationalized cultural equity to identify Ethno-STEM and Indigenous/culturally responsive designs and their supports. Each study received: (a) population focus (Indigenous, underserved/minoritized, rural/remote, and general); (b) an equity code (0–3) where 0 = no explicit equity/culture focus, 1 = contextual or access-broadening elements, 2 = culturally situated or place-based design and/or explicit access supports, 3 = justice-oriented/Indigenous frameworks or community-led work; (c) co-designed (Y/N) with communities/partners; (d) context supports (Y/N) such as multilingual materials, transport/fee waivers, or community audiences/benefit; and (e) equity outcomes reported (e.g., belonging/identity, participation/agency, and stewardship). Conceptual pieces were coded for orientation (e.g., decolonial/TribalCrit cues) but excluded from outcome tallies and equity-outcome denominators. For synthesis, we presented a descriptive summary: corpus-level counts (e.g., share of studies with equity code ≥ 2), cross-tabs by sustainability topic and approach, and illustrative examples of co-design and supports; study-level details appear in [Supplementary material](#); and conceptual papers inform interpretation only.

2.7 Risk of bias (RoB) appraisal

We appraised study-level risk of bias using the Mixed Methods Appraisal Tool (MMAT 2018/2022), selecting the appropriate pathway for each empirical study (qualitative, quantitative non-randomized, or mixed methods). For each study, we answered the five MMAT criteria (Yes/No/Cannot Tell) using information already charted in our extraction sheet (Research Design, Sample/Participants, Intervention Components, Evaluation Metrics, and Challenges/Limitations). We then assigned a prespecified overall tier: Low (≥ 4 “Yes,” ≤ 1 “Cannot Tell,” 0 “No”); High (≥ 2 “No” or a critical flaw); or Some

TABLE 1 Outcomes by instructional approach: number of studies reporting positive effects across four domains, with representative metrics.

Approach	Cognitive	Affective	Skills	Agency/behavior
PjBL	7/8—knowledge/concept tests; post-quizzes	9/10—attitude/self-efficacy; sustainability awareness; motivation surveys	5/5—model analysis; problem-solving rubrics; artifact reviews	4/4—preparedness; responsibility; action-intent surveys
IBL	9/9—science/chemical literacy tests; unit exams; concept tests	6/6—values (GSLQ); NR scale; self-efficacy	2/2—Inventive Problem Test; SEP performance	1/1—willingness-to-act (GSLQ)
SSI/argumentation	2/2—scientific/chemical literacy tests	3/3—values/motivation surveys	1/1—argument-quality coding	3/3—willingness; citizenship questionnaires
Modeling	1/2—model coherence/integration coding	3/3—NR scale; engagement surveys	2/2—modeling & systems-thinking rubrics	2/2—conservation commitment; action phases
Engineering design	2/2—post-quizzes; concept tests	3/3—attitude/awareness reflections	2/2—design/problem-solving artifacts	—
Game-based	—	1/1—Attention, Relevance, Confidence, Satisfaction (ARCS) interview coding	—	—
STEAM	1/1—pre/post knowledge; safety behaviors	—	1/1—expert artifact validation	1/1—disaster-preparedness choices
Context/place-based	4/4—knowledge tests; model-based tasks; competence interviews	5/5—relevance/engagement; NR; motivation	3/3—data & modeling skills; platform competence	2/2—preparedness; conservation commitment

Cells show n/N: *n* = studies with a positive effect in that domain; *N* = studies that measured that domain for the approach. Denominators vary because not all studies assessed all outcomes. Conceptual/methods papers (*n* = 7) excluded.

TABLE 2 Sustainability/ESD topics × subject anchors with percentage using technology.

Sustainability/ESD focus	Environmental Science	Biology	Chemistry	Physics	Mixed	Percentage of studies using tech
Climate	9	1	0	1	3	36%
Energy	0	0	2	0	3	0%
Water	3	0	1	2	0	67%
Biodiversity	3	1	0	0	1	20%
Waste/circular	1	0	4	0	1	67%
Disaster	1	0	0	0	1	50%
Built environment	1	0	0	0	1	50%
Justice/policy	0	0	0	0	2	0%

Empirical, ESD-anchored interventions only (*N* = 42). “Percentage of studies using tech” = topic-level n/N: Seven conceptual/non-anchored studies excluded.

Concerns. We also recorded comparator presence (Y/N), analytic sample (*N*), and instrument reliability (Cronbach’s α for the primary outcome when reported). Conceptual/methods papers were not appraised with MMAT and are excluded from sensitivity summaries. The complete study-level RoB table appears in [Supplementary material](#).

3 Results

To support transparency and reuse, a complete, paper-by-paper extraction is provided as [Supplementary material](#). This file contains every coded field used in the analyses—authors, year, country/region, education level, subject focus, STEM integration approach, sustainability/ESD focus, intervention components, technology use, teacher professional development, outcomes, and notes. It is the

authoritative source behind all figures and tables in the Results. Variable names match those referenced in the text; categorical bins (e.g., subject anchors; approach types and sustainability topics) follow the scheme defined in Methods. Where a study reported multiple foci (e.g., “Chemistry” and “Environmental Science”), all declared values were retained in the coding. For aggregate displays, these values were collapsed into the reported bins (“Chemistry,” “Environmental Science,” or “Mixed,” as specified).

3.1 RQ1: Publication trends and geographic coverage (2019–2025)

Annual output shows a clear post-2020 acceleration in integrated STEM–ESD research. Publications rise from 2019 (*n* = 1)

to 2020 ($n = 6$) and 2021 ($n = 8$), remain steady in 2022 ($n = 6$), and then surge through 2023 ($n = 11$) to a peak in 2024 ($n = 12$) (see Figure 2). The apparent dip in 2025 ($n = 5$) almost certainly reflects a partial-year window rather than a true decline. Across 2019–2025, the corpus totals 49 papers, with a majority published recently ($\approx 57\%$ in 2023–2025; $\approx 69\%$ in 2022–2025), indicating a fast-growing area.

Geographic coverage is broad but uneven as shown in Figure 3. The United States contributes the largest single share (13/49; $\sim 27\%$), followed by Indonesia (7/49; $\sim 14\%$). Roughly one in five records are not tied to a single country (e.g., theoretical papers, “not stated,” or regional labels such as Europe). The remaining studies form a long tail of single or double contributions across many settings—e.g., Republic of Korea (2), Vietnam (2), and one each from Canada, Mexico, Sweden, Finland, Qatar, Greece, China, Portugal, Norway, Malaysia, Spain, Türkiye, and the United Kingdom, along with a regional case in the Southeastern United States.

Implications. The recency surge justifies updating/expanding prior review windows. Regionally, the evidence base is strongest in North America and Southeast/East Asia, with scattered coverage in Europe and comparatively little from Africa and much of Latin America. Readers should keep these imbalances in mind when judging generalizability and when targeting future searches and partnerships.

3.2 RQ2: How are subject anchors distributed across STEM integration approaches?

Across the Corpus, Environmental Science is the modal anchor and carries the widest spread of integration approaches, which is clearly shown in Figure 4. Within this anchor, PjBL is most common, often integrated with IBL and modeling when students investigate local systems (e.g., water, biodiversity, and built environments) or carry out citizen science-style data work. Modeling is especially visible in hydrologic and ocean acidification units and in sustainability-themed systems tasks, whereas SSI/argumentation appears where decisions and trade-offs are central (waste, energy, and climate action). Engineering design is present but comparatively smaller within Environmental Science; when it appears, it typically targets devices or processes tied to water quality or resource use.

Chemistry anchors skew toward SSI and IBL, reflecting a strong emphasis on chemical literacy, decision-making, and safe/green

laboratory practices; design work is less frequent here than in mixed or physics-linked contexts. Physics entries are fewer and tend to pair with lab-based PjBL and engineering design (e.g., measurement devices and energy/heat applications), sometimes co-anchored with Environmental Science. Biology appears primarily in place-based or inquiry-oriented designs connected to ecosystems, gardens, and biodiversity, with modeling used to surface systems relations. Finally, Mixed (interdisciplinary) anchors often adopt PjBL and context/place-based designs to integrate multiple disciplines around authentic briefs (e.g., restoration science and transport decarbonization), occasionally layering computational thinking or simulation elements; game-based and STEAM approaches appear more sparingly and are concentrated in motivation-oriented climate units and hazards/disaster education, respectively.

Overall, the stacked distribution shows a clear pattern: PjBL is the cross-cutting backbone across subjects; IBL and modeling cluster in Environmental Science and Mixed anchors; SSI concentrates in Chemistry and climate-oriented studies; engineering design is most visible where physics or mixed STEM problems call for tangible artifacts; and game-based/STEAM play targeted roles rather than serving as dominant integration modes.

3.3 RQ3: Which sustainability topics are addressed, and how is technology employed within these studies?

We mapped sustainability/ESD topics to subject anchors for the empirical intervention studies only. Seven studies were not included in Table 2 because they were conceptual/review papers ($n = 6$) or an intervention without an explicit ESD anchor ($n = 1$). Those studies remain in the corpus (see Supplementary material) and inform the thematic synthesis, but they are excluded from the topic-by-subject counts below.

Coverage and distribution. Among the 42 mapped studies, climate was the most frequent topic ($n = 14$), mainly in Environmental Science (9), with smaller shares in Mixed (3) and Physics (1). Water and waste/circularity followed ($n = 6$ each). Water-related units were anchored in Environmental Science (3), Chemistry (1), and Physics (2), while waste/circularity was concentrated in Chemistry (4) with minor entries in Environmental Science and Mixed. Biodiversity ($n = 5$) appeared mostly in Environmental Science (3), with single cases in Biology and Mixed. Energy ($n = 5$) was represented in Chemistry (2)

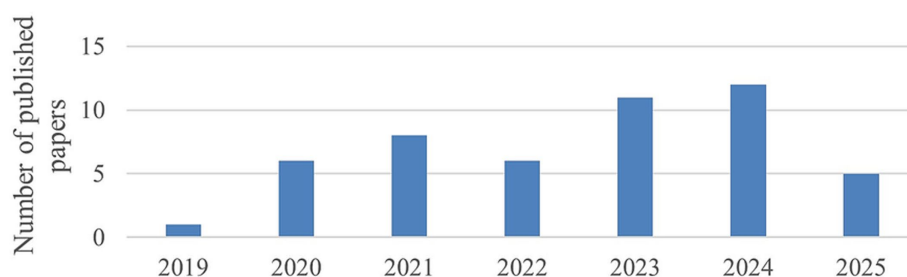


FIGURE 2
Annual distribution of included publications (2019–2025).

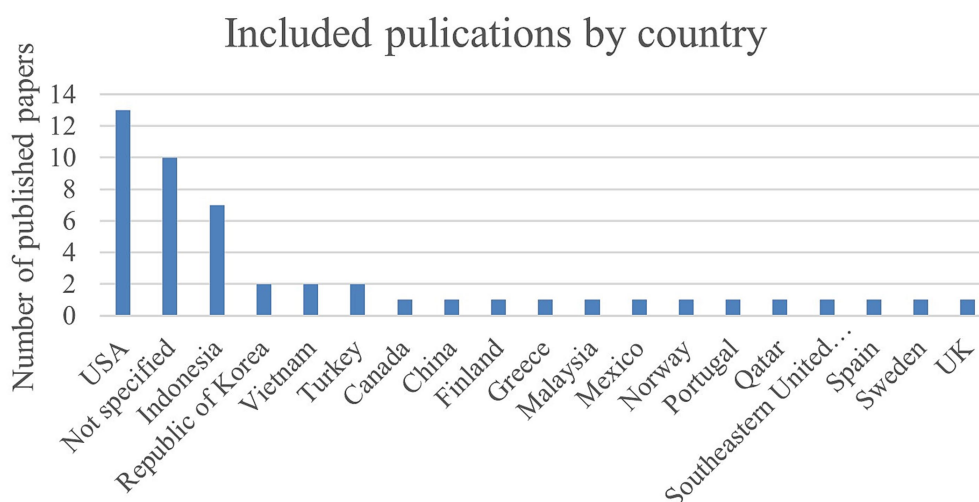


FIGURE 3
Distribution of included publications by country/region.

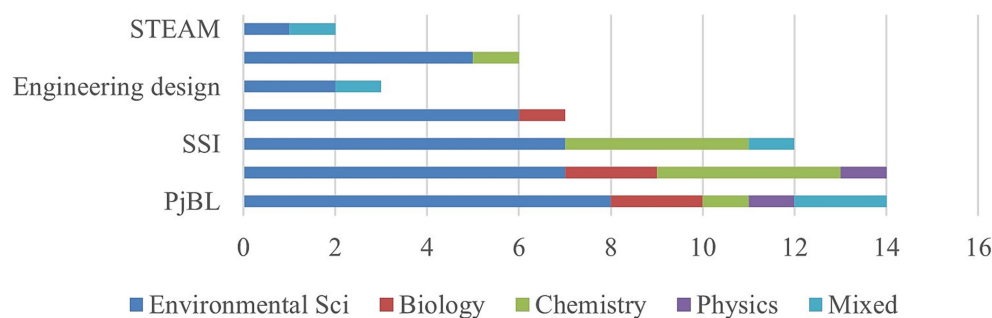


FIGURE 4
Distribution of STEM integration approaches across subject foci.

and Mixed (3) but had no Environmental Science anchors. Smaller clusters included Disaster ($n = 2$), Built environment ($n = 2$), and Justice/Policy ($n = 2$), all within Environmental Science or Mixed domains.

Technology use patterns. Tech use is highest in Water and Waste/Circular (both 67%), consistent with instrumented measurement, fabrication, or data-platform work. Disaster and Built environment show moderate adoption (50%), typically mapping apps, field-data tools, or classroom modeling. Climate—despite being the largest topic—shows lower uptake (36%), reflecting many discussion/SSI or concept-focused inquiries. Biodiversity uses tech in 20% of cases, often for observation/identification rather than analysis. Notably, Energy and Justice/Policy show 0% tech use in this sample, indicating opportunities to incorporate lightweight tools (e.g., household energy monitors, scenario simulators, and civic data dashboards) to deepen analysis and move beyond discourse.

Takeaway. Topics that naturally invite measurement or making (e.g., water quality and circular materials) show highest technology integration; more discourse-heavy areas (energy policy and justice) underutilize technology, representing a clear design gap.

3.4 RQ4: For each approach, what cognitive, affective, skills, and agency/behavior outcomes are most consistently improved?

Table 1 collates, for each instructional approach, how often studies reported positive effects in four outcome domains and the typical metrics used. Three approaches emerge as reliable “all-rounders.” PjBL shows the broadest pattern of gains—cognitive 7/8 (~88%), affective 9/10 (90%), skills 5/5 (100%), and agency 4/4 (100%)—measured with knowledge/concept tests and post-quizzes; attitude, self-efficacy, and sustainability-awareness surveys; artifact/rubric reviews; and preparedness, responsibility, or action-intent indicators. IBL displays a similar profile in a smaller evidence set—cognitive 9/9, affective 6/6, skills 2/2, agency 1/1—using science/chemical-literacy tests, unit exams, Global Science Literacy Questionnaire (GSLQ)/Nature Relatedness (NR)/self-efficacy scales, the Inventive Problem Test, and Science and Engineering Practices (SEP) aligned performances. Context/place-based designs are likewise consistently positive—cognitive 4/4, affective 5/5, skills 3/3, agency 2/2—with knowledge tests, model-based tasks,

competence interviews, relevance/NR/motivation scales, data/modeling skill checks, and preparedness or conservation-commitment measures.

Approaches that explicitly foreground civic reasoning tend to be strongest for agency and values while still delivering targeted literacy gains. SSI/Argumentation studies report cognitive 2/2, affective 3/3, skills 1/1, and agency 3/3, drawing on literacy tests, values/motivation questionnaires, argument-quality coding, and willingness/citizenship instruments. These results indicate that structured deliberation and decision-making around SSI reliably move dispositions and participation while consolidating key concepts.

Designs that center representational rigor or making tend to excel on skills, with complementary gains elsewhere when scaffolds are present. Modeling shows affective 3/3, skills 2/2, and agency 2/2, but cognitive 1/2—a split that aligns with the use of model-coherence/integration coding, NR/engagement surveys, systems-thinking rubrics, and conservation-commitment/action phases. The mixed cognitive signal suggests that explicit supports for connecting mechanisms and evidence are pivotal if modeling is to translate into test-score gains. Engineering design yields skills 2/2 and affective 3/3 with cognitive 2/2, assessed via design/problem-solving artifacts, attitude/awareness reflections, and post-quizzes or concept tests; agency measures were not reported in this bin.

Two smaller bins provide directional but tentative read-outs. Game-based work in this corpus chiefly demonstrates affective improvement (1/1 via ARCS coding) with no concurrent cognitive/skills/agency measures reported, implying that tighter curricular integration and outcome instrumentation are needed to evidence learning beyond motivation. STEAM shows cognitive 1/1, skills 1/1, and agency 1/1—all from hazards/preparedness contexts that used pre/post knowledge checks, expert validation of artifacts, and preparedness-choice tasks; no affective instruments were reported.

Taken together, the pattern in [Table 1](#) suggests that if broad impact is the aim, PjBL, IBL, and context/place-based designs are the most dependable choices. When the priority is to cultivate agency and value commitments, SSI/Argumentation is a robust route. Modeling and engineering design are the most efficient levers for skills (systems reasoning; design/problem-solving) and can deliver cognition when coherence supports and concept assessments are built in. Finally, the small denominators in several bins warrant cautious interpretation; reporting the *n* with positive effect/total reporting alongside typical metrics is essential for transparent strength-of-evidence claims.

3.5 RQ5: What thematic design patterns link approaches, sustainability topics, and outcome gains?

[Table 3](#) reveals a small number of dominant patterns that integrate instructional design with topic choice and outcomes. First, place-based & community partnerships are the modal cluster. Typically implemented via PjBL/IBL around water, built environments, or justice briefs, these designs consistently lift agency/behavior (participation and local action), alongside skills (data/communication) and affective relevance—a profile that mirrors the broad gains we saw for context/place-based approaches in [Table 1](#).

Second, SSI with action-taking (often paired with explicit argumentation scaffolds) anchors climate, waste/incineration, and energy topics. These studies jointly deliver cognitive gains (e.g., literacy tests and GSLQ) while also increasing agency and values/

emotions when deliberation culminates in tangible action (campaigns and decision briefs). This cluster is the clearest route to moving dispositions without sacrificing content.

Third, modeling & systems thinking concentrates on water, ocean acidification, and urban/bioeconomy contexts. Typical outcomes are stronger systems reasoning skills and improved conceptual understanding when coherence supports are present—aligning with the mixed cognitive but strong skills/affect pattern in [Table 1](#).

Fourth, engineering design for ESD (e.g., salinometers and circular biorefinery labs) reliably develops design/problem-solving skills and posts complementary concept gains, especially in physics-linked or mixed anchors. In contrast, game-based/simulation entries chiefly raise motivation/affect (ARCS); cognitive effects appear when games are tightly scaffolded and integrated with assessment.

Two cross-cutting clusters operate as enablers. Data/citizen science & computational thinking—common in biodiversity and restoration—builds data/CT skills and stewardship/agency, dovetailing with the higher technology uptake observed in measurement-heavy topics (see [Table 2](#)). Teacher PCK/PD for SD (e.g., CoRe + video cycles and co-teaching) strengthens teaching practice and self-efficacy, a prerequisite for coherent integration across subjects and topics.

Finally, specialized clusters round out the map: equity/cultural relevance (Ethno-STEM and Indigenous partnerships) improves belonging and often agency; green chemistry & circular economy shows cognitive and lab-skills gains; gardens/biodiversity boosts knowledge and participation; climate literacy/critical thinking yields moderate cognitive gains and higher self-efficacy; futures thinking primarily moves values/willingness; critical/decolonial & justice reframes purposes and builds critical literacy; disaster/hazards programs improve knowledge and preparedness; and authentic industry briefs heighten relevance and argumentation when tied to a concrete “commission.”

Within the equity/cultural relevance entries, most designs were place-based or citizen science (e.g., gardens, restoration, and local hazards) and occasionally SSI where policy/justice was foregrounded. Co-design with communities and concrete access supports (e.g., transport and multilingual materials) were reported in only a few cases, and equity-specific outcomes (belonging/identity, participation/agency, and stewardship) were seldom directly measured. Where reported, gains concentrated in participation/stewardship (restoration programs), preparedness (co-produced wildfire curricula), and community participation in Indigenous partnerships. Study-level coding appear in [Supplementary material](#).

Design takeaway. Choosing a cluster is tantamount to choosing the outcomes you most want to move: place-based and citizen-science designs for agency/skills; SSI + action for agency/values with solid cognition; modeling/engineering for skills with targeted concept gains; games for motivation (plus learning when scaffolded); and PD/equity clusters to make any of the above work with fidelity and inclusion. This synthesis sets up RQ6, where we examine recurrent implementation challenges and the remedies that make these patterns stick at scale.

3.6 RQ6: What challenges and remedies recur across implementations?

Recurring barriers cluster into three bands. System-level constraints include curriculum fit and standards alignment, equity and access (transport, costs, and language), and the socio-politics of energy/land use; effective remedies are co-produced, locally relevant units aligned

TABLE 3 Thematic design patterns linking approaches, sustainability topics, and outcome gains.

Theme	Concise description	Outcomes most affected (metrics)	Representative studies
Place-based & community partnerships	Learning tied to local places, partners, and issues	Agency/behavior—improved (participation, action tasks); skills—improved (data, communication); affective—improved (NR scale, relevance)	Littrell et al. (2020); Birney and McNamara (2021); Spencer et al. (2022); Cole et al. (2024); Ellington and Prado (2024)
SSI & action-taking for citizenship	Socio-scientific issues with deliberation and action	Cognitive—improved (tests, GSLQ); agency—improved (action logs); affective—improved (emotion/values)	Kim and Kim (2020); Alcaraz-Dominguez and Barajas (2021); Nida et al. (2021); Zhu and He (2022); Georgiou and Kyza (2023)
Modeling & systems thinking	Learners build/explain models of socio-ecological systems	Cognitive—improved (model quality, post-quizzes); skills—improved (systems reasoning)	McCance et al. (2021); Sezen-Barrie et al. (2023); Cole et al. (2024); Cuong et al. (2025)
Engineering design for ESD	Designing devices/processes addressing sustainability	Skills—improved (design, problem-solving); cognitive—improved (concept tests)	Candan Helvacı and Helvacı (2019); McCance et al. (2021); Dung et al. (2023); Pramasyahsari et al. (2024)
Game-based & simulation	Serious games/sims to build motivation & literacy	Affective—improved (ARCS: attention, relevance); cognitive—mixed improvement	Kim et al. (2023); Besalti and Smith (2024)
Data/citizen science & CT	Authentic data collection/analysis with computational thinking (CT) elements	Skills—improved (data/CT); agency—improved (stewardship)	Birney and McNamara (2021); Herodotou et al. (2024)
Teacher pedagogical content knowledge (PCK) & PD for sustainable development (SD)	Building teachers' SD-PCK and practices	Skills—improved (teaching practices); cognitive—improved (teacher self-efficacy)	Maass et al. (2022); Forsler et al. (2024); Wang et al. (2025)
Equity, access & cultural relevance	Culturally situated or equity-oriented designs	Affective—improved (belonging, relevance); agency—improved	Spencer et al. (2022); Izzah et al. (2023); Ellington and Prado (2024)
Green chemistry & circular economy	Safer, SD goals-linked chemistry activities	Cognitive—improved (concept tests); skills—improved (lab practices); affective—improved	Jefferson et al. (2020); McCance et al. (2021); Sharif et al. (2021); Celestino (2023)
Gardens, biodiversity & bioliteracy	School gardens/citizen science for plant/bio knowledge	Cognitive—improved (knowledge items); agency—improved (participation)	Azevedo et al. (2022); Herodotou et al. (2024)
Climate literacy & critical thinking	Content + practices to grow climate literacy	Cognitive—improved (N-gain, exams); affective—improved (self-efficacy)	Holley and Park (2020); Hakim et al. (2023); Sigit et al. (2024)
Futures thinking & agency	Imagining sociotechnical futures to build agency	Affective/agency—improved (willingness, values paths)	Kang and Tolppanen (2024); Pramasyahsari et al. (2024)
Critical/decolonial & justice orientations	Justice-oriented framing of science/ESD	Affective/agency (conceptual); skills (critical literacy)	Gandolfi (2024); Lowan-Trudeau and Fowler (2025)
Disaster & hazards literacy	Natural hazards content with STEAM tasks	Cognitive—improved (pre/post); agency—improved (preparedness)	Mereli et al. (2023)
Authentic industry/real-world briefs	Real clients/commissions to drive relevance	Affective—improved (relevance); skills—improved (argumentation)	Kostol and Remmen (2022); Restaino et al. (2024); Wang et al. (2025)

explicitly to standards, plus place-based partnerships and multilingual logistics, and, where issues are politically charged, critical/decolonial framings that surface multiple perspectives. Capacity and infrastructure gaps span insufficient teacher PCK/PD, limited lab resources, and technology hurdles; here, structured PD cycles (e.g., CoRe + video and co-teaching), low-cost/green kits and simple calculators, and stepwise scaffolds for simulations/games are repeatedly successful. Design and assessment pitfalls involve misaligned assessment with PjBL/SSI/modeling, superficial modeling practice, weak argumentation, short durations that fail to influence behavior, field trips disconnected from deliverables, and prior-knowledge mismatches; recommended practices include rubric-based assessment of products/arguments/models, iterative systems modeling tied to real infrastructures, explicit claim-evidence-reasoning routines, multi-week action components, pre-/debriefed visits anchored to a concrete “commission,” and targeted ramp-up mini-lessons. Table 4 presents the full challenge-remedy map

with author-year citations that underpin each recommendation and can be implemented directly in new STEM-ESD designs.

4 Discussion

4.1 Summary of principal findings (RQ1–RQ6)

This review maps a rapidly expanding evidence base on integrated STEM for sustainability/ESD (2019–2025). Publication volume accelerates after 2020 and concentrates in North America and Southeast/East Asia, with fewer studies from Africa and Latin America (RQ1; Figures 2, 3). Subject-approach patterns show project-based learning as a cross-cutting backbone, inquiry-based learning and modeling clustered in Environmental Science/Mixed anchors, SSI/

TABLE 4 Recurring challenges in integrated STEM–ESD implementation and illustrative remedies with supporting references.

Challenge	Illustrative remedy/practice (examples)	References
Curriculum adoption & fit to standards	Co-produce locally relevant units with stakeholders; align explicitly to standards; pilot → iterate.	Kostøl and Remmen (2022); Restaino et al. (2024); Lowan-Trudeau and Fowler (2025)
Insufficient teacher PCK/PD for ESD & integration	Run structured PD with planning–teaching–reflection tools (e.g., CoRe + video), interdisciplinary co-teaching, and citizenship-oriented tasks.	Maass et al. (2022); Forsler et al. (2024); Wang et al. (2025)
Assessment misaligned with PjBL/SSI/modeling	Design assessment with rubrics for argumentation, models, and products; assess iterative modeling coherence, not just recall.	Alcaraz-Dominguez and Barajas (2021); Kostøl and Remmen (2022); Sezen-Barrie et al. (2023)
Technology hurdles (access, cognitive load, integration)	Start with low-cost/green kits and simple calculators; scaffold complex simulations/games with worked examples and stepwise complexity.	Sharif et al. (2021); Kim et al. (2023); Nurramadhani et al. (2024)
Equity & access barriers (transport, costs, language)	Use place-based partnerships; budget for buses/fees; provide multilingual materials and flexible formats.	Birney and McNamara (2021); Ellington and Prado (2024); Herodotou et al. (2024)
Sociopolitical sensitivity around energy/land use	Adopt socio-critical & decolonial framing; surface multiple perspectives; vet industry-funded materials carefully.	Nida et al. (2021); Gandolfi (2024); Lowan-Trudeau and Fowler (2025)
Attitudes/behavior do not shift with short lessons	Add action-taking components, longer duration, and local projects to build agency.	Kim and Kim (2020); Park and Kim (2020); Georgiou and Kyza (2023)
Weak argumentation & decision-making on SSI	Structure collaborative argumentation cycles; teach claim–evidence–reasoning explicitly; provide diverse evidence sets.	Fadly et al. (2022); Zhu and He (2022); Sezen-Barrie et al. (2023)
Superficial modeling practice	Scaffold systems modeling (iterations, connections, mechanisms) and link to real infrastructures/ecosystems.	Sezen-Barrie et al. (2023); Cole et al. (2024)
Interdisciplinary coherence & disciplinary silos	Use co-teaching and explicit integration maps (concept ↔ practice ↔ sustainability driver); sequence courses to revisit anchors.	McCance et al. (2021); Dung et al. (2023); Wang et al. (2025)
Persistent misconceptions (e.g., ozone vs. climate)	Run targeted, hands-on measurements with reflection on sources of error and concept contrasts; revisit ideas across units.	Holley and Park (2020); Ramirez-Gonzalez et al. (2020)
Too short to build depth/skills	Extend to multi-week programs with iterative cycles and follow-ups; embed in school-year pathways.	Birney and McNamara (2021); Mereli et al. (2023); Restaino et al. (2024).
Field trips feel disconnected from learning goals	Tie visits to a concrete “commission” or audience; pre-brief and debrief to map experiences to deliverables.	Kostøl and Remmen (2022); Spencer et al. (2022)
Prior knowledge gaps vs. technical content	Bridge with ramp-up activities, mini-lessons, and concept primers; iterate designs after early trials.	Kim et al. (2023); Restaino et al. (2024)
Cultural relevance & student identification	Use Ethno-STEM/local wisdom and community partnerships (including Indigenous knowledge) to situate tasks.	Spencer et al. (2022); Izzah et al. (2023); Pramasdyahsari et al. (2024)
Knowledge ≠ action (motivation pathways)	Design for intrinsic value and relevance; cultivate biospheric values and responsibility through meaningful contexts.	Littrell et al. (2020); Kang and Tolppanen (2024)
Limited lab resources & safety concerns	Adopt low-cost/green alternatives and household materials that still surface core concepts.	Jefferson et al. (2020); Ramirez-Gonzalez et al. (2020); Sharif et al. (2021)
Underdeveloped data & computational skills	Embed data collection/curation and platform use; integrate CT tasks (modeling, simulation) with science aims.	Birney and McNamara (2021); Kim et al. (2023)
Unclear student agency & futures thinking	Add futures-oriented tasks (scenarios, back casting) linked to local action opportunities.	Georgiou and Kyza (2023); Rasa et al. (2024)

argumentation concentrated in Chemistry and climate contexts, and engineering design most visible when physics or mixed problems require tangible artifacts (RQ2; Figure 4).

Topic distributions (RQ3; Table 2) are led by climate ($n = 14$), followed by water ($n = 6$) and waste/circular ($n = 6$); biodiversity and energy each total $n = 5$, while disaster, built environment, and justice/policy are smaller clusters ($n = 2$ each). Technology use is highest in water and waste/circular (both 67%), moderate in disaster and built environment (50%), and lower in climate (36%); energy and justice/policy show 0% tech within this empirical set. Seven studies were not included in Table 2 because they were conceptual/review papers ($n = 6$) or an intervention without an explicit ESD anchor ($n = 1$); they still inform the thematic synthesis.

Outcome synthesis by approach (RQ4; Table 1) indicates three “all-rounders:” PjBL, IBL, and context/place-based designs show consistent gains across cognitive, affective, skills, and agency domains (with denominators varying by what each study measured). SSI/argumentation most reliably moves agency/values while also consolidating literacy. Modeling and engineering design excel on skills (systems reasoning; design/problem solving) and can yield cognitive gains when coherence supports and concept assessments are built in. Game-based and STEAM bins are smaller; game studies chiefly evidence affective benefits unless tightly scaffolded and assessed.

Thematic patterns (RQ5; Table 3) integrate place-based/community partnerships, SSI with action-taking, modeling/systems thinking, and engineering design with topic choices to produce

predictable outcome profiles. Cross-cutting enablers include data/citizen science + CT, teacher PCK/PD for SD, and equity/cultural relevance moves (Ethno-STEM and Indigenous partnerships). Finally, a consolidated challenge–remedy map (RQ6; [Table 4](#)) highlights recurrent barriers—curricular fit, PD capacity, technology/cognitive-load issues, assessment misalignment, equity/logistics—and practical solutions that have been shown to work (e.g., co-produced units aligned to standards, CoRe + video PD cycles, stepwise scaffolds for simulations/games, rubric-based assessment of products/arguments/models, and pre-/de-briefed fieldwork tied to a concrete commission).

Equity-oriented or culturally situated designs comprised roughly a quarter of the empirical corpus, while co-design with communities and concrete access supports were comparatively uncommon; explicit measurement of belonging/identity or community agency was rare (see [Supplementary material](#)).

4.2 Design implications: choosing the right lever for the desired outcome

- Broad impact across domains (knowledge, affect, skills, and agency): Favor PjBL, IBL, or context/place-based designs ([Table 1](#)).
- Civic agency/values with solid cognition: Use SSI with explicit argumentation and action-taking culminating in public products or decisions ([Table 4](#)).
- Skills (systems reasoning; design/problem solving): Emphasize modeling (with coherence scaffolds) and engineering design (with concept-aligned assessment).
- Motivation/engagement boosts: Pair game-based elements with explicit concept/skill assessments and stepwise complexity to convert affect into learning.

4.3 Technology integration: close the design gap in energy and justice/policy

High tech-use in water and waste/circular suggests that topics inviting measurement or making naturally absorb sensors, data platforms, and fabrication ([Table 2](#)). By contrast, energy and justice/policy contexts underutilize technology. Practical routes to close this gap include:

- Energy: low-cost household energy monitors, simple data loggers, and scenario simulators embedded in PjBL/IBL; parametric BIM or spreadsheet-based audits with guided interpretation (coherence scaffolds).
- Justice/Policy: civic-data dashboards, participatory mapping (open GIS), and evidence assemblies that feed directly into SSI argumentation cycles and action briefs.

4.4 Equity, culture, and place

Place- and community-based designs consistently elevate relevance and participation, particularly when equity barriers (transport, fees, and language) are addressed up front through partnerships and multilingual materials. Culturally situated approaches (Ethno-STEM and Indigenous collaborations) help students see science as connected to identities and community practices; these designs frequently strengthen affect and

agency and should be planned as integral—not peripheral—components. In our sample, however, co-design and explicit access supports were reported in only a minority of studies, and equity outcomes (belonging/identity, participation/agency, and stewardship) were seldom instrumented; details appear in the [Supplementary material](#).

4.5 Teacher learning and implementation fidelity

Teacher capacity is the fulcrum for coherent integration. Evidence favors structured PD that surfaces pedagogical reasoning (e.g., CoRe + video reflection), supports co-teaching across disciplines, and provides vetted, standards aligned materials. District-level adoption is eased when units are co-produced with local stakeholders and when assessments are aligned to products, models, and arguments rather than solely to recall tests.

4.6 Reporting and measurement recommendations

To improve comparability and strength of evidence:

1. Report comparators, fidelity checks, and validated instruments; include agency/behavior measures where claims are made.
2. Make assessment rubrics for models/designs/arguments public; include sample artifacts.
3. Specify technology roles (purpose, scaffolds, and cognitive demands) and provide stepwise task designs for complex tools (e.g., simulations and games).
4. When multiple approaches are integrated, identify the primary learning cycle and the outcomes each approach is intended to move.
5. Report instrument reliability (e.g., Cronbach's α) and flag null/contradictory findings; interpret low-reliability results with caution.
6. Differentiate technology roles—content delivery, process scaffolding, or transformative tasks—to clarify depth of integration (e.g., a TPACK-aligned description).

4.7 Limitations

This review was limited to English publications (2019–2025) indexed in the selected databases, and the 2025 data reflect a partial year. Geographic coverage was uneven, with concentration in a few regions. Instruments and outcomes were heterogeneous, denominators varied by what each study measured, and agency was not consistently assessed (e.g., in engineering-design bins). Conceptual/review papers and one non-ESD intervention were excluded from topic counts ([Table 2](#)) but informed the thematic synthesis; empirical risk-of-bias features varied across studies. Technology integration was coded broadly by presence and type; finer grained distinctions such as content delivery, scaffolding, or transformative use (cf. TPACK) were not applied. Similarly, many studies did not report measurement reliability (e.g., Cronbach's α), limiting our ability to systematically account for null or low-reliability results. These issues constrain the depth of interpretation and highlight directions for future reviews.

4.8 Future research

Priorities include (a) longitudinal tracking of agency/behavior and transfer, (b) expansion to under-represented regions and multi-site designs with community co-design and explicit equity outcome measures, (c) robust comparators and fidelity reporting, (d) tighter integration of technology in energy and justice/policy contexts with cognitive-load-aware scaffolds, (e) alignment of assessment to products/arguments/models, and (f) studies that connect teacher PD models to student outcomes at scale.

5 Conclusion

This review provides a design-ready evidence map of integrated STEM for sustainability/ESD. We show (1) a surging publication trend with uneven geography; (2) stable subject $\times$ approach patterns with PjBL/IBL/context as dependable cores; (3) topic distributions and technology-use profiles that highlight measurement-friendly areas (water and circular) and under-instrumented ones (energy and justice/policy); (4) outcome profiles by approach indicating where to invest for cognition, skills, affect, or agency; (5) thematic design clusters that integrate place, SSI + action, modeling, and design into predictable gains; and (6) a challenge–remedy map that turns recurrent implementation problems into actionable practices.

For practitioners and policymakers, the guidance is straightforward: choose the lever that matches your desired outcomes, co-produce standards aligned units with community partners, scaffold technology use deliberately, and align assessment to the products and reasoning students actually create. For researchers, the agenda is to broaden contexts, strengthen study designs and measures—especially for agency—and document fidelity and costs so promising models scale with equity.

Finally, our topic mapping (Table 2) covers 42 empirical, ESD-anchored interventions; seven additional studies (conceptual/review or without explicit ESD anchoring) inform the synthesis but are excluded from those counts. Together, the tables and figures (Tables 1–4; Figures 1–4) provide a coherent scaffold for planning, implementing, and evaluating integrated STEM designs that help young people reason about—and act on—pressing socio-ecological issues.

Data availability statement

The original contributions presented in the study are included in the article/[Supplementary material](#), further inquiries can be directed to the corresponding author.

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AmK: Writing – original draft, Supervision, Methodology, Conceptualization. SL: Data curation, Investigation, Writing – review & editing. BA: Validation, Formal analysis, Writing – review & editing. AT: Writing – review & editing, Data curation, Visualization. MN: Resources, Project administration, Validation, Writing – original draft. AsK: Investigation, Writing – review & editing.

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Supplementary material

The Supplementary material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/feduc.2025.1697058/full#supplementary-material>

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