Journal of General Education and Humanities
Vol. 5, No. 4, August 2026, pp. 4975 – 4993, https://doi.org/10.58421/gehu.v5i4.1864
ISSN 2963-7147

Students' Environmental Decision-Making in Secondary Biology Education: A Bibliometric Analysis and Systematic Literature Review

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Article Info

Article history:

Received 2026-07-01
Revised 2026-08-01
Accepted 2026-08-01

Keywords:

Bibliometric Analysis
Biology Learning
Decision-Making Skill
Environmental Issues
Socioscientific Issues
Systematic Literature Review

ABSTRACT

Decision-making skills on environmental issues are a key 21st-century competency that should be systematically fostered through biology learning. However, research on this topic remains fragmented across educational contexts, learning approaches, and research designs, limiting a comprehensive understanding of publication trends, effective interventions, and research gaps. This study aimed to map research trends, identify learning interventions that enhance students' decision-making skills, and reveal thematic, methodological, and contextual gaps. A mixed review approach combining bibliometric analysis and a systematic literature review (SLR) was employed. The bibliometric analysis examined 414 Scopus-indexed publications from 2005–2025, while the SLR synthesized 11 eligible empirical studies. Bibliometric data were processed using OpenRefine and analyzed with VOSviewer and Biblioshiny, whereas the selected studies were narratively synthesized based on intervention type, research design, outcomes, and thematic coding of reported limitations and future research directions. The findings reveal a steady increase in publications over the past two decades, indicating growing scholarly interest in environmental decision-making. The reviewed studies suggest that socioscientific issues, open inquiry, role-play, and explicit decision-making frameworks, such as OIDDE and the Four Component Model, can improve evidence-based reasoning, value consideration, and environmental responsibility. However, variations in research designs, interventions, assessment instruments, and outcome measures limit comparisons across studies. Key research gaps include the limited development of comprehensive assessment instruments, the scarcity of longitudinal studies, and insufficient investigation of local educational contexts. These findings provide directions for future research and practical implications for developing biology curricula and environmental education that strengthen students' informed and responsible decision-making skills.

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1. INTRODUCTION

Biology learning at the secondary-school level plays a strategic role in shaping a generation that is sensitive and responsible toward increasingly complex environmental issues, such as climate change, biodiversity loss, contamination, pollution, and ecosystem degradation [1]. These issues demand not only conceptual understanding but also students' ability to make appropriate decisions based on scientific information, value considerations, and possible socio-ecological impacts. Within the framework of education for sustainable development, decision-making skill is regarded as one of the key 21st-century competencies that needs to be developed systematically in the science-learning process, particularly in biology [2].

In this study, environmental decision-making skill is defined as a student's capacity to identify alternative courses of action in response to an environmental problem, evaluate available scientific evidence, weigh the risks and consequences of each alternative, consider relevant ethical and value-based considerations, justify the chosen decision, reflect on potential biases in the reasoning process, and translate the decision into concrete action [3]. This construct is closely related to, yet analytically distinct from, several neighboring constructs frequently used in the literature. Unlike general decision-making, which concerns choice-making across any domain of everyday life, environmental decision-making skill is anchored specifically in socio-ecological problems that carry scientific uncertainty and ethical weight [4]. It also differs from scientific reasoning and argumentation, which emphasize the evaluation and justification of evidence-based claims but do not necessarily require an explicit behavioral commitment or action outcome [5], [6]. It further differs from problem-solving, which targets a single optimal solution to a well- or ill-defined problem, whereas environmental decision-making explicitly requires weighing competing values and consequences among several viable alternatives [7]. Although environmental decision-making skill overlaps substantially with socioscientific reasoning, in that both are exercised through socioscientific issues (SSI) contexts, socioscientific reasoning is typically operationalized as the cognitive process of evaluating multiple perspectives on a controversial issue. In contrast, environmental decision-making skill additionally requires the learner to arrive at, and justify, an actionable decision [8]. Finally, environmental decision-making skill is broader than environmental literacy, which primarily denotes knowledge of and attitude toward environmental issues; decision-making skill presupposes such literacy but adds the procedural competence of using it to reach and act on a judgment [9].

Prior studies converge on the finding that environmental decision-making skill is most often cultivated through a socioscientific issues (SSI) context, in which students are encouraged to consider evidence, arguments, values, and the consequences of the choices they make [10]. Within this body of work, a consistent pattern emerges: interventions ranging from argumentation-based approaches, place-based learning, and deliberative discussion to structured decision-making frameworks have generally been found to strengthen students' evidence evaluation and value consideration [10], [11], [12]. However, a second recurring pattern is that most of these interventions concentrate on the cognitive

and discursive dimensions of decision-making: identifying alternatives, evaluating evidence, and justifying a position. Dimensions such as reflecting on cognitive bias and translating decisions into concrete environmental action receive comparatively little attention [3], [12]. Classroom practice further compounds this imbalance: several studies report that everyday science instruction remains dominated by confirmatory, factual-knowledge-oriented teaching, limiting students' opportunities to practice decision-making on real, contextualized issues [13], [14].

Along with the increasing global attention to environmental education and sustainable development, scientific publications discussing students' decision-making skill in the context of environmental issues have also grown; nevertheless, such studies remain scattered across various journals, national contexts, and learning models, so a comprehensive picture of research trends, the types of interventions used, and the resulting scientific contributions has not yet been documented comprehensively [15]. Moreover, few studies have specifically mapped how research on environmental decision-making is situated within biology learning at the secondary-school level. This domain is particularly relevant given its direct engagement with the biological and ecological content (e.g., ecosystems, biodiversity, pollution) that underlies most environmental decision-making tasks, as well as its role in shaping students' cognitive and moral development during adolescence [16]. This leaves unclear which strategies are most effective specifically within biology instruction, and where thematic, methodological, and contextual gaps remain.

This study addresses these gaps by combining two complementary analytical lenses that, to date, have rarely been applied together in this area: a bibliometric analysis to map the overall scientific landscape (publication trends, productivity, and thematic structure) across 414 Scopus-indexed documents, and a systematic literature review (SLR) that narrows the focus specifically to secondary-school biology learning to synthesize which interventions are associated with improvements in environmental decision-making skill and what gaps remain. This dual-method design distinguishes the present study from prior reviews that have typically relied on either a bibliometric mapping or a narrative/systematic review alone, and from reviews that examine decision-making or socioscientific reasoning broadly across science education without isolating the biology-specific evidence base.

Accordingly, this study aims to (1) map the publication trends and scientific contributions related to students' decision-making skill in the context of environmental issues, (2) identify learning interventions or strategies associated with improvements in this skill within biology learning, and (3) identify research gaps in terms of theme, methodology, and learning context. These objectives are translated into the following research questions:

(1) How have publication trends and scientific contributions of research related to students' decision-making skill in the context of environmental issues developed over time?

(2) What learning interventions or strategies have been associated with improvements in students' decision-making skill in the context of environmental issues within biology learning?

(3) What research gaps remain in studies on the development of students' decision-making skill in the context of environmental issues, viewed from the aspects of theme, methodology, and learning context?

This study is expected to contribute theoretically by clarifying the conceptual boundaries of environmental decision-making skill relative to adjacent constructs, and by consolidating a fragmented evidence base into a coherent map of effective interventions and persistent research gaps. Practically, the findings may inform biology teachers and curriculum designers in selecting instructional strategies, such as socioscientific issue discussion, open inquiry, role-play, and explicit decision-making frameworks, that are more likely to develop students' environmental decision-making skill in a balanced manner across its cognitive, value-based, and action-oriented dimensions. At the policy level, given the limited number of eligible studies identified, the findings offer preliminary directions rather than definitive guidance for strengthening biology curricula and environmental education policy at the secondary-school level.

2. METHOD

This study employs two analyses, namely bibliometric analysis and a systematic literature review (SLR). Bibliometric analysis is used to map publication trends, author and institutional productivity, journal distribution, and the thematic structure of the research. Meanwhile, the SLR is used to comprehensively examine the development of research, learning interventions, and research gaps related to students' decision-making skills on environmental issues in senior-high-school biology learning.

The primary data source in this study is scientific articles indexed in an international database, namely Scopus. The search used the combination (TITLE-ABS-KEY ("decision making" OR "decision-making" OR "environmental decision" OR "ecological decision") AND TITLE-ABS-KEY ("biology" OR "biology learning" OR "biology class" OR "biology curriculum" OR "biology topic") AND TITLE-ABS-KEY ("student" OR "secondary school" OR "senior high school")). The search was carried out on the title, abstract, and keywords using a combination of terms related to decision-making, secondary school students, and biology learning/environmental topics within the 2005–2025 period (final search conducted on 03 December 2025).

Bibliometric analysis was carried out on the entire set of documents identified from the Scopus database (n = 414) using a .csv dataset to map publication trends and scientific contributions over time. The bibliometric analysis was conducted through three steps: first, data cleaning using the OpenRefine application to avoid keyword duplication. Second, data analysis using VOSviewer and Biblioshiny. Biblioshiny facilitated descriptive analysis of annual scientific production, keyword trends, and country productivity. Third, VOSviewer was used to map the main research themes explored in the literature and to identify possible future research areas. The results of the analysis were then compiled and reported descriptively, followed by a critical discussion of related studies.

Bibliometric analysis alone is not yet able to describe in depth how decision-making skills are developed through learning interventions or strategies in the context of science and biology education. Subsequently, a systematic literature review (SLR) was carried out on

the articles that passed the selection process to answer the research questions related to learning strategies and research gaps. The inclusion and exclusion criteria are presented in Table 1.

Table 1. Inclusion and exclusion criteria

Criteria	Inclusion	Exclusion
Publication type	Journal article	Others (book, book chapter, conference, etc.)
Publication stage	Final	Article in press
Language	English	Others
Respondent	Senior high school students	Other than senior high school students
Access	All open-access	Not accessible
Keywords	"decision making" "decision-making" "environmental decision" "ecological decision" "biology" "biology learning" "biology class" "biology curriculum" "biology topic" "student" "secondary school" "senior high school"	Others

The inclusion and exclusion criteria were established because the term decision-making skill applies not only to biology learning but also to career choice and health. Using the SLR method allowed the researchers to systematically review and identify journals, with each process following the established PRISMA 2020 protocol steps. The article-selection process is shown in the following Figure 1.

The SLR was conducted through a staged selection process in accordance with the PRISMA 2020 guidelines, which includes the identification, screening, and eligibility-assessment stages. This two-stage approach enabled the integration of broad research mapping through bibliometric analysis with an in-depth synthesis of learning strategies and research gaps related to senior-high-school students' decision-making skills on environmental issues. The identification stage retrieved 414 records from Scopus. Before screening, 171 records were removed based on database filters, leaving 243 records for title-and-abstract screening. At this stage, 204 records were excluded, leaving 39 reports sought for retrieval. Seven reports could not be retrieved due to limited open access, leaving 32 reports assessed for eligibility through full-text review. At this stage, 21 reports were excluded, resulting in 11 studies included in the final review.

To identify research gaps, the limitations and future research recommendations reported in each of the 11 included studies were extracted and thematically coded into categories covering issue/context, decision-making dimension, assessment instrument, methodology, and population. The coding was conducted by the researcher together with the research supervisor to enhance the trustworthiness of the resulting gap categories.

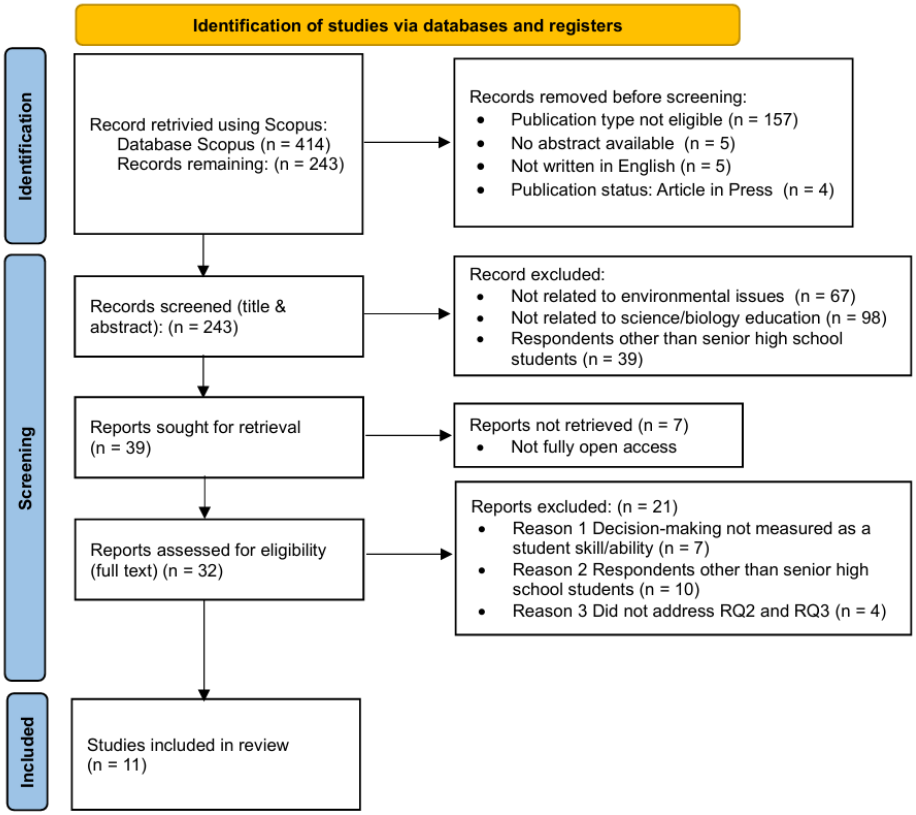

Figure 1. PRISMA Flow Diagram

3. RESULTS

3.1 Bibliometric Patterns

Bibliometric analysis was carried out as an initial map confirming that decision-making skill is an established, growing, and globally relevant topic. The main information from this search is shown in Table 2.

Table 2. Main Information about the Search Results

Description	Results
MAIN INFORMATION ABOUT DATA	
Timespan	2005:2025
Sources (Journals, Books, etc.)	209
Documents	414
Annual Growth Rate %	5.65
Document Average Age	8.86
Average citations per doc	22.44
References	3222
DOCUMENT CONTENTS	
Keywords Plus (ID)	2486
Author's Keywords (DE)	1092
AUTHORS	
Authors	1425
Authors of single-authored docs	91
AUTHORS COLLABORATION	
Single-authored docs	93
Co-Authors per Doc	3.62
International co-authorships %	14.49

Description	Results
DOCUMENT TYPES	
article	257
book	42
book chapter	17
conference paper	45
conference review	2
editorial	5
note	20
review	20
short survey	6

Figure 2 shows the annual scientific production trend, indicating a gradual increase in publications, particularly over the last decade. An annual growth rate of 5.65% and an average document age of 8.86 years were recorded, alongside 22.44 average citations per document.

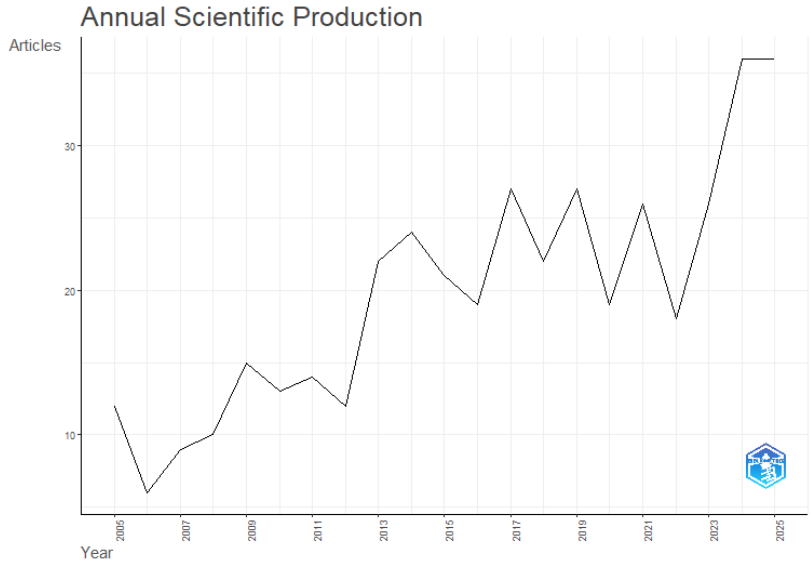

Figure 2. Annual Scientific Production

In addition, an identification of country contributions and the dynamics of global publications related to decision-making research was carried out. Figure 3 shows the top 5 countries in terms of the distribution of scientific production related to decision-making over time.

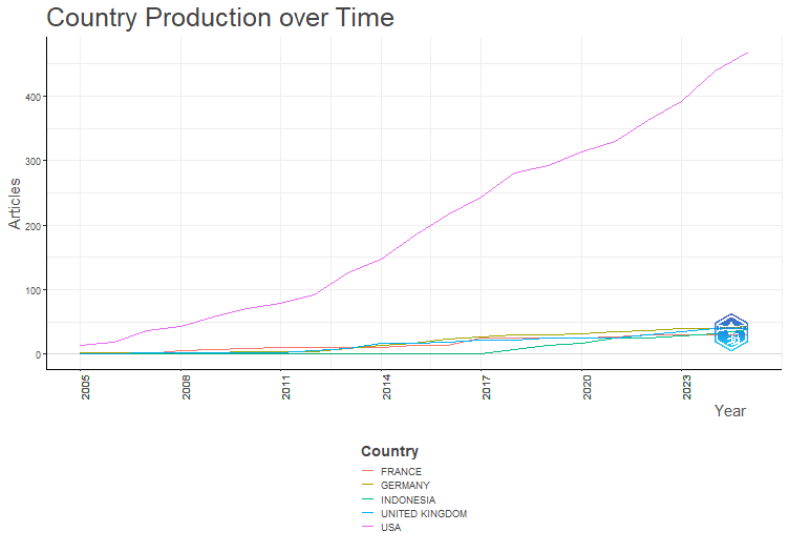

Figure 3. Country Production over Time

In addition, to observe developments and research gaps, a keyword network visualization was examined, forming several thematic clusters. The keyword decision-making appears as the main node connected to various other concepts, indicating its role as a central concept across various fields of study. Keyword network visualization of the full corpus (Figure 4) produced clusters reflecting decision-making in the context of education, environment, and policy; the same corpus-wide map also included clusters outside biology education, such as medical education, career choice, and biomedical research.

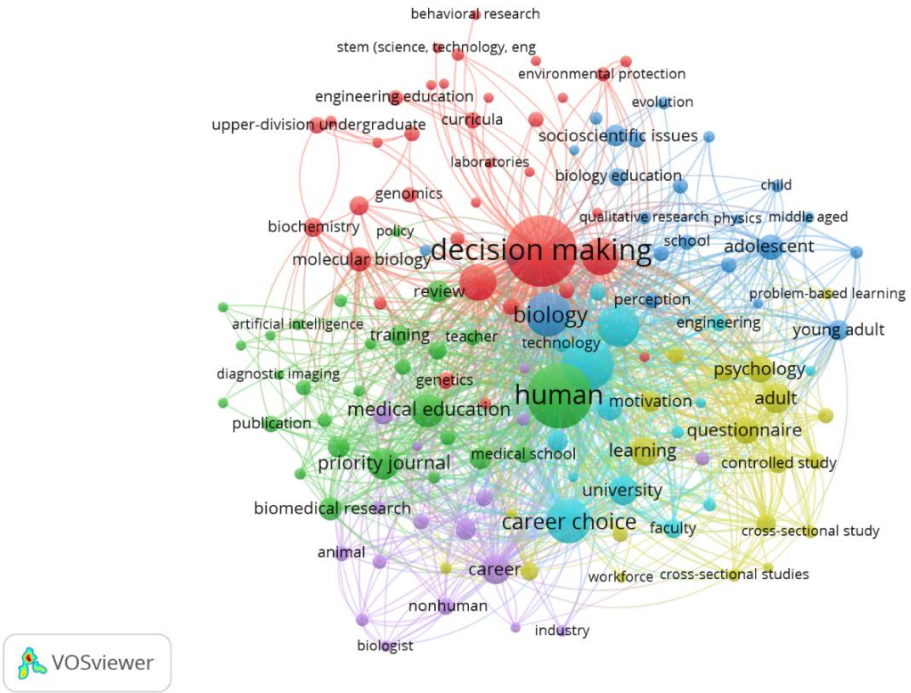

Figure 4. Network Visualization

A narrower keyword network restricted to the science- and biology-education domain (Figure 5) produced three clusters: (1) decision-making skills linked with socioscientific issues, science education, biology education, and biology; (2) decision-making skills linked with inquiry-based learning and hands-on learning; and (3) decision-making skills linked with curriculum, education, training, and teaching.

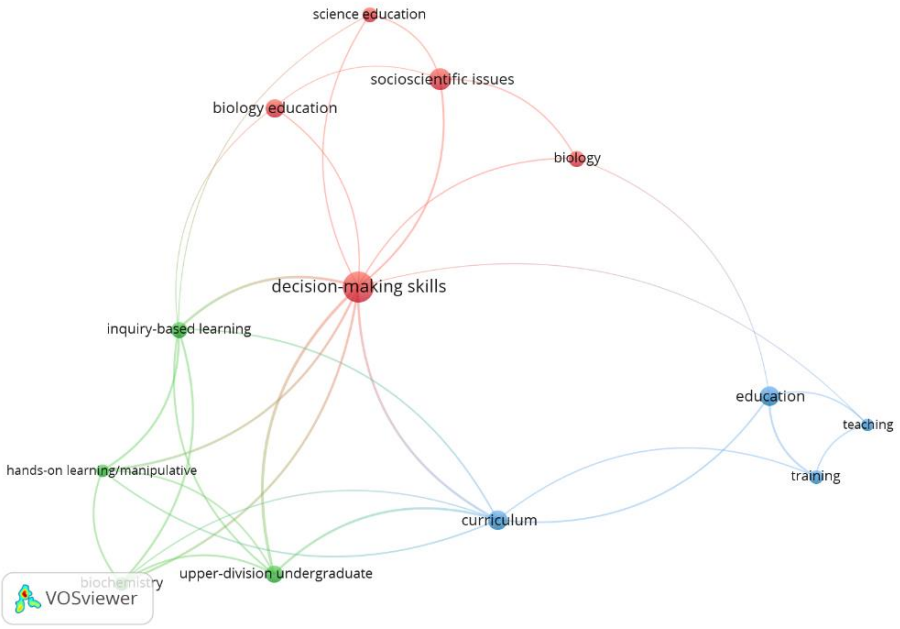

Figure 5. Keyword Network Visualization in the Science and Biology Education Domain

The identification of each keyword that has developed from year to year in relation to decision-making can be seen in Figure 6. It can be seen that the integration of decision-making skills within the field of biology education began to develop from 2019 to the present.

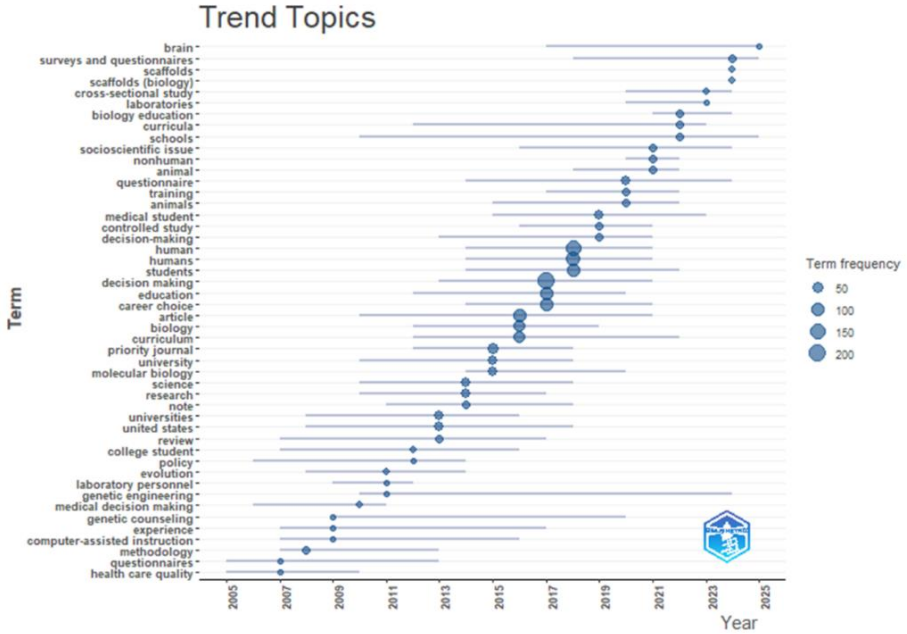

Figure 6. Topic Trends

3.2 Study Characteristics

Following the PRISMA 2020 procedure described in Section 2, the identification stage retrieved 414 records from Scopus; after removing 171 records via database filters, 243 records underwent title-and-abstract screening, from which 204 were excluded. Of the remaining 39 reports sought for retrieval, 7 could not be accessed, leaving 32 reports assessed for eligibility. After full-text review, 21 reports were excluded, resulting in 11 studies included in the final synthesis (Figure 1). The 11 included studies were published between 2009 and 2025, span multiple national contexts, and employed a mix of quasi-experimental, correlational, and qualitative designs targeting senior-high-school students.

3.3 Intervention Findings

Based on the SLR analysis results, several families of learning strategies with similar characteristics were grouped together to facilitate the mapping of intervention types, instruments used, and the form of impact on students' decision-making skills. A summary of the mapping results is presented in Table 3.

Table 3: Summary of Learning Interventions for Developing Senior-High-School Students' Decision-making Skills

Learning Strategy	Authors	Key Intervention Form	Decision Making Indicator/Instrument	Impact on Decision Making
SSI-based debate and case analysis	• Darmawan et al., 2025 [17] • Van der Leij et al., 2021[18] • Villarín & Fowler, 2019[19] • Gutirez, 2014 [20]	Local SSI case discussion, debate, article/video analysis, moral games	SSI essay + DM rubric, QuASSR, DMSS	Increased argument complexity, richer reasoning, and significantly higher DMSS scores in SSI classes compared to conventional ones.
OIDDE Model and FCM Framework	• Hudha et al, 2024 [21] • Van der Leij et al., 2021[18]	Orientation–identify–discussion–decision–engage stages, SSI curriculum with FCM-based interviews	Observation, ethical attitude questionnaire, FCM interview	Strengthened ethical decision-making processes and revealed the important role of moral emotion in environmental decisions.
Ecological dilemmas and EDM instruments	• Altmeyer & Dreesmann, 2021 [22]	Everyday ecological dilemma scenarios to reveal personal EDM orientation	Scenario-based questionnaire, factor/cluster analysis	Produced a typology of environmental DM orientations (ecoactivists, etc.) as a basis for differentiating instructional design.
Open inquiry in biology projects	• Sadeh & Zion, 2009 [23]	Field and laboratory inquiry projects, open vs. guided inquiry	Dynamic inquiry index (4 criteria)	Open inquiry improved the ability to manage decisions within the inquiry process (changing plans, choosing procedures, solving problems).

Learning Strategy	Authors	Key Intervention Form	Decision Making Indicator/Instrument	Impact on Decision Making
Climate-change SSI role-play	• Belova et al., 2015 [24]	Multi-stakeholder role-play scenario on climate policy	Video analysis, argumentation evaluation grid	Showed that role-play can emulate social DM processes; DM quality strongly depends on role-card design and teacher moderation.
Reflective and metacognitive approach	• Rachmatullah & Ha, 2019 [25]	Confidence reflection, bias analysis	Decision calibration and bias-awareness measures	Still rarely applied as an explicit intervention, but has potential as a DM indicator.

Table 3 summarizes the learning strategies identified across the 11 studies, grouped into six families based on shared characteristics: (1) SSI-based debate and case analysis; (2) the OIDDE Model and Four Component Model (FCM) framework; (3) ecological dilemmas and environmental decision-making (EDM) instruments; (4) open inquiry in biology projects; (5) climate-change SSI role-play; and (6) reflective and metacognitive approaches. Each family is reported together with its intervention form, decision-making indicator/instrument, and reported impact on decision-making.

3.4 Identified Gaps

Following up on the question above, the limitations and recommendations of each study were analyzed thematically, forming several main gap categories. These categories cover aspects of environmental-issue theme and context, assessment instruments, methodological design, and dispositional targets within decision-making skill. A summary of these research gaps is presented in Table 4.

Table 4. Summary of Research Gaps in Studies on Environmental-Issue Decision-Making

Aspect	General Findings in the Literature	Main Gaps
Environmental issue theme	Focus on global and popular issues (climate, conservation)	Limited exploration of multi-SSI, local issues, and real decision complexity
Decision-making dimension	Dominated by reasoning & argumentation	Emotion, value orientation, cognitive bias, and real action are rarely integrated.
Assessment instruments	Essay rubrics, SSR, partial questionnaires	Instruments are often single essays or specific scales; do not comprehensively capture the fact–process–value–emotion–bias dimensions.
Methodology	Short-term quasi-experiments and case studies	Minimal longitudinal studies, mixed-methods, and design-based research
Context & population	Developed countries, homogeneous school contexts	Very limited in developing countries and Indonesian senior-high-school contexts
Intervention target	Focus on general learning strategies.	Interventions targeting bias (e.g., overconfidence) and emotion regulation are still rare.

Table 4 summarizes the research gaps identified through thematic coding of the limitations and future research recommendations reported across the 11 included studies,

conducted jointly with the research supervisor. Six gap categories were identified: (1) environmental issue theme (dominance of global/popular issues such as climate and conservation, with limited attention to multi-SSI, local issues, and real decision complexity); (2) decision-making dimension (dominance of reasoning and argumentation, with emotion, value orientation, cognitive bias, and real action rarely integrated); (3) assessment instruments (reliance on single essays or specific scales rather than instruments capturing fact, process, value, emotion and bias dimensions comprehensively); (4) methodology (dominance of short-term quasi-experiments and case studies, with minimal longitudinal, mixed-methods, or design-based research); (5) context and population (concentration in developed-country, homogeneous school contexts, with developing-country and Indonesian senior-high-school contexts underrepresented); and (6) intervention target (focus on general learning strategies, with interventions targeting bias or emotion regulation still rare).

4. DISCUSSION

4.1 Principal Findings

Four principal findings emerge from this study. First, publication activity on decision-making is growing steadily (5.65% annual growth rate), reflecting increasing attention to decision-making amid the growing complexity of global challenges such as environmental sustainability and 21st-century education [7], [20]. However, the underlying bibliometric corpus is conceptually broad rather than specific to biology or environmental education. Second, among the 11 eligible studies, SSI-based and discourse-oriented approaches, such as debate, case analysis, and role-play, dominate as the primary intervention format. Third, across these approaches, the emphasis falls overwhelmingly on cognitive reasoning outcomes: identifying alternatives, evaluating evidence, and justifying decisions. Fourth, comparatively limited attention is given to emotion, cognitive bias, the translation of decisions into concrete action, and local (Indonesian/Southeast Asian) contexts.

4.2 Interpretation of the Findings

The steady 5.65% annual growth rate and above-average citation impact (22.44 citations per document) suggest that decision-making is an established rather than emerging research area [7], [19]. However, this growth should not be read as evidence of a maturing biology-education-specific literature.

The full-corpus keyword network Figure 4 includes substantial clusters outside biology or science education, most notably medical education, career choice, and biomedical research, that are unrelated to the environmental decision-making construct this study investigates. This pattern should be treated as a methodological limitation of the bibliometric search strategy, rather than as evidence that decision-making research is inherently multidisciplinary in the sense intended by this review: because the term "decision-making" is used broadly across psychology, medicine, business, and career-guidance literature, a Scopus search built around this keyword necessarily captures substantial off-target content. Consequently, corpus-wide indicators such as growth rate, citation counts, and country dominance describe the decision-making literature broadly, and should not be over-

interpreted as describing biology-education research specifically. Only the narrower keyword subnetwork restricted to the science education and biology education domain Figure 5, with more precisely the 11-study SLR, can support claims specific to biology learning.

Within that narrower domain, the dominance of SSI-based and discourse-oriented interventions is consistent with the field's historical development: SSI has functioned for over a decade as the primary pedagogical vehicle through which decision-making is operationalized in science classrooms [26]. The concentration on cognitive reasoning outcomes, meanwhile, likely reflects a measurement artifact as much as a pedagogical choice: rubrics for scoring argumentation quality and justification (e.g., DMSS, QuASSR) are comparatively well-established, whereas standardized instruments capturing emotional response, bias, or follow-through action remain underdeveloped [27], [28] that making cognitive outcomes easier to measure and therefore more likely to be reported, regardless of whether they represent an intervention's primary target.

4.3 Comparison with Previous Study

These findings both align with, and extend, several strands of prior review work. In relation to socioscientific issues research, the dominance of debate, discussion, and role-play identified here mirrors patterns reported in broader SSI reviews [26], [29], [30], confirming that discourse-oriented pedagogy remains the default instructional mode for SSI-based learning generally, not only within the narrower environmental-decision-making subset examined here. In relation to climate-change education, Monroe et al. [31]similarly found that effective strategies for climate-change learning tend to emphasize cognitive and knowledge-based outcomes over affective or behavioral change. A nearly identical pattern can be found in this review's findings in Table 4, within the environmental decision-making context. In relation to sustainability-competency frameworks, the present findings extend Wiek et al.'s [32] and UNESCO's [33] tripartite model by providing empirical evidence, specific to biology-based environmental decision-making, that the cognitive dimension is disproportionately well-developed.

In contrast, the socio-emotional and action-oriented dimensions remain comparatively neglected. Finally, in relation to broader science decision-making reviews, Molina et al. [34] and Fang, Hsu & Lin [35] likewise report that models of decision-making which integrate bias and emotion remain rarer than models that focus purely on reasoning. This supports this review's finding that instruments capturing bias and emotion are scarce even in the wider decision-making literature.

4.4 Theoretical Explanation

These findings can be further interpreted through the socioscientific issues (SSI) framework proposed by Zeidler & Nichols [26], which conceptualizes SSI-based learning as operating through three interconnected components: scientific content knowledge, moral-ethical reasoning, and sociomoral discourse. Viewed through this lens, the SSI-based debate and case-analysis strategies identified in this review primarily strengthen the content-knowledge and discourse components, whereas the OIDDE model and Four Component Model strategies more explicitly target the moral-ethical reasoning component. This

distinction suggests that no single strategy addresses all three SSI components simultaneously, and that combining discourse-oriented strategies with explicit ethical-reasoning frameworks may be necessary to develop decision-making skills in a more balanced manner. Positioning these findings within the sustainability-competencies framework of Wiek et al. and UNESCO indicates that the reviewed interventions predominantly cultivate the cognitive dimension of sustainability competence. In contrast, the socio-emotional dimension (empathy, value clarification) and the action-oriented dimension (translating decisions into environmental action) remain comparatively underdeveloped [32], [33].

This is consistent with the wider literature on education for sustainable development and climate-change education, which emphasizes that sustainable environmental decisions involve a combination of knowledge, values, emotion, and identity [36], [37], [38], underscoring why the socio-emotional gap identified in this review is educationally consequential rather than merely descriptive.

This methodological gap can additionally be explained through dual-process theory of reasoning [39], which distinguishes fast, intuitive System 1 thinking from slower, deliberate System 2 thinking. The overconfidence bias reported by Rachmatullah & Ha [25] and the cognitive biases discussed by Korteling et al. [27] appear to reflect System 1 processes that current instruments, designed primarily to measure System 2 reasoning outcomes such as argumentation essays and SSI rubrics, rarely capture. This theoretical mapping reinforces the pattern already identified in Table 4 and suggests that future instructional design and assessment should deliberately target all three competency domains and both reasoning systems, rather than treating decision-making as a purely cognitive, deliberate construct.

4.5 Explanation of Unexpected Findings

Two findings warrant closer explanation because they diverge from what the dominant SSI-centered narrative would predict. First, although environmental decision-making research overall has grown steadily since 2005, its specific integration into biology education only becomes visible in the keyword trend data from 2019 onward Figure 6, later than might be expected given that biology content provides an intuitive substantive basis for environmental decision-making. A plausible explanation is that environmental-issue framing in biology curricula has itself only recently been formalized under ESD and climate-change-education agendas [31], [40], so that the conceptual pairing of "decision-making" with "biology" as a distinct, indexable research focus is a comparatively recent development. Second, the open-inquiry intervention reported by Sadeh & Zion [23] showed a positive effect on decision-making within the inquiry process itself despite not being framed as an SSI or environmental-issue intervention at all, an inconsistency with the otherwise SSI-dominated pattern in Table 3. This suggests that decision-making skill can also be developed through open-ended inquiry activities in general, even without specific environmental or ethical content. In other words, part of the 'SSI advantage' reported in previous studies might actually come from the open-inquiry teaching format itself, not from the SSI content (the environmental/social issues) itself.

4.6 Implications of the Study

Theoretical implications: This review positions decision-making as a bridging concept between scientific literacy, socioscientific issues, and sustainability-competency frameworks [26], [32], [33], clarifying that existing interventions address cognitive, content-based reasoning well but leave socio-emotional and action-oriented competencies comparatively underdeveloped.

Practical implications: These findings suggest that biology teachers and curriculum developers could combine SSI-based debate or case analysis with explicit ethical-reasoning models (e.g., OIDDE, FCM) and reflective or metacognitive activities, supported by an active teacher role in guiding the process [41], [42], [43], [44], so that decision-making skill develops as a holistic, multidimensional competency rather than an isolated cognitive skill.

Policy implications: Given the small number of eligible studies (n = 11) and the concentration of existing research within a limited set of mostly developed countries, these findings should be treated as preliminary directions rather than firm policy guidance. They nonetheless point toward a research agenda that could eventually inform biology curriculum and environmental education policy at the secondary-school level, particularly in underrepresented contexts such as Indonesia.

4.7 Limitations and Future Research

Several limitations should be acknowledged. First, as discussed in 4.2, the bibliometric corpus (n = 414) is cross-disciplinary by construction: the inclusion of medical, career-choice, and biomedical clusters reflects a methodological limitation of the search strategy rather than genuine evidence of multidisciplinary relevance. Second, the relatively low rate of international co-authorship (14.49%) combined with the concentration of publications within a limited number of countries suggests that the field remains shaped predominantly by the research agendas of a small set of national systems, limiting the contextual transferability of current findings to more diverse socio-cultural settings, including Indonesia.

Third, the systematic review itself is based on only 11 eligible studies, restricted to accessible journal articles, which limits the generalizability of the intervention and gap findings. Fourth, the included studies are dominated by short-term, cross-sectional quasi-experimental and case-study designs, using varied and often non-standardized instruments that capture only part of the decision-making construct (e.g., argumentation scores without bias, values, or reflection), limiting both generalization and theory development [27], [28].

Future research should therefore prioritize: (1) developing comprehensive assessment instruments that capture fact-based, process-based, value-based, emotional, and bias-related dimensions of decision-making simultaneously, explicitly distinguishing intuitive (System 1) from deliberate (System 2) decision processes [39]; (2) conducting longitudinal, mixed-method, and design-based studies capable of tracking decision-making development over time while iteratively refining instructional designs in real classrooms [28], [45]; and (3) exploring local Indonesian and Southeast Asian contexts, including issues such as deforestation, flooding, and unequal access to resources, to strengthen the contextual relevance and equity of future environmental education curricula and policy [36], [46].

5. CONCLUSION

This study set out to map the research landscape on students' environmental decision-making skills and to identify which instructional approaches and research gaps characterize this field, with a particular focus on secondary biology education. To achieve this, a bibliometric analysis of 414 Scopus-indexed documents (2005–2025, annual growth rate of 5.65%) was combined with a systematic literature review of 11 eligible studies.

The bibliometric mapping confirms that decision-making is a steadily growing but conceptually broad research area, with a coherent link to biology education only becoming clearly visible in the literature from 2019 onward. Within the narrower set of 11 studies, socioscientific issues (SSI)-based and discourse-oriented strategies, such as debate, case analysis, and role-play, were the most frequently reported approaches, generally associated with stronger argumentation and more elaborate reasoning; however, this association should be read as a recurring pattern across studies rather than as proof of a causal effect, given the heterogeneity of designs involved. Frameworks that made decision-making stages explicit, such as OIDDE and the Four Component Model, were associated with stronger ethical and moral reasoning specifically. Across all 11 studies, cognitive and discursive outcomes were assessed far more often than emotional, bias-related, or action-oriented outcomes.

In direct answer to the research objectives, this review indicates that (1) research attention to environmental decision-making has grown steadily but remains only loosely anchored to biology education specifically; (2) SSI-based and discourse-oriented strategies, together with explicit decision-making frameworks, are the interventions most consistently associated with improvements in students' decision-making skill within biology learning; and (3) the clearest research gaps lie in the underrepresentation of emotional and bias-aware dimensions, real-action outcomes, comprehensive assessment instruments, longitudinal designs, and studies conducted in developing-country contexts, including Indonesia.

Theoretically, this review contributes by positioning decision-making as a bridging competency between the socioscientific issues framework and the sustainability-competencies framework, showing empirically that existing interventions cultivate the cognitive dimension of this competency well. In contrast, the socio-emotional and action-oriented dimensions remain comparatively underdeveloped. Practically, these findings suggest that biology teachers and curriculum developers may benefit from combining SSI-based debate or case analysis with explicit ethical-reasoning models and reflective activities; it should be noted, however, that this specific combination was not directly tested as a single intervention in any of the 11 reviewed studies, and its effectiveness as a combined approach therefore remains a proposition for future testing rather than an established finding. At the policy level, given the limited number of eligible studies, these findings offer preliminary, rather than definitive, direction for strengthening biology curricula and environmental education policy at the secondary-school level.

These conclusions should be interpreted with caution, for reasons discussed more fully in Section 4.7: the evidence base is small and heterogeneous (11 studies), most reported outcomes are cognitive or self-reported rather than behavioral, and the broader bibliometric corpus reflects a methodologically wide search rather than a biology-specific literature. Future research should therefore prioritize validated multidimensional instruments that

capture cognitive, emotional, and bias-related dimensions together; longitudinal designs; outcome measures based on actual behavior rather than self-report; interventions grounded in culturally and locally relevant environmental issues; and a stronger evidence base from developing-country contexts, including Indonesia and Southeast Asia.

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