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Designing a Socioecology-Based Coding Curriculum for Preservice Elementary Teachers: Computational Thinking, Measurement, Geometry, and Climate Mitigation

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Abstract
Integrating coding into the education of prospective primary school teachers offers opportunities to develop computational thinking while simultaneously strengthening understanding of mathematics and environmental issues. However, coding instruction is often treated as a technological skill isolated from socio-ecological contexts and mathematics learning. This study aims to develop a socio-ecologically grounded coding framework that integrates computational thinking, measurement, and geometry as a means of climate action education for prospective primary school teachers. A qualitative approach utilizing a literature review design was employed. Data were gathered through a search and analysis of literature concerning computational thinking, educational coding, mathematics education, socio-ecological approaches, and climate change education. The data were analyzed thematically to identify concepts, inter-component connections, and principles of integration applicable to curriculum design. The findings indicate that coding can be contextualized through socio-ecological problems involving measurement and geometry such as monitoring energy consumption, measuring green spaces, mapping school environments, and analyzing changes in environmental conditions. This integration provides a learning framework that links computational thinking with mathematical literacy and ecological awareness. The study contributes to the development of a curriculum framework for prospective primary school teachers that integrates digital competence, mathematics, and climate action education.

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Introduction

Climate change has become not only an environmental crisis but also an educational challenge that requires learners to understand complex systems, interpret quantitative evidence, evaluate competing alternatives, and formulate responsible responses to socioecological problems. The Intergovernmental Panel on Climate Change reported that human activities have unequivocally caused global warming, with global surface temperature reaching approximately 1.1°C above the 1850–1900 baseline during 2011–2020, while climate-related impacts are increasingly evident across ecological, economic, health, food, and water systems (Intergovernmental Panel on Climate Change [IPCC], 2023). Consequently, education can no longer approach climate change merely as disciplinary knowledge to be transmitted. Contemporary environmental and climate-change education increasingly emphasizes participatory, locally meaningful, interdisciplinary, and action-oriented learning that enables students to connect scientific understanding with decision making and practical responses (Ardoin et al., 2020; Nepraš et al., 2022; Rousell & Cutter-Mackenzie-Knowles, 2020). This orientation is particularly important in teacher education because prospective teachers will be responsible for translating complex sustainability issues into pedagogically accessible learning experiences. Recent research nevertheless shows that positive attitudes toward sustainability do not necessarily translate into sufficient knowledge, confidence, or capacity to teach sustainability effectively, while climate-change education continues to vary considerably across curricula, countries, and institutional settings (Albion et al., 2025; Ben Zvi Assaraf et al., 2025; Tolppanen et al., 2021). Therefore, preparing preservice elementary teachers for climate-related education requires a pedagogical architecture that connects environmental understanding with analytical, mathematical, digital, and problem-solving capabilities rather than treating these competencies as independent curricular outcomes.

This need has become particularly salient in Indonesia, where digital competence, computational reasoning, and sustainability education increasingly intersect with curriculum reform. Indonesia's current curriculum policy has introduced Coding and Artificial Intelligence as elective learning areas beginning progressively in Grades 5, 7, and 10 from the 2025/2026 academic year, while official policy simultaneously emphasizes the preparation of teachers and prospective teachers in content knowledge, technical competence, pedagogy, digital ethics, and literacy. Such developments create an important opportunity for teacher-education institutions to move beyond teaching coding as an isolated technical subject and instead explore how computational practices can contribute to meaningful disciplinary and societal problem solving. This issue is especially relevant because evidence from Indonesian teacher education demonstrates the need to systematically develop preservice teachers' competencies in information and data literacy, digital content creation, collaboration, safety, and problem solving (Hidayat et al., 2023), while international evidence similarly shows that digital competence alone does not guarantee meaningful technology integration unless technological capabilities are connected to pedagogical and disciplinary knowledge (Çebi et al., 2022; Dong et al., 2024). Moreover, recent Indonesian work on primary mathematics illustrates growing interest in integrating computational thinking into mathematical instruction, reinforcing the need for teacher-education curricula that prepare future teachers to work across disciplinary boundaries (Danoebroto et al., 2026). Thus, the contemporary Indonesian policy context provides both an institutional rationale and a pedagogical imperative for examining how coding and computational thinking can be integrated with elementary mathematics and sustainability-oriented learning.

Theoretically, this study is grounded in the contemporary conceptualization of computational thinking (CT) as a general problem-solving orientation rather than as a synonym for computer programming. Wing (2006) initially conceptualized CT as a way of formulating problems and designing solutions by drawing upon fundamental ideas from computing, while subsequent scholarship has elaborated CT through practices such as decomposition, abstraction, pattern recognition, algorithmic thinking, modeling, debugging, iteration, and evaluation (Angeli & Giannakos, 2020; Shute et al., 2017; Yadav et al., 2022). This distinction between *coding* and *computational thinking* is essential: coding constitutes one representational and operational means through which computational solutions may be implemented, whereas CT concerns the broader cognitive practices used to structure and reason about complex problems. Systematic research involving preservice teachers likewise demonstrates that effective CT preparation requires more than technical programming exercises; it requires pedagogical experiences that enable prospective teachers to recognize where, why, and how computational practices can be meaningfully integrated into subject teaching (Dong et al., 2024; Molina-Ayuso et al., 2022; Yadav et al., 2017). Accordingly, the present study positions coding as a pedagogical medium for computational modeling and problem solving, rather than as the curriculum's ultimate objective. Such a position is especially appropriate for elementary teacher education, where future teachers must be capable of translating computational practices into age-appropriate learning activities connected with mathematical reasoning, authentic contexts, and socially relevant problems.

A second theoretical foundation is provided by a socioecological perspective, which understands environmental problems as outcomes of dynamic interactions among human practices, social structures, resource use, technologies, and ecological processes. Rather than separating society from nature, socioecological thinking emphasizes reciprocal relationships between socioeconomic activities and biophysical systems and, consequently, requires learners to examine environmental problems through multiple forms of evidence and interconnected levels of analysis (Eisenmenger et al., 2020; Reimers, 2024). This perspective is highly compatible with CT because socioecological problems are frequently characterized by multiple variables, feedback relationships, spatial patterns, incomplete information, and alternative solution pathways. Christensen's (2023) learning progression, for example, demonstrates how computational thinking can support learning about environmental sustainability by enabling learners to process information, identify patterns, reason about systems, and develop computationally informed environmental solutions. At the same time, sustainability education must extend beyond technical optimization. Socioecological problems involve value judgments, distributional consequences, human behavior, social responsibility, and environmental trade-offs; hence, computational solutions should be interpreted within their broader ecological and social consequences rather than evaluated exclusively for technical efficiency (Ardoin et al., 2020; Eisenmenger et al., 2020; Tolppanen et al., 2021). This theoretical combination enables the proposed curriculum to position CT as the analytical mechanism, socioecology as the problem context, and sustainability-oriented action as the broader educational purpose.

Mathematics, particularly measurement and geometry, offers a crucial disciplinary bridge between computational reasoning and socioecological interpretation. Environmental phenomena become pedagogically analyzable when learners can quantify, compare, represent, model, and spatially interpret them. Measurements of energy consumption, rainfall, temperature, water use, green-space coverage, or carbon-related indicators require attention to quantities, units, ratios, scales, and data representations, whereas mapping land use, estimating areas, analyzing distances, designing green spaces, or representing flood-prone zones draws directly upon geometric and spatial reasoning. Research on CT integration in mathematics confirms a growing reciprocal relationship between computational and mathematical reasoning. Systematic reviews have found that mathematics is among the most prominent disciplinary contexts for CT, with programming environments frequently being used to develop algorithmic reasoning, mathematical modeling, and problem solving (Nordby et al., 2022; Ye et al., 2023). Empirical work with preservice primary teachers also suggests that Scratch-based programming can contribute to the development of CT within mathematics teacher education (Molina-Ayuso et al., 2022), while more recent classroom research warns that the use of computational tools does not automatically strengthen mathematical learning; poorly designed activities can shift attention toward the technological tool itself rather than the mathematical ideas being investigated (Nordby et al., 2024). Consequently, an effective curriculum must preserve a genuine epistemic role for mathematics: measurement and geometry should not merely decorate coding exercises but function as analytical resources through which learners quantify and model authentic environmental phenomena.

Despite these developments, the literature indicates that CT, mathematics, sustainability, and teacher education have largely developed through partially connected research trajectories. Studies of CT in primary mathematics have documented promising applications of coding and digital tools, but the literature continues to distinguish between *partial integration*, where CT primarily supports existing mathematical tasks, and stronger forms of integration in which computational and mathematical reasoning are developed reciprocally (Nordby et al., 2022; Nordby et al., 2024; Ye et al., 2023). Research focused specifically on preservice teachers has similarly examined CT competence, training methods, programming experience, digital competence, and technology integration, yet comparatively less attention has been devoted to preparing prospective elementary teachers to apply those competencies to socioecological problems through subject-specific mathematics (Çebi et al., 2022; Dong et al., 2024; Molina-Ayuso et al., 2022). In parallel, project-based approaches have demonstrated considerable potential for positioning CT within authentic problem solving because learners must formulate problems, design procedures, test solutions, revise models, and collaboratively create artifacts (Bertacchini et al., 2022; Saad & Zainudin, 2022; Ye et al., 2023). Nevertheless, reviews of project-based CT also indicate that integrated implementations remain relatively limited and continue to be concentrated primarily within computing and STEM contexts. These findings suggest that merely adding coding activities to mathematics courses is insufficient; curricular coherence depends on whether coding, mathematics, and real-world problems are intentionally structured around common learning purposes.

A comparable fragmentation appears in climate-change and sustainability education. Breslyn and McGinnis (2019) demonstrated that computational and systems-thinking perspectives can help preservice elementary science teachers engage with complex climate phenomena such as sea-level rise, suggesting that CT has considerable potential to mediate understanding of environmental systems. Christensen (2023) similarly proposed a learning progression connecting computational thinking and environmental sustainability. Yet these lines of research are primarily anchored in science or environmental education rather than in the purposeful integration of elementary mathematical content such as measurement, geometry, scale, spatial representation, and quantitative modeling. Moreover, sustainability knowledge by itself does not guarantee action competence. Tolppanen et al. (2021) found that preservice teachers had substantial difficulty estimating the relative impact of climate-mitigation actions and that knowledge did not straightforwardly correspond to willingness to undertake higher-impact actions. Cross-national research likewise indicates that climate-change education is widely understood as multidisciplinary but remains inconsistently implemented, with educators calling for clearer curricular connections, active pedagogies, professional development, and stronger institutional resources (Albion et al., 2025; Ben Zvi Assaraf et al., 2025). Therefore, there remains a pedagogical need for learning designs in which preservice teachers do not simply *learn about* climate change, but use quantitative, spatial, and computational practices to investigate environmental conditions and reason about possible responses.

The Indonesian literature adds an important contextual dimension to this argument. Research involving Muhammad Sufian and colleagues demonstrates that technology-mediated learning becomes educationally meaningful when digital resources are embedded in culturally recognizable contexts; for example, the development of a Lampung local-wisdom film illustrates an approach in which digital media, disciplinary learning, and local cultural context are deliberately connected (Koderi et al., 2023). Similarly, research on integrated learning in Indonesian schools indicates the pedagogical value of connecting curricular content with learners' lived contexts rather than presenting knowledge as isolated disciplinary fragments (Al Khansa et al., 2024). These studies do **not** directly investigate computational thinking or climate mitigation, but they provide relevant Indonesian evidence supporting contextual and integrative curriculum design. Recent studies from *Digital Learning, Social Science, and Life-course Studies* further show that the mere presence of digital technologies does not ensure pedagogical transformation; classroom technology frequently remains presentation-oriented unless teachers possess sufficient pedagogical competence and institutional support to design inquiry, collaboration, and higher-order learning (Hariandini et al., 2026). Likewise, Indonesian research published in *JPI: Jurnal Pustaka Indonesia* demonstrates the potential of combining digital resources, problem-based learning, and local wisdom to construct contextualized problem-solving environments (Mahfud et al., 2026), while comparative work in *Gender, Islamic Law, and Sustainability* emphasizes the need for stronger connections between education, environmental governance, local participation, and sustainability objectives in Indonesia (Febriani et al., 2026). Collectively, this national evidence strengthens the rationale for a curriculum that is technologically informed yet locally contextualized, pedagogically integrated, and directed toward authentic socioecological problems.

Taken together, the literature reveals a more specific research gap than a simple shortage of studies on coding, CT, mathematics, or sustainability. First, research integrating CT and primary mathematics has established productive relationships between computational and mathematical reasoning, but socioecological and climate-mitigation contexts remain peripheral rather than constitutive components of the curriculum (Nordby et al., 2022; Nordby et al., 2024; Ye et al., 2023). Second, research connecting CT with environmental sustainability and climate change demonstrates the value of systems thinking, modeling, and environmental problem solving, but has rarely operationalized measurement and geometry as central mathematical resources through which environmental phenomena are investigated (Breslyn & McGinnis, 2019; Christensen, 2023; Tolppanen et al., 2021). Third, studies of preservice teachers have concentrated predominantly on CT competence, programming preparation, digital competence, and teacher readiness, rather than on a coherent curriculum architecture connecting computational, mathematical, ecological, and pedagogical knowledge (Çebi et al., 2022; Dong et al., 2024; Hidayat et al., 2023). Fourth, climate and sustainability education emphasizes interdisciplinarity and action-oriented learning, yet there remains limited guidance on how preservice elementary teachers can translate those principles into concrete computational-mathematical learning activities grounded in measurable and spatially interpretable local environmental problems (Albion et al., 2025; Ben Zvi Assaraf et al., 2025; Nepraš et al., 2022). This multidimensional disconnection constitutes the central gap addressed by the present study.

Accordingly, the novelty of this study lies in proposing a socioecology-based coding curriculum framework for preservice elementary teachers that deliberately connects four components that previous research has predominantly examined separately: computational thinking and coding as problem-solving mechanisms; measurement and geometry as quantitative and spatial tools; socioecological issues as authentic and locally adaptable problem contexts; and climate mitigation as an action-oriented educational purpose. The framework therefore moves beyond the conventional logic of teaching coding as an independent technological competence and beyond using CT merely as a supplementary tool for explaining mathematics. Instead, it conceptualizes coding as a medium through which prospective teachers can collect or organize data, construct representations, develop algorithms, model mathematical relationships, examine socioecological patterns, evaluate alternative solutions, and translate these processes into elementary-school learning designs. Given that the present investigation is literature-based, its contribution is intentionally conceptual and curricular rather than a claim of empirically demonstrated effectiveness. Specifically, this study aims (1) to synthesize the theoretical and empirical intersections among computational thinking, coding, measurement and geometry, socioecological education, and climate-change education; (2) to identify the curricular and pedagogical principles required to integrate these domains within preservice elementary teacher education; and (3) to formulate a socioecology-based coding curriculum framework that can guide future development, implementation, and empirical validation of climate-action-oriented mathematics and digital learning. In this way, the study contributes a theoretically grounded bridge between digital transformation, mathematical literacy, teacher preparation, and sustainability education while providing a foundation for subsequent empirical testing across diverse teacher-education contexts.

Method

This study employs a structured qualitative literature review method an approach conducted in a structured manner to transparently identify, evaluate, compare, and synthesize findings from prior research. A literature review serves not merely as a summary of previous studies but functions as a research method capable of generating knowledge syntheses, identifying patterns and discrepancies in findings, and uncovering unresolved research gaps. Snyder emphasizes that when a literature review is used as a research methodology, it must be conducted through systematic and accountable procedures to ensure the resulting synthesis is not ad hoc in nature (Snyder, 2019). In this study, literature concerning computational thinking (CT), socio-ecological education, primary school mathematics, coding, curriculum, and climate change mitigation education was reviewed based on its relevance to the research focus, and subsequently categorized according to themes and conceptual relationships among the findings.

The literature synthesis was conducted qualitatively using a thematic synthesis approach. Thomas and Harden (2008) explain that thematic synthesis enables findings from various qualitative studies to be coded and grouped into descriptive themes, which are then developed into analytical themes that yield a broader conceptual understanding (Thomas & Harden, 2008). This approach also maintains a transparent link between primary research findings and the conclusions drawn from the synthesis process. In the context of this study, the synthesis focuses on several key themes: the characteristics and components of CT; the integration of CT into primary school mathematics instruction; the use of coding and CT tools; socio-ecological education; climate change education; and opportunities to integrate CT and mathematics to understand and address socio-ecological issues. Thus, the analysis goes beyond merely cataloging prior research; it seeks to identify relationships, limitations, and opportunities for conceptual development.

Theoretically, this study is grounded in the concept of computational thinking (CT) as developed by Wing, which views CT as a broad thinking skill not limited to programming activities

(Wing, 2006). Computational Thinking (CT) encompasses the use of abstraction and decomposition to address complex problems, as well as the application of computational methods and models to solve problems and design systems. This perspective frames CT in the present study not merely as a coding skill, but as a problem-solving approach applicable to mathematics education and to understanding complex issues involving the interrelationships between humans, society, and the environment.

In the context of primary school mathematics, this study also considers the concept of CT integration, distinguishing between full integration and partial integration. Nordby, Bjerke, and Mifsud have shown that the majority of CT research in primary school mathematics falls under the category of partial integration, where mathematics remains the primary focus while CT serves as a tool to demonstrate or reinforce the understanding of mathematical concepts. These findings provide a basis for exploring the potential for broader integration positioning CT not merely as a support tool for learning mathematics, but as a framework for connecting mathematical concepts with authentic, complex issues, including socio-ecological challenges and climate change.

Based on this foundation, the study constructs a conceptual framework linking computational thinking, mathematics, and socio-ecological education. CT is positioned as a cognitive approach that enables learners to decompose complex problems, recognize patterns, abstract information, build models, design procedures or algorithms, and evaluate solutions. Mathematics serves as a tool for quantifying, representing, analyzing, and modeling phenomena, while the socio-ecological context provides authentic problems with both environmental and social dimensions. Through this framework, the integration of CT and mathematics aims to foster not only the mastery of academic concepts but also the ability to understand complex systems and devise alternative solutions to sustainability challenges, including climate change mitigation and adaptation.

Result and Discussion

Result

The thematic synthesis generated three principal sets of findings corresponding to the objectives of the study: (1) the conceptual intersections among computational thinking, mathematics, socioecological education, and climate-change education; (2) the curricular and pedagogical principles required to connect these domains in preservice elementary teacher education; and (3) the structure of a proposed socioecology-based coding curriculum framework. Because the study employed a qualitative literature-review and document-analysis design, the findings are presented as thematic patterns, conceptual categories, and curriculum components rather than as measures of intervention effectiveness. No student achievement data, pre-test–post-test comparisons, or experimental outcomes were generated in the present study. This distinction is consistent with the methodological design, which synthesized literature on computational thinking, coding, mathematics education, socioecological education, and climate-change education through thematic categorization.

Conceptual Intersections Identified in the Literature

The first finding concerns the recurring conceptual relationships among computational thinking (CT), mathematical reasoning, socioecological contexts, and climate-related problem solving. Across the reviewed literature, CT was represented through a set of recurring cognitive practices comprising decomposition, pattern recognition, abstraction, algorithmic thinking, data analysis, modeling, and the evaluation of solutions. Within the synthesized framework, these practices function as mechanisms for structuring and processing complex problems rather than as isolated programming techniques.

Mathematics emerged as the principal quantitative and spatial domain through which computational processes could be connected to environmental phenomena. Measurement was associated with quantities such as electricity consumption, water use, temperature, rainfall, air-quality indicators, distance, and other measurable environmental variables. Geometry was associated with area, perimeter, scale, spatial arrangement, land coverage, mapping, and the representation of environmental spaces. The original analysis therefore positioned mathematics as a means of quantifying, representing, analyzing, and modeling socioecological phenomena.

The socioecological dimension supplied the contextual problems to which the computational and mathematical processes could be applied. The synthesis identified examples including school energy consumption, water consumption, air quality, green-space measurement, land-use change, temperature distribution, flood-prone areas, and environmental conditions in school surroundings. These contexts appeared repeatedly as possible data sources or problem environments for integrated curriculum activities. The climate-related component was represented through mitigation-oriented tasks such as examining energy consumption, estimating environmental indicators, analyzing spatial patterns, and considering alternative responses to local ecological problems. Table 1 summarizes the four domains and the specific functions identified through the thematic synthesis.

Table 1. Thematic Intersections Among Computational Thinking, Mathematics, Socioecology, and Climate Action

Domain	Components identified in the synthesis	Function within the proposed curriculum	Examples of application
Computational thinking	Decomposition, pattern recognition, abstraction, algorithmic thinking, data analysis, modeling, evaluation	Structures problems and organizes solution processes	Decomposing energy-use problems, detecting patterns in environmental data, designing algorithms
Measurement	Units, quantities, ratios, comparison, data representation	Quantifies environmental phenomena	Electricity use, water consumption, rainfall, temperature, air-quality measurements
Geometry and spatial reasoning	Area, perimeter, distance, scale, spatial representation	Represents and analyzes environmental space	Green-space measurement, school mapping, land-cover analysis, flood-zone representation
Socioecology	Human–environment relationships, resource use, environmental conditions, social consequences	Provides authentic problem contexts	School resource consumption, waste, green spaces, local environmental change
Climate-action orientation	Mitigation-related analysis, evidence-based alternatives, environmental monitoring	Provides the intended sustainability context	Carbon-related calculations, resource-efficiency analysis, environmental monitoring

Note. *The categories represent qualitative themes identified from the literature synthesis. They should not be interpreted as frequency counts or quantitative effect estimates.*

As shown in Table 1, the synthesis did not yield four completely independent curricular areas. Instead, the reviewed material provided overlapping functions that could be organized into a common curriculum architecture. CT supplied procedural and cognitive operations; measurement and geometry supplied mathematical representations; socioecological issues supplied the context of application; and climate mitigation supplied a sustainability-oriented problem domain.

Curriculum Learning Outcomes

The second major finding was the identification of three learning-outcome domains: cognitive, psychomotor/technical, and affective–socioecological. These domains were already distinguishable in the original curriculum prototype.

The cognitive domain consisted of the ability to identify and analyze local socioecological problems through decomposition, pattern recognition, abstraction, algorithmic reasoning, mathematical reasoning, modeling, and problem solving. Within this domain, CT was not positioned as supplementary content but as a process embedded within mathematical and environmental problem analysis.

The psychomotor and technical domain consisted of elementary programming and data-handling activities. The proposed activities included programming through environments such as Scratch, Python, or JavaScript, together with spreadsheet-based or other data-processing tools. Environmental datasets identified in the source manuscript included school energy consumption, temperature, rainfall, water usage, and air-quality indicators.

The affective and socioecological domain consisted of responsible technology use, environmental awareness, ethical treatment of data, concern for the environmental consequences of technological decisions, and consideration of potential social consequences. In the proposed framework, these elements were formulated as intended curriculum outcomes rather than as empirically observed changes in preservice teachers. The resulting outcome structure can therefore be summarized as follows.

Table 2. Learning-Outcome Structure of the Proposed Socioecology-Based Coding Curriculum

Learning domain	Intended competencies	Observable curriculum activities
Cognitive	Decomposition, abstraction, pattern recognition, algorithmic reasoning, mathematical modeling, problem analysis	Identifying a local problem, defining variables, constructing a model, designing a solution procedure
Psychomotor/technical	Coding, data organization, data processing, visualization, digital tool use	Writing basic code, processing environmental datasets, producing tables/maps/graphs
Affective/socioecological	Environmental awareness, technological responsibility, ethical data use, consideration of social consequences	Evaluating environmental consequences, reflecting on resource use, considering stakeholder impacts

Note. *These competencies are design outcomes derived from the literature synthesis; they were not measured empirically in the current study.*

Structure of the Proposed Curriculum

A third finding was the emergence of four curriculum modules that operationalized the relationships identified in the thematic synthesis. The manuscript specified four areas: programming fundamentals and technology ethics; environmental data analysis; geospatial modeling and geometry; and an optional hardware-based socioecological project.

Module 1, Programming Fundamentals and Technology Ethics, introduces basic computational structures including variables, data types, conditional statements, loops, functions, and algorithms. These technical elements are combined with contexts involving responsible technology use, digital footprints, device energy consumption, and environmental implications of technology.

Module 2, Data Analysis for the Environment, focuses on simple environmental datasets. Identified datasets include electricity consumption, water usage, temperature, and air-quality measurements. Mathematical content includes measurement units, quantitative comparison, descriptive representation, tables, and visualization.

Module 3, Geospatial Modeling and Geometry, connects spatial technologies with mathematical concepts. Potential environmental contexts include land-cover change, flood-prone locations, temperature distribution, and urban environmental patterns. The associated mathematics comprises area, perimeter, distance, scale, ratio, and spatial representation.

Module 4, Hardware-Based Socioecological Projects, is designated as an optional component because implementation depends on institutional facilities and instructor competence. Possible technologies identified in the source text include Arduino or Raspberry Pi devices connected to environmental sensors for temperature, humidity, or air-quality measurements. The relationship among the four modules is presented in Table 3.

Table 3. Proposed Curriculum Modules and Their Integrated Components

Module	Computational component	Mathematical component	Socioecological context	Suggested tools
1. Programming Fundamentals and Technology Ethics	Variables, conditions, loops, functions, algorithms	Logical sequencing and quantitative representation	Digital footprints, energy use, environmental impacts of technology	Scratch, Python, JavaScript
2. Environmental Data Analysis	Data processing, pattern identification, visualization	Measurement, units, descriptive representation	Electricity, water, temperature, rainfall, air quality	Spreadsheet, Python, data-visualization tools
3. Geospatial Modeling and Geometry	Modeling and spatial-data processing	Area, perimeter, distance, scale, ratio	Land use, green space, flood risk, environmental mapping	QGIS or comparable mapping tools
4. Hardware-Based Socioecological Project	Data acquisition and basic programming	Measurement and quantitative comparison	Temperature, humidity, air-quality monitoring	Arduino, Raspberry Pi, environmental sensors

Note. Module 4 is optional and contingent upon infrastructure and instructor expertise.

The Learning Sequence and Pedagogical Organization section goes on to identify a recurring project-oriented teaching sequence. The proposed learning process consists of problem identification, data collection, decomposition, solution design, programming, testing, evaluation, and reflection. This sequence is explicitly outlined in the curriculum design described in the manuscript.

Two representative project structures have been identified. The first, "Calculating Our Class's Carbon Footprint," organizes information about transportation, travel distances, and energy-related variables into a computational task in which data can be processed and represented using simple programs. The second, "Designing a Sustainable School Garden," uses geometric concepts to calculate area and layout, allocate planting space, and integrate spatial considerations with environmental information. These projects are presented as curriculum examples, not as the results of completed interventions.

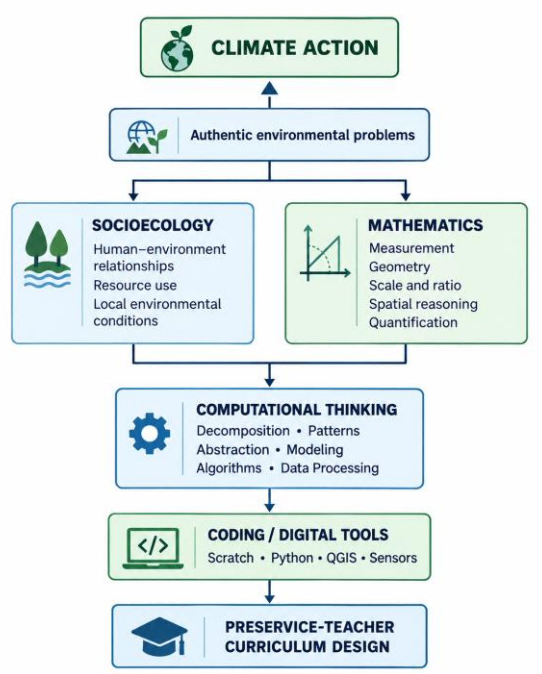

Figure 1. *Integrated Learning Sequence of the Socioecology-Based Coding Curriculum*

As shown in Figure 1, mathematical analysis occupies an intermediate position between problem identification and computational modeling. The proposed sequence therefore does not treat coding as the starting point of learning; rather, coding follows problem definition, data acquisition, and mathematical representation.

The findings also produced a differentiated structure for selecting digital platforms. Technology was categorized according to learner readiness and the type of activity to be conducted. Scratch was designated for introductory algorithmic thinking and visual programming. Python was identified for more advanced programming and environmental-data processing. QGIS or comparable geospatial platforms were identified for mapping, area and distance measurement, and spatial visualization. Arduino and related devices were identified for optional physical data collection through sensors.

Importantly, the source material did not establish these platforms as mandatory requirements. Instead, platform selection was conditioned by accessibility, learner competence, instructional goals, infrastructure, and teacher expertise. Thus, the technological findings resulted in a tiered rather than standardized platform structure.

The document-analysis component produced several additional findings. First, technology integration in mathematics education was not uniformly documented across the analyzed materials. In some documents, technology was incorporated directly into mathematics learning, whereas in others it appeared as a separate subject or broader competency. Second, documented instructional time for technology was inconsistent, preventing uniform comparison across curricula. Third, explicit relationships among CT, mathematics, sustainability, and socioecological problem solving were limited. Although individual components such as technology, sustainability, environmental education, or project-based learning appeared in the analyzed documents, their simultaneous integration into learning objectives, content, activities, and assessment was not consistently documented.

The analysis also established a boundary regarding the available evidence. The curriculum documents did not provide data concerning preservice teachers' perceptions, needs, or readiness. Such information would require primary evidence collected through interviews, surveys, observations, or comparable instruments. Therefore, no findings concerning preservice teachers' attitudes, perceived usefulness, learning gains, or acceptance of the curriculum are reported in this section.

Table 4. Document-Analysis Patterns Identified in the Reviewed Curriculum Materials

Dimension examined	Pattern identified
Educational technology	Present in varying forms across curriculum documents
Technology integrated with mathematics	Inconsistent; sometimes integrated, sometimes treated separately
Explicit CT/coding component	Present in selected documents but not uniformly articulated
Sustainability/environmental education	Present in some curricula
CT–sustainability connection	Limited explicit integration
Mathematics–socioecology connection	Limited systematic articulation
Real-world/project-based orientation	Present in some documents
Instructional time	Insufficiently standardized for consistent comparison
Preservice-teacher perceptions/readiness	Not available from the document data

Note. The manuscript does not report the number of documents exhibiting each characteristic; consequently, frequencies and percentages are not presented.

Collectively, the findings produced a curriculum architecture consisting of four interdependent elements: computational thinking and coding, measurement and geometry, socioecological problems, and climate-action-oriented applications. The framework further contained three learning-outcome domains, four curriculum modules, a project-oriented learning sequence, and differentiated technological platforms. The resulting structure is summarized in Figure 2.

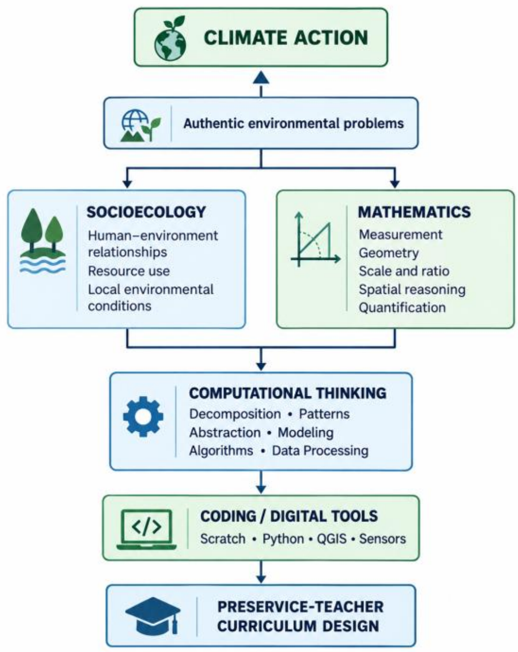

Figure 2. Socioecology-Based Coding Curriculum Framework for Preservice Elementary Teachers

The diagram represents the conceptual structure derived from the qualitative literature synthesis and curriculum-document analysis; it does not represent an empirically validated causal model. Overall, the present findings are therefore conceptual and curricular findings, not evidence of the effectiveness of the proposed curriculum. The manuscript itself states that the prototype emerged from literature and document synthesis and that empirical testing with preservice teachers remains necessary.

Discussion

The findings of this study identify a persistent curricular fragmentation in the preparation of prospective teachers in Southeast Asia, particularly in the relationship among computational thinking (CT), mathematics education, and socio-ecological sustainability. Although these three domains are increasingly recognized as important components of twenty-first-century education, they are not yet consistently integrated within a coherent instructional architecture. In response to this gap, the present study proposes an integrative curriculum prototype comprising socio-ecological problem-solving, environmental data analysis, pattern recognition, abstraction, mathematical modelling, and algorithmic solution design. The primary contribution of this prototype lies not in demonstrating empirical improvement in learning outcomes, but in articulating a curricular mechanism through which CT can be repositioned from a predominantly programming-oriented competence toward a broader cognitive and problem-solving practice embedded in mathematics and authentic environmental contexts. This interpretation is consistent with disciplinary perspectives that conceptualize CT as a set of reasoning practices that can be integrated into mathematics and science rather than being confined to coding activities (Lee et al., 2020). It also corresponds with systematic evidence demonstrating that effective CT integration in mathematics depends on the explicit connection between computational practices, mathematical learning goals, abstraction, modelling, task design, and disciplinary reasoning (Nordby et al., 2022, 2024).

The proposed *Carbon Footprint Calculator* further illustrates how this integration may be operationalized within teacher education. Measurement and unit conversion can be applied to school energy consumption, geometry can facilitate comparisons between green spaces and built areas, statistics can support the interpretation of longitudinal patterns of electricity use, and programming can translate mathematical representations into a computational tool for environmental decision-making. Such an approach is significant because computation is embedded within an authentic socio-ecological problem rather than taught as an isolated technical exercise. Christensen (2023) similarly positions CT as a productive framework for environmental sustainability education, particularly because decomposition, data processing, modelling, feedback, and systems reasoning can support learners in examining complex environmental phenomena. Likewise, Li and Tsai (2022) argue that mathematics education can make a meaningful contribution to Education for Sustainable Development when mathematical activities are explicitly linked to socially and environmentally relevant problems. Nevertheless, the changes in electricity consumption observed during the preliminary implementation of the project must be interpreted cautiously. The absence of a clearly defined pre-intervention baseline, equivalent post-intervention measurement periods, comparison conditions, and controls for factors such as school population, weather, operating hours, equipment use, and institutional energy policies prevents causal attribution. Accordingly, the case should be understood as an indication of curricular feasibility and contextual applicability rather than as empirical proof that the application itself reduced electricity consumption.

These findings are broadly consistent with international studies published between 2020 and 2026, which demonstrate that the success of CT integration depends more strongly on pedagogical design and teacher competence than on the mere availability of digital technologies. Kong et al. (2020) showed that sustained professional development integrating CT concepts, programming practices, pedagogy, classroom enactment, and reflection strengthened teachers' technological pedagogical content knowledge related to CT. This finding is particularly relevant to the present prototype because prospective teachers need more than technical proficiency; they must also understand how computational concepts can be transformed into meaningful mathematical learning experiences. Kong et al. (2023) further demonstrated that sustainable CT implementation requires collaborative professional development, instructional planning, subject integration, and systematic institutional support. At the same time, teacher readiness, instructional time, staffing, and learner diversity remain substantial barriers. These findings provide a strong empirical foundation for the phased implementation proposed in this study, particularly the recommendation that master-teacher preparation, instructional module development, and institutional readiness assessment should precede broader implementation.

Similar evidence emerges from research involving pre-service teachers. Bal et al. (2022) reported improvements in prospective teachers' understanding of CT and associated pedagogical knowledge following a structured micro-credential intervention. This finding indicates that teacher preparation should integrate conceptual understanding of CT with opportunities to design, implement, and reflect upon computationally enriched instruction. Pajela et al. (2021) likewise demonstrated that prospective teachers' use of mathematics and computational thinking is strongly influenced by the cognitive demand and disciplinary integration embedded in instructional tasks. This point is crucial for interpreting the proposed curriculum because an activity cannot be considered computationally meaningful simply because students use Python or another programming language. Rather, substantive CT emerges when learners engage in decomposition, abstraction, pattern identification, modelling, algorithmic reasoning, testing, interpretation, and revision while simultaneously developing disciplinary understanding.

The sustainability dimension of the prototype also corresponds with emerging international developments in mathematics education. Li and Tsai (2022) note that the connection between mathematics education and Education for Sustainable Development remains insufficiently developed despite increasing global emphasis on sustainability. The present study addresses this gap by positioning socio-ecological issues not merely as examples added to mathematical lessons but as contexts through which mathematical modelling and CT practices can operate simultaneously. More recent research with pre-service teachers similarly indicates that sustainability-oriented mathematical modelling can strengthen prospective teachers' perceptions of the relevance of mathematics and improve their confidence in designing contextualized learning activities (Polydoros & Antoniou, 2026). The present curriculum extends this orientation by explicitly connecting mathematical modelling to decomposition, abstraction, pattern recognition, algorithmic design, and computational implementation. Research from Finland also suggests that maker-oriented and computational learning environments can support interdisciplinary competencies and twenty-first-century skills when accompanied by appropriate pedagogical scaffolding (Iwata et al., 2020). Likewise, So et al. (2020) show that computational thinking reforms across the Asia-Pacific region involve substantially more than the introduction of coding; they require curriculum redesign, teacher development, institutional support, and policy alignment. Consequently, international benchmarking should not be interpreted as a justification for directly transferring Finnish or Singaporean educational practices into Indonesia. Instead, these international experiences demonstrate the importance of systemic alignment while reinforcing the need for contextual adaptation.

Within Indonesia, the findings are particularly relevant because emerging research indicates that CT remains unevenly translated from conceptual policy aspirations into concrete instructional practices. Maharani et al. (2021), for example, identified considerable variation in Indonesian pre-service mathematics teachers' ability to incorporate CT into lesson planning, particularly in relation to generalization and the pedagogical application of computational processes. This suggests that merely introducing CT terminology into teacher-education curricula is unlikely to be sufficient. Prospective teachers require repeated opportunities to convert CT principles into mathematically meaningful tasks, contextualized problems, instructional activities, and assessment strategies. These conditions support the phased implementation proposed in this study because structured professional preparation and limited institutional trials are more defensible than immediate large-scale implementation without evidence of teacher readiness, infrastructure, and instructional feasibility.

Local research also strengthens the argument for culturally and environmentally contextualized learning. Koderi, Sufian, and Erlina (2023), although working within Arabic language education rather than mathematics, demonstrated the potential of digitally mediated learning incorporating Lampung local wisdom to connect formal curriculum content with learners' cultural environments. Similarly, Al Khansa et al. (2024) found that integrated learning became more meaningful when instructional content was connected with learners' lived experiences and contextual realities. These findings should not be interpreted as direct evidence of CT effectiveness because their disciplinary contexts differ substantially from mathematics and computing. Nevertheless, they support the broader curricular principle that contextualization can increase the relevance of educational experiences. In the context of the proposed curriculum, this principle can be operationalized through socio-ecological issues that are directly recognizable within Indonesian communities, including waste management, energy consumption, water quality, agriculture, coastal degradation, land-use change, flooding, and disaster resilience. Such issues provide authentic datasets and problem situations through which prospective teachers can develop mathematical reasoning and CT while simultaneously engaging with sustainability challenges.

Recent Indonesian digital-learning research further suggests that the educational value of technology depends on how it is pedagogically employed. Hariandini et al. (2026) reported that digital technologies were frequently available within classroom practices but were often used primarily for presentation and visualization rather than for higher-order inquiry, collaboration, assessment, and knowledge construction. This finding provides an important caution for the implementation of the proposed prototype. The use of Python, digital simulations, or environmental datasets should not be regarded as innovative merely because they involve digital tools. Their educational significance depends on whether learners are required to formulate problems, analyze data, construct models, design computational procedures, test solutions, interpret outcomes, and evaluate their limitations. Sidik et al. (2025) similarly highlight the relevance of problem-based and project-based learning for developing programming-related analytical and problem-solving capacities. These findings support the use of authentic projects in the proposed curriculum but simultaneously emphasize the importance of structuring such projects around clearly defined mathematical and computational learning objectives. In addition, Febriani et al. (2026) identify local wisdom, community participation, and environmentally oriented educational practices as important dimensions within Indonesia's implementation of sustainable development. This reinforces the argument that an Indonesian CT curriculum should not merely reproduce generic international computing exercises but should engage learners with environmental problems embedded within their own social and ecological contexts.

The findings generate interconnected theoretical, pedagogical, and policy implications. Theoretically, they support an understanding of CT as an integrative cognitive practice in which decomposition, abstraction, pattern recognition, modelling, algorithmic reasoning, computational implementation, and evaluation interact with mathematical and socio-ecological knowledge. In this sense, the prototype extends narrow coding-centred interpretations of CT by positioning computation as a bridge between mathematical representation and sustainability-oriented problem-solving. Pedagogically, teacher-education institutions should therefore organize learning sequences in which prospective teachers identify authentic environmental problems, collect and analyse relevant data, formulate mathematically tractable questions, construct and evaluate models, develop computational procedures, and critically interpret the social and ecological implications of their solutions. Professional preparation should consequently integrate technological competence, pedagogical knowledge, mathematical reasoning, critical digital literacy, responsible data use, collaborative problem-solving, and reflective evaluation rather than focusing exclusively on programming proficiency (Kong et al., 2020; Mardianti et al., 2026). Such an approach may strengthen student engagement by linking learning to recognizable and socially meaningful problems; however, because the present study did not directly measure engagement, emotional well-being, media literacy, online behaviour, or identity formation, claims regarding these outcomes should remain prospective rather than causal. From a policy perspective, effective implementation requires alignment among teacher-education standards, curriculum outcomes, assessment frameworks, professional development, infrastructure, sustainability agendas, and institutional funding. National scaling should therefore be preceded by teacher-readiness assessments, resource audits, pilot evaluation, and strategies for reducing inequalities associated with the digital divide. Policies should also address ethical data practices, accessibility, equity, and low-resource instructional alternatives so that CT is understood as a mode of reasoning that may be cultivated with or without advanced technological infrastructure.

The novelty of this study lies in bringing together three domains that are frequently treated separately in teacher education: computational thinking, mathematics education, and socio-ecological sustainability. Rather than conceptualizing programming as an additional stand-alone subject, the proposed curriculum organizes computational practices around authentic environmental problems and mathematical modelling processes. In doing so, computation functions as an analytical mechanism for understanding contextual challenges rather than as an end in itself. The framework additionally proposes a curricular progression from socio-ecological problem identification and environmental data analysis to pattern recognition, abstraction, mathematical modelling, algorithm development, computational implementation, and evidence-based interpretation. Methodologically, the contribution of the study lies in translating the findings of curriculum-document analysis, comparative review, and international benchmarking into an explicit curriculum design proposition that can subsequently be subjected to empirical testing. Furthermore, the incorporation of local environmental issues and culturally responsive contexts distinguishes the prototype from more generic CT frameworks and provides a potential mechanism for reconciling global digital competencies with Indonesian educational, cultural, and ecological priorities.

Several limitations must nevertheless be acknowledged when interpreting these findings. First, the proposed curriculum was primarily developed through curriculum-document analysis and literature synthesis and should therefore be understood as a theoretically informed design rather than as a validated instructional intervention. Second, cross-national comparisons are constrained by differences in curriculum structure, policy terminology, institutional expectations, and stages of implementation across Southeast Asian educational systems. Third, the *Carbon Footprint Calculator* case does not provide sufficiently controlled longitudinal evidence to establish that the project caused changes in school electricity consumption. Fourth, potentially influential variables, including teacher competence, institutional culture, access to digital infrastructure, urban-rural inequalities, and differences in student preparedness, were not empirically examined. Future research should consequently employ design-based research, mixed-methods studies, or quasi-experimental approaches across several teacher-education institutions. Such studies should utilize validated measures of CT, mathematical modelling competence, socio-ecological literacy, pedagogical knowledge, student engagement, and implementation fidelity. Environmental projects should also collect standardized baseline and follow-up data, incorporate appropriate comparison conditions where feasible, and control analytically for relevant confounding variables. Qualitative evidence from interviews, classroom observations, learning artefacts, reflective journals, and teacher experiences should complement quantitative findings to explain how, why, and under what institutional conditions the curriculum operates effectively. Ultimately, multi-site and longitudinal research will be required before the proposed prototype can provide a sufficiently robust empirical basis for broader national implementation.

Conclusion

Based on the analysis of data and literature, the development of a socio-ecological coding curriculum shows potential for enhancing the computational thinking skills of prospective teachers. This offers an initial indication that integrating socio-ecological contexts into coding instruction can foster computational thinking skills while simultaneously raising awareness of environmental issues. The developed curriculum also demonstrates potential as an integrative learning framework that links mathematics, technology, and environmental education within a contextual learning experience. However, since the empirical evidence stems from limited-scope trials, these findings cannot yet serve as a basis for concluding the curriculum's overall effectiveness or ensuring its applicability across diverse educational contexts. Adaptation to local socio-ecological characteristics and learning needs remains necessary and requires testing through broader-scale research.

Future research should involve wider implementation and longitudinal studies to assess the consistency of improvements in computational thinking skills, as well as the curriculum's long-term impact on instructional practices and student competence. From a technological perspective, developing a learning management system specifically designed to support socio-ecological coding education could enhance the integration of materials, activities, assessments, and progress monitoring. At the regional level, collaboration and benchmarking with ASEAN countries could help identify contextual variations, instructional practices, and factors contributing to successful implementation. Furthermore, cost-benefit and feasibility analyses should be conducted before considering large-scale adoption. Consequently, this curriculum development should be viewed as a promising initial model requiring further empirical validation, rather than a fully proven model ready for immediate, widespread replication.

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