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DEVELOPING FUTURE PRIMARY SCHOOL TEACHERS' ENVIRONMENTAL COMPETENCE THROUGH STEAM EDUCATION AND ARTIFICIAL INTELLIGENCE: A PEDAGOGICAL FRAMEWORK

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Abstract

Environmental education has become an important priority in teacher preparation as educational institutions respond to climate change, biodiversity loss, and environmental pollution. This article examines how the integration of Science, Technology, Engineering, Arts, and Mathematics (STEAM) education with digital technologies and artificial intelligence (AI) can support the development of future primary school teachers' environmental competence. The study adopts a conceptual and analytical approach based on the synthesis of relevant pedagogical literature and educational policy documents. It identifies five interconnected areas of pedagogical implementation: curriculum integration, digital environmental inquiry, AI-supported learning, collaborative project-based learning, and continuous professional development. A conceptual pedagogical framework is proposed to connect environmental knowledge, interdisciplinary inquiry, technological application, and reflective teaching practice. The article argues that STEAM-based environmental education can provide opportunities to strengthen prospective teachers' scientific reasoning, problem-solving, collaboration, and environmental responsibility. However, the educational value of AI depends on the reliability of generated information, teachers' digital competence, equitable access to technology, and appropriate pedagogical supervision. The proposed framework provides a conceptual basis for future empirical research into the effectiveness of technology-enhanced environmental education in primary teacher preparation.

Keywords

environmental competence, primary teacher education, STEAM education, artificial intelligence, digital pedagogy, environmental education, interdisciplinary learning, sustainability, teacher professional development.

1. Introduction.

Environmental challenges have become increasingly significant for contemporary education. Climate change, biodiversity loss, pollution, and the unsustainable use of natural resources require educational approaches that enable learners to understand environmental processes and make informed decisions. In this context, environmental education should extend beyond the acquisition of scientific information and contribute to the development of environmental

awareness, responsible attitudes, practical skills, and a commitment to sustainable behaviour.

The importance of addressing environmental challenges has also been emphasized in international discussions. At the 78th session of the United Nations General Assembly, the President of Uzbekistan, Shavkat Mirziyoyev, drew attention to the interconnected global environmental crises and the particular vulnerability of Central Asia to climate change [7]. These challenges underline the need to strengthen environmental education and prepare teachers who can translate environmental knowledge into meaningful educational experiences.

Primary school teachers occupy an important position in this process. Their pedagogical decisions influence how children understand nature, interpret environmental problems, and develop attitudes towards the responsible use of natural resources. Consequently, future primary school teachers need more than subject-specific knowledge. They require the ability to integrate environmental concepts across disciplines, organize inquiry-based activities, interpret evidence, and encourage environmentally responsible behaviour among pupils.

The Science, Technology, Engineering, Arts, and Mathematics (STEAM) approach offers opportunities to address these requirements through interdisciplinary learning. Science provides explanations of natural processes; technology supports observation and data collection; engineering enables the design and testing of practical solutions; arts contribute creativity and environmental communication; and mathematics facilitates measurement, quantitative analysis, and interpretation of environmental data.

Digital technologies further expand the possibilities of STEAM-based environmental education. Interactive simulations, virtual field trips, environmental sensors, digital maps, and geographic information systems can help future teachers investigate environmental conditions and develop instructional materials. Artificial intelligence (AI) can complement these resources by supporting the preparation of differentiated learning activities, the organization of information, the generation of research questions, and the preliminary analysis of environmental datasets.

Nevertheless, the availability of digital tools does not automatically result in improved environmental competence. Their effectiveness depends on the quality of pedagogical design, the reliability of information, teachers' professional readiness, and the integration of technology into meaningful learning activities. AI-generated content also requires verification, particularly when it concerns scientific explanations or environmental data.

Against this background, the central problem addressed in this article is how STEAM education, digital technologies, and AI can be integrated into a coherent pedagogical framework for developing future primary school teachers' environmental competence.

The purpose of the study is to develop a conceptual pedagogical framework that explains how interdisciplinary STEAM activities and responsible AI-supported learning can contribute to environmental competence in primary teacher education.

The study addresses the following research questions:

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1. What pedagogical opportunities does the STEAM approach offer for developing future primary school teachers' environmental competence?
2. How can digital technologies and AI support environmental inquiry and interdisciplinary learning in teacher preparation?
3. What pedagogical conditions are necessary for the effective and responsible integration of STEAM education, digital technologies, and AI?

The article contributes a conceptual framework linking environmental knowledge, interdisciplinary inquiry, digital technology use, practical problem-solving, and reflective pedagogical practice. The framework is intended to inform future empirical studies rather than to represent an experimentally validated intervention.

2. Literature Review and Theoretical Background

2.1. Environmental competence in primary teacher education

Environmental competence can be understood as the integrated capacity to apply environmental knowledge, values, practical skills, and reflective judgment when interpreting environmental problems and developing appropriate responses.

Within teacher education, this competence includes understanding fundamental ecological processes, recognizing the interdependence of natural systems, evaluating human impacts on the environment, and designing age-appropriate environmental learning activities.

For future primary school teachers, environmental competence also has a professional dimension. Prospective teachers must be able to explain environmental concepts clearly, organize observation and inquiry, encourage pupils to investigate local environmental issues, and assess learning outcomes in ways that account for both knowledge and responsible action.

Accordingly, environmental competence should be developed through a combination of theoretical instruction, practical investigation, collaborative learning, and pedagogical reflection. Isolated lectures on environmental problems may provide important background knowledge, but they do not necessarily offer sufficient opportunities to practise environmental inquiry or develop instructional strategies.

2.2. The pedagogical potential of STEAM education

STEAM education integrates scientific and mathematical reasoning with technological applications, engineering design, and artistic creativity. Its interdisciplinary orientation enables learners to approach complex problems from multiple perspectives.

In environmental education, this approach can be implemented through projects involving water conservation, waste reduction, biodiversity monitoring, energy efficiency, and sustainable product design.

For example, a project on water conservation may require prospective teachers to investigate water use, collect and organize observations, calculate consumption, design a water-saving device, and develop an illustrated educational resource for primary school pupils. Such an activity combines scientific inquiry, mathematical analysis, engineering design, technological tools, and visual communication.

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Yakman's work on STEAM education provides a conceptual point of reference for understanding the integration of disciplines within an educational framework [3]. However, the inclusion of several disciplines alone is insufficient to establish effective interdisciplinary learning. Activities should be organized around a clearly defined problem, meaningful learning objectives, and an assessment strategy that captures both disciplinary understanding and the application of knowledge.

2.3. Digital technologies and AI-supported environmental learning

Digital technologies provide opportunities to observe, document, visualize, and analyze environmental phenomena. Their applications include digital field notebooks, interactive maps, virtual laboratories, online databases, environmental monitoring tools, and simulation environments.

These resources can make environmental processes more accessible by connecting classroom learning with observations of the natural and built environments. They may also support collaboration between teacher education institutions, schools, and environmental specialists.

AI introduces additional possibilities for preparing educational materials, generating alternative explanations, organizing research questions, and assisting with preliminary data analysis. For example, a future teacher may use an AI tool to develop age-appropriate questions about waste management or to compare alternative lesson activities addressing biodiversity.

However, AI-generated explanations and numerical outputs should not be treated as inherently accurate. Teachers need to verify scientific claims against reliable sources, protect personal data, recognize potential bias, and maintain responsibility for educational decisions. AI should support rather than replace professional judgment, direct observation, and authentic environmental investigation.

The integration of AI into STEAM-based environmental education should therefore be guided by clear learning objectives and appropriate ethical safeguards.

2.4. Research gap and conceptual rationale

The integration of STEAM education, digital technologies, and environmental learning offers substantial pedagogical potential. Nevertheless, their combined application in preparing future primary school teachers requires a coherent framework that connects environmental knowledge with practical inquiry, digital competence, instructional design, and reflective evaluation.

A fragmented approach may result in the use of digital applications without meaningful environmental investigation or the inclusion of environmental topics without sufficient interdisciplinary integration.

This article addresses that conceptual problem by proposing a pedagogical framework in which STEAM activities and AI-supported tools serve clearly defined educational purposes. The framework emphasizes the relationship between environmental understanding, practical problem-solving, technology-supported inquiry, and the prospective teacher's capacity to design effective learning experiences for primary school pupils.

The contribution is conceptual: the article organizes relevant pedagogical principles into a proposed framework and identifies conditions that can be examined in subsequent empirical research. It does not claim to establish the effectiveness of the framework through experimental evidence.

3. Research Methodology

3.1. Research design

The study adopts a conceptual and analytical research design. It examines the pedagogical relationship between environmental competence, STEAM education, digital learning resources, and AI-supported teaching practices.

The analytical process is organized around three dimensions: the educational requirements of environmental competence, the interdisciplinary learning opportunities offered by STEAM, and the pedagogical conditions necessary for responsible technology integration.

Relevant educational policy documents and selected publications on STEAM education and environmental learning provide the contextual basis for the discussion. The cited materials are used to frame the educational problem and develop the conceptual rationale for the proposed framework.

This approach is intended to develop a pedagogical model and identify directions for subsequent empirical investigation. It should not be interpreted as a systematic review or a completed experimental study, because a documented systematic search protocol, predefined inclusion criteria, and original experimental dataset are not provided in the source material.

3.2. Analytical procedure

The conceptual analysis follows four stages.

First, the principal dimensions of environmental competence are identified, including environmental knowledge, responsible attitudes, practical inquiry, and reflective evaluation.

Second, the contribution of each STEAM discipline to environmental learning is examined in relation to authentic educational problems.

Third, potential applications of digital technologies and AI are mapped to specific learning activities, such as environmental observation, data organization, model construction, and instructional resource development.

Fourth, the relationships between these elements are synthesized into a proposed pedagogical framework that connects learning objectives, teaching activities, digital support, and assessment.

3.3. Proposed pedagogical components

The framework incorporates five interrelated components.

Environmental and scientific knowledge. Future teachers acquire an understanding of ecological relationships, environmental challenges, biodiversity, pollution, and sustainable resource use.

Interdisciplinary integration. Environmental problems are examined through scientific investigation, technological applications, engineering design, artistic communication, and mathematical reasoning.

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Digital and AI-supported inquiry. Digital resources assist with data collection, visualization, information organization, and the preparation of learning materials, while AI outputs are critically evaluated.

Practical and collaborative activity. Prospective teachers work individually and in groups to investigate local environmental issues, develop solutions, and prepare educational projects.

Reflection and assessment. Participants evaluate their learning, justify their decisions, assess the feasibility of proposed solutions, and reflect on how environmental activities can be adapted for primary school pupils.

These components are intended to function as a coherent pedagogical system rather than as independent instructional techniques.

4. Results and Discussion

4.1. A conceptual framework for developing environmental competence

The conceptual analysis results in a proposed framework that connects environmental knowledge, STEAM-based inquiry, digital technology integration, practical application, and pedagogical reflection.

The framework is organized around the following instructional sequence:

Environmental problem identification → theoretical understanding → interdisciplinary inquiry → digital and AI-supported analysis → practical solution design → pedagogical reflection → assessment of learning outcomes.

The sequence provides a logical structure for organizing environmental learning activities in primary teacher education. Although presented linearly for clarity, the process may be iterative: reflection or assessment can lead participants to revise their initial questions, collect additional data, or redesign their proposed solutions.

The framework can be implemented through the following stages.

Stage 1: Identifying an environmental problem.

Future teachers identify an environmental issue that is relevant to their local community or educational setting. Examples include water wastage, littering, excessive energy consumption, soil degradation, and the decline of local biodiversity.

The selected problem should be sufficiently specific to support observation and investigation. Participants formulate research questions and identify the information needed to understand the problem.

Stage 2: Establishing theoretical foundations.

Participants examine relevant scientific concepts and determine how the selected problem relates to ecological processes and human activities. They identify appropriate information sources and distinguish between established scientific evidence, assumptions, and questions requiring further investigation.

This stage ensures that practical activities are grounded in scientific understanding rather than relying solely on general environmental awareness.

Stage 3: Conducting interdisciplinary inquiry.

Participants apply the STEAM approach to investigate the selected problem.

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Science supports the explanation of environmental processes. Technology provides tools for recording and presenting observations. Engineering supports the design and testing of potential solutions. Arts facilitate the visual communication of findings. Mathematics enables quantitative comparisons, measurement, and interpretation.

The interdisciplinary structure should be determined by the needs of the problem rather than by an arbitrary requirement to include every discipline in equal proportions.

Stage 4: Using digital technologies and AI.

Participants use appropriate digital tools to organize observations, create visual representations, prepare digital presentations, or examine environmental datasets. Where suitable, AI may support the generation of alternative research questions, the preparation of differentiated learning materials, and the organization of information.

AI-generated claims should be checked against authoritative sources, and conclusions should be based on verified evidence. Where participants collect environmental measurements, they should also consider measurement accuracy, sampling conditions, and the limitations of available equipment.

Stage 5: Developing and testing solutions.

Participants design a practical response to the identified environmental problem. Depending on the project, this may involve a resource-saving model, a waste-sorting activity, a biodiversity observation guide, an educational poster, or a classroom environmental investigation.

The proposed solution is assessed in terms of its scientific justification, feasibility, environmental relevance, educational value, and suitability for primary school pupils.

Stage 6: Reflecting on learning and pedagogical application.

Participants evaluate what they have learned, identify the limitations of their investigation, and consider how the activity could be adapted for primary school teaching.

Reflection should address both environmental understanding and professional competence, including the ability to explain findings, facilitate inquiry, use digital tools responsibly, and assess pupils' learning.

Stage 7: Assessing learning outcomes.

Assessment may include knowledge-based tasks, project portfolios, observation records, presentations, practical products, and reflective reports. The selection of assessment instruments should correspond to the intended learning outcomes and the dimensions of environmental competence being evaluated.

The framework is a proposed pedagogical structure. Its effectiveness and practical feasibility require validation through empirical research.

4.2. Integrating STEAM disciplines into environmental projects

The proposed framework can be translated into practical learning activities that combine disciplinary knowledge with environmental problem-solving.

Table 1. Integration of STEAM disciplines into environmental education

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STEAM component	Application in environmental learning	Expected learning outcome
Science	Investigating ecosystems, pollution, biodiversity, and natural processes	Improved environmental and scientific understanding
Technology	Using digital maps, sensors, simulations, and educational applications	Improved digital literacy and environmental data-handling skills
Engineering	Designing and testing models for water conservation, waste reduction, or energy efficiency	Development of design thinking and practical problem-solving
Arts	Creating environmental posters, visual narratives, models, and awareness campaigns	Development of creativity and environmental communication
Mathematics	Measuring resource consumption, organizing observations, and interpreting quantitative data	Development of quantitative reasoning and evidence-based decision-making

Source: Conceptual synthesis developed for this article.

Table 1 demonstrates that STEAM disciplines can contribute different but complementary forms of knowledge and skills. Their integration becomes educationally meaningful when participants use these contributions to investigate a shared environmental problem and justify a practical solution.

For instance, a water-conservation project can combine the measurement of water use, the scientific interpretation of water scarcity, the design of a water-saving model, and the creation of visual educational materials. This structure encourages prospective teachers to move from theoretical understanding towards practical application.

4.3. The role of artificial intelligence in the proposed framework

AI should be integrated selectively, according to the learning objectives of each activity. Its purpose is not simply to increase the technological complexity of a lesson but to support inquiry, analysis, and instructional design.

Table 2. Potential applications of AI in STEAM-based environmental education

Educational activity	Potential AI application	Pedagogical safeguard
Environmental problem identification	Generating possible research questions and project ideas	Teachers assess relevance and scientific validity
Preparation of learning materials	Adapting explanations and questions to pupils' learning needs	Content is checked for accuracy and age appropriateness
Data interpretation	Assisting with the organization or preliminary interpretation of datasets	Findings are verified using original observations and appropriate analytical methods
Project development	Comparing possible solutions and generating design alternatives	Decisions are justified using evidence and practical constraints
Assessment and reflection	Supporting feedback prompts and reflective questions	Teachers retain responsibility for evaluation and educational decisions

Source: Conceptual framework proposed by the author.

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Table 2 illustrates how AI can complement environmental learning when its use is connected to clearly defined pedagogical tasks. For example, an AI tool may help a prospective teacher generate several explanations of waste sorting for different age groups. The teacher must then verify the explanations, select appropriate examples, and ensure that the final materials are scientifically accurate and suitable for the intended pupils.

Similarly, AI may assist in organizing environmental observations, but it should not replace direct measurement or be treated as proof that an environmental condition exists. Conclusions must remain grounded in credible evidence.

These safeguards are particularly important in teacher education because prospective teachers need to develop the professional judgment required to evaluate digital information and guide pupils towards responsible technology use.

4.4. Pedagogical conditions for effective implementation

The proposed framework depends on several conditions.

Curricular alignment. Environmental projects should be connected to defined learning outcomes and relevant curriculum requirements. Interdisciplinary activities need a clear educational purpose and should not become disconnected collections of unrelated tasks.

Teacher preparedness. Future teachers require appropriate knowledge of environmental science, STEAM pedagogy, digital tools, and the limitations of AI. Professional development should address both technical skills and the pedagogical reasoning required to select and evaluate technologies.

Access to resources. Effective implementation requires suitable digital devices, reliable learning materials, and opportunities for practical investigation. Where access to advanced technologies is limited, low-cost experiments, direct observation, and collaborative learning can provide viable alternatives.

Scientific reliability. Environmental information and AI-generated outputs should be checked against credible sources. Data collection and interpretation should account for measurement limitations, uncertainty, and the difference between observed patterns and causal explanations.

Ethical and responsible technology use. Activities should protect personal information, respect copyright, promote academic integrity, and ensure that technology does not undermine learners' independent thinking.

Assessment and feedback. Assessment should address environmental knowledge, inquiry skills, practical application, collaboration, and reflection. Multiple sources of evidence are preferable to relying exclusively on a single test or a digital platform's automated evaluation.

Taken together, these conditions suggest that the successful integration of STEAM, digital technologies, and AI requires a pedagogically coherent environment supported by teacher expertise, appropriate resources, and systematic evaluation.

4.5. Implications for primary teacher education in Uzbekistan

The proposed framework is relevant to teacher education in Uzbekistan because environmental challenges affecting Central Asia create a need for context-

sensitive environmental learning. Local examples can help prospective teachers connect broader environmental concepts with issues that pupils may observe in their own communities.

Potential project themes include responsible water use, household waste reduction, urban green spaces, soil protection, biodiversity conservation, and energy efficiency. The selection of a particular topic should be informed by local conditions and the availability of reliable information.

Teacher education institutions can incorporate these activities into seminars, laboratory sessions, project-based assignments, school-based practice, and independent research. Collaboration with schools and relevant environmental specialists may strengthen the connection between university learning and practical educational needs.

The national policy context also provides a rationale for considering environmental sustainability and the modernization of educational infrastructure. Relevant policy documents include the presidential decree approving the Concept for Environmental Protection of the Republic of Uzbekistan until 2030 [1] and other education-related policy measures [2]. The precise legal titles, numbers, and applicability of these documents should be verified against official sources before publication.

The principal implication is that digital technologies and AI should be integrated into teacher preparation as means of supporting scientifically grounded, interdisciplinary, and practice-oriented environmental learning. Their contribution should be evaluated in relation to measurable educational outcomes rather than the mere presence of technology.

4.6. Limitations and directions for further research

This article presents a conceptual pedagogical framework and does not report original experimental findings. No participant sample, intervention period, control group, pre-test or post-test scores, or inferential statistical results were provided in the underlying material. Accordingly, the proposed framework cannot yet be considered empirically validated.

Future research should examine its effectiveness through a clearly designed empirical study involving future primary school teachers. A possible design would compare an intervention group participating in STEAM-based environmental projects supported by digital tools with a comparison group receiving the established instructional approach.

The study could assess environmental knowledge, environmental attitudes, inquiry skills, digital competence, and the quality of pedagogical project design before and after the intervention. Appropriate assessment instruments should be selected or validated, and the data-analysis procedures should be specified before conclusions are drawn.

Further research could also investigate which components of the framework contribute most strongly to learning outcomes, how AI-supported activities influence prospective teachers' independent reasoning, and whether the approach

can be implemented equitably across institutions with different levels of technological provision.

These investigations would provide the empirical evidence necessary to evaluate the framework's effectiveness, feasibility, and transferability to different educational contexts.

5. Conclusion

Developing the environmental competence of future primary school teachers requires an educational approach that integrates scientific understanding, environmental responsibility, practical inquiry, interdisciplinary learning, and reflective pedagogical practice.

The STEAM approach provides a framework for connecting environmental problems with science, technology, engineering, arts, and mathematics. Digital technologies can support environmental observation, data organization, visualization, and collaboration, while AI may assist with the preparation of learning materials, the generation of research questions, and the preliminary analysis of information.

The conceptual framework proposed in this article organizes these opportunities into a sequence that connects environmental problem identification, theoretical understanding, interdisciplinary inquiry, digital support, practical solution design, reflection, and assessment. Its implementation requires curricular alignment, teacher preparedness, access to appropriate resources, scientific verification, ethical technology use, and systematic evaluation of learning outcomes.

The framework's contribution is conceptual rather than experimental. Its effectiveness should therefore be examined through future empirical research using transparent methods, appropriate assessment instruments, and clearly reported findings. Overall, integrating STEAM education, digital technologies, and responsibly used AI into primary teacher preparation offers a promising direction for strengthening prospective teachers' environmental competence. When supported by sound pedagogical design and empirical evaluation, this approach may help prepare teachers to foster environmental awareness, scientific reasoning, and responsible attitudes towards sustainability among primary school pupils.

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