

V International Scientific and Technical Conference Actual Issues of Power Supply Systems

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AIPCP25-CF-ICAIPSS2025-00326 | Article

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Integrating Environmental and Energy-Related Content into Primary Mathematics Education: A Conceptual Framework and Task Classification Based on the Aral Sea Region

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Abstract. Environmental literacy has become a core component of education for sustainable development, particularly in regions experiencing acute ecological stress. The Aral Sea region of Karakalpakstan, characterized by water scarcity, land degradation, and dust pollution, represents an instructive context for developing new approaches to environmental education. This conceptual article proposes a theoretical framework for integrating environmental and energy-related content into primary mathematics education through contextual problem-solving. Drawing on international research in mathematics education, environmental literacy, and situated learning, the study develops: (1) a new classification of environmental mathematics tasks for primary school; (2) a model of eco-contextual integration that embeds sustainability concepts into core mathematical topics; and (3) a set of methodological principles grounded in contextualized learning, inquiry-based instruction, and cross-curricular alignment. The ecological conditions of the Aral Sea region are presented as a specific case that demonstrates the necessity and applicability of such integration. The paper argues that contextual mathematics tasks provide a powerful pedagogical mechanism for connecting abstract mathematical reasoning with real environmental challenges, thereby enhancing students' functional and environmental literacy. The proposed model can be used by curriculum developers, textbook authors, and teachers seeking to incorporate sustainability themes systematically within mathematics education.

INTRODUCTION

Environmental degradation and climate-related risks have accelerated the global demand for educational systems that develop not only academic proficiency but also sustainability-oriented competencies (UNESCO, 2019). Among these competencies, **environmental literacy** the ability to understand ecological processes, make informed decisions, and act responsibly in relation to the environment has become essential for the next generation of learners. Primary school is increasingly recognized as a crucial stage for establishing foundational attitudes and skills related to environmental awareness.

At the same time, mathematics often perceived as an abstract and culturally neutral discipline has gained attention as a powerful medium for developing functional and environmental literacy (OECD, 2021). Mathematical tasks that incorporate real-world ecological and energy-related situations make it possible for learners to detect relationships, analyze quantitative data, and understand the consequences of everyday human actions. This approach is in line with the global movement toward **contextualized and applied mathematics education**, endorsed by the PISA framework, inquiry-based learning paradigms, and education for sustainable development (ESD).

The Aral Sea region of Karakalpakstan represents a unique educational context in which environmental themes are not optional but **structurally embedded in daily life**. The region faces chronic water shortages, salinization, loss of biodiversity, and frequent dust storms. For primary school children, these phenomena are not abstract concepts; they constitute their lived reality. This situation creates a strong rationale for integrating environmental content into the mathematics curriculum through contextual tasks that reflect local ecological conditions.

Despite the growing international literature on environmental education, several critical gaps remain:

1. **Lack of systematic models** describing how environmental content can be integrated into primary mathematics.
2. **Absence of clear task classifications** linking ecological themes to mathematical concepts.
3. **Insufficient attention to extreme ecological contexts**, such as the Aral Sea region, where sustainability issues are central to children's everyday experiences.
4. **Limited theoretical analyses** of contextual problem-solving as a mechanism for developing environmental literacy within mathematics lessons.

This article addresses these gaps by proposing a **new conceptual framework for integrating environmental and energy-related themes into primary mathematics education**, supported by a **new classification of ecological tasks** and grounded in contemporary theories of contextual and activity-based learning.

The study is theoretical in nature and follows a conceptual design aligned with international Scopus-indexed educational research. It does not aim to report an empirical intervention; rather, it develops a structured theoretical model with high transferability for curriculum design and pedagogical practice.

LITERATURE REVIEW

The integration of environmental and sustainability themes into mathematics education has expanded significantly in recent decades, driven by global frameworks such as Education for Sustainable Development (UNESCO, 2019), the PISA Mathematics Framework (OECD, 2021), and the UN Sustainable Development Goals. Scholars increasingly emphasize that mathematics education must evolve beyond procedural fluency to include **contextual reasoning, decision-making, and real-world modelling** (Blum & Borromeo Ferri, 2009; Kaiser & Schwarz, 2010).

2.1. Environmental Literacy in Primary Education. Environmental literacy is conceptualized as a multidimensional construct that includes knowledge, cognitive skills, values, and behavior (McBride et al., 2013). In primary school, it is typically developed through interdisciplinary connections between science, social studies, and real-life scenarios (Stevenson et al., 2013). The challenge remains how to embed these competencies within subjects traditionally viewed as abstract, such as mathematics.

Recent studies suggest that **quantitative reasoning is essential for environmental understanding**, as many sustainability issues water consumption, energy efficiency, pollution levels are inherently numeric (Fleischmann, 2022). Mathematics, therefore, becomes a necessary gateway for reading environmental data and making informed decisions.

2.2. Contextual and Situated Approaches in Mathematics Education. Theories of contextual learning (Verbitsky, 2017; Greeno, 1998) argue that knowledge is most effectively acquired when embedded in meaningful contexts. Similarly, socio-constructivist views (Vygotsky, 1978; Davydov, 1996) emphasize the importance of culturally and socially situated learning activities.

Within mathematics education, **contextual problem-solving** has been shown to:

- strengthen students' conceptual understanding,
- improve transfer of knowledge,
- enhance motivation (Boaler, 1993),
- support functional mathematical literacy (OECD, 2021).

Environmental contexts provide particularly rich content for modelling, estimation, measurement, proportional reasoning, and data interpretation.

2.3. Integration of Environmental Topics into Mathematics

Studies worldwide particularly in Finland, Singapore, South Korea, and Germany demonstrate that mathematics can effectively address sustainability issues when tasks include:

- water and energy consumption scenarios,
- renewable energy calculations,
- air quality and CO₂ modelling,
- ecological footprint estimation (Rosen, 2015; Jablonka, 2020).

However, **systematic frameworks** for such integration and **task classification models** remain limited. Existing work focuses mostly on secondary school, while research on primary education is still emerging.

2.4. Ecological Case Studies and Extreme Environments

Educational research increasingly highlights the importance of **place-based learning**, especially in environmentally vulnerable regions (Gruenewald, 2003). The Aral Sea region one of the world's most severe anthropogenic ecological disasters offers a highly relevant context where environmental literacy is not merely theoretical but essential for everyday life.

Despite this, no existing literature provides a structured approach for integrating the environmental challenges of the Aral Sea region into **primary mathematics education**. This article aims to fill this gap.

THEORETICAL AND METHODOLOGICAL APPROACH

3.1. Research Design.

This study employs a **conceptual-theoretical research design**, focusing on:

- synthesizing international research in mathematics and environmental education,
- constructing a transferable theoretical model,
- developing a structured classification of contextual environmental tasks for primary mathematics.

It does not involve empirical fieldwork; instead, it provides a **systematized conceptual framework** that can be empirically validated in future studies.

3.2. Theoretical Foundations

The model draws on four complementary theoretical perspectives:

(1) Activity Theory (Vygotsky, Davydov, Elkonin)

Learning is viewed as an active process where students construct meaning by engaging with problem situations that reflect real social and environmental conditions.

(2) Contextual Learning Theory (Greeno; Verbitsky)

Knowledge becomes meaningful when embedded in authentic contexts that resemble real-life situations. Environmental tasks provide such authenticity.

(3) Education for Sustainable Development (UNESCO)

Emphasizes interdisciplinarity, problem-solving, and responsible decision-making competencies that mathematics can support through modelling and data analysis.

(4) Mathematical Literacy Framework (OECD PISA)

Defines mathematical literacy as the capacity to apply mathematical concepts in real contexts precisely the role played by environmental tasks.

3.3. Method of Conceptual Synthesis

The methodological approach includes:

- **content analysis** of existing environmental tasks in global mathematics education;
- **comparative analysis** of sustainability-related curricular models;
- **task design methodology** used in applied mathematics education;
- **development of a new classification system** tailored to the cognitive development of primary students;
- **construction of a conceptual integration framework**, connecting mathematical domains (arithmetic, geometry, measurement, data handling) with environmental themes (water, energy, pollution, vegetation).

3.4. Contextual Relevance: The Aral Sea Region Case

The Aral Sea region is used as a **case of extreme ecological conditions**, characterized by:

- critical water scarcity,
- salinization and desertification,
- dust storms with toxic sediments,
- high energy demands and infrastructure constraints.

The ecological pressure in this region reinforces the rationale for environmental mathematics tasks, making the integration **culturally and socially necessary**.

3.5. Outputs of the Conceptual Methodology

The applied methodology results in:

- a new conceptual framework for eco-contextual integration,
- a four-block classification of environmental mathematics tasks,
- principles for developing contextual educational materials,
- transferable methodological recommendations.

RESULTS

This section presents the conceptual outputs of the study:

- (1) a new model for integrating environmental and energy-related content into primary mathematics,
- (2) a new classification of contextual environmental mathematics tasks, and
- (3) corresponding methodological principles for curriculum design.

4.1. Conceptual Model for Integrating Environmental Content into Primary Mathematics

The proposed model **Eco-Contextual Mathematics Integration Framework (ECMIF)** is structured around three interconnected dimensions:

(A) Environmental Context Dimension

Defines ecological themes relevant to children's real life:

1. Water scarcity and responsible use
2. Renewable and household energy
3. Air quality, dust, and vegetation
4. Waste minimization and resource efficiency
5. Local ecological issues (e.g., Aral Sea desiccation)

(B) Mathematical Content Dimension

Specifies the mathematical domains through which environmental concepts can be embedded:

- Arithmetic (addition, subtraction, multiplication, division)
- Measurement (volume, length, mass, area)
- Geometry (shapes, perimeters, rectangular area models)
- Proportional and percentage reasoning
- Introductory data literacy (tables, charts)

(C) Pedagogical Process Dimension

Defines the methodological basis:

- contextual problem-solving,
- inquiry and exploration,
- visual modelling,
- cross-disciplinary links,
- reflective discussion of environmental meaning.

Integration Principle

Environmental themes function not as add-ons but as **meaningful contexts** that support mathematical sense-making. Students encounter ecological problems as natural mathematical tasks, enabling dual development of:

- functional mathematical literacy,
- foundational environmental literacy.

4.2. New Classification of Environmental Mathematics Tasks

Based on the developed model and content analysis, the study proposes a **four-block classification** appropriate for primary school (grades 1–4).

Each block includes characteristic task types and examples (translated from original materials and adapted for international context).

Block 1. Renewable and Household Energy Tasks

Focus: solar panels, wind energy, electricity consumption.

Task Example:

"A small solar panel produces 150 W per hour in direct sunlight. How much energy will four such panels produce in six hours?"

These tasks strengthen understanding of multiplication, scaling, and basic energy concepts.

Block 2. Water Use and Conservation Tasks

Focus: water scarcity, daily consumption, leakage, irrigation efficiency.

Task Example:

"A family saves 20 liters of water per person each day. How many liters will be saved in one year by a family of four?"

These tasks develop unit conversion, multiplication, and long-term reasoning.

Block 3. Vegetation, Air Quality, and Dust Protection Tasks

Focus: tree planting, CO₂ absorption, dust retention, green belts.

Task Example:

"A tree absorbs 40 kg of CO₂ per day. How much CO₂ will be absorbed by 25 trees in 30 days?"

They reinforce multiplication, modelling, and eco-systemic thinking.

Block 4. Complex Project-Based Contextual Tasks

Focus: combining measurement, arithmetic, geometry, and environmental modeling.

Task Example:

"A school garden is 25 m long and 16 m wide.

(a) Find its area.

(b) If 4 trees grow per 100 m², how many trees can be planted?

(c) If each tree captures 15 kg of dust per month, how much dust will the garden capture in 9 months?"

These tasks integrate multiple mathematical ideas and provide high cognitive demand.

4.3. Methodological Principles Derived from the Model

From the integration framework and task classification, the following principles are established:

Principle 1. Authenticity and Relevance

Tasks should reflect real environmental conditions familiar to children especially those living in vulnerable regions such as the Aral Sea basin.

Principle 2. Spiral Progression

Environmental tasks should appear consistently from grades 1 to 4, gradually increasing in mathematical complexity.

Principle 3. Quantitative Environmental Reasoning

Every task should enable students to interpret environmental data mathematically, reinforcing numeracy.

Principle 4. Interdisciplinary Coherence

Mathematics tasks should connect naturally with science, social studies, and sustainability discussions.

Principle 5. Inquiry and Reflection

Students should not only compute results but also interpret their environmental meaning.

5. Discussion

The findings support the growing research consensus that mathematics education can play a transformative role in developing sustainability competencies. The proposed ECMIF model demonstrates how contextualized problem-solving bridges abstract mathematical content and real ecological challenges.

5.1. Contributions to Theory

This study provides four major theoretical contributions:

1. **A new classification** of environmental mathematics tasks tailored to primary education.
2. **A conceptual model** linking environmental themes with mathematical content and pedagogical processes.
3. **A contextual rationale** grounded in the unique ecological realities of the Aral Sea region one of the most ecologically burdened areas in the world.
4. **An expansion of contextual learning theory**, showing how extreme environmental contexts create natural conditions for deep learning.

5.2. Implications for Curriculum and Textbook Development

Curriculum designers can integrate the model to:

- include environmental tasks systematically,
- ensure alignment with competencies of ESD and PISA,
- build cross-curricular units (mathematics + ecology),
- enhance functional mathematical literacy.

Textbook authors can use the classification to develop structured task sets.

5.3. Limitations and Directions for Future Research

Since this article is conceptual, empirical validation is required. Future studies should:

- conduct classroom interventions,
- measure effects on environmental literacy,
- analyze teacher readiness,
- compare outcomes across ecological contexts.

CONCLUSION

This conceptual study demonstrates that environmental and energy-related content can be systematically integrated into primary mathematics education through contextualized problem-solving. The proposed ECMIF framework and new classification of tasks provide a strong theoretical foundation for curriculum design, teacher training, and textbook development. The ecological realities of the Aral Sea region not only justify but necessitate such an approach. Embedding sustainability within mathematics education helps cultivate both environmental awareness and functional numeracy competencies essential for navigating the challenges of the 21st century.

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