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Jurnal Sosiohumaniora Kodepena
Information Center for Indonesian Social Sciences
Vol. 7, No.2, Nopember 2026
pISSN 2723–7516
eISSN 2723–4762

Integrating Education for Sustainable Development (ESD) in Physics Education through a Contextual Approach to Earth Phenomena

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Abstract
Education for Sustainable Development (ESD) is a learning approach that emphasizes the integration of principles, values, and practices of sustainable development into the educational process. In physics learning, ESD can serve as a bridge to connect scientific concepts with real-world phenomena relevant to the Sustainable Development Goals (SDGs). This article aims to analyse ESD integration strategies in physics education by utilizing earth phenomena as a learning context, identifying the relationship between physics material and SDG indicators, and formulating a learning model capable of developing 21st-century skills. This study uses a literature analysis method of previous research, UNESCO policy documents, and classroom implementation practices. The results of the analysis indicate that ESD integration in physics learning can be carried out through a contextual approach based on earth phenomena, such as geothermal energy, earthquake dynamics, tsunamis, and climate change issues. This strategy can strengthen scientific literacy, increase environmental awareness, and foster students' social responsibility towards sustainability challenges. The implications of this research confirm that the application of ESD-oriented physics learning not only deepens conceptual understanding but also equips students with critical perspectives and skills to address global and local issues.

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Jurnal Sosiohumaniora Kodepena
pp. 204-216

Keywords; Physics Education, Education for Sustainable Development (ESD), Contextual Approach, Earth Phenomena,

INTRODUCTION

Sustainable development has become a global agenda to address the increasingly complex environmental, social, and economic challenges of the 21st century (Shao et al., 2026). In this context, UNESCO's Education for Sustainable Development (ESD) plays a strategic role in equipping communities with the knowledge, skills, values, and attitudes

necessary to shape a sustainable future (UNESCO, 2020a). ESD emphasizes core competencies such as systemic thinking, critical thinking, collaboration, and evidence-based decision-making—competencies that are highly relevant for integration into various disciplines, including physics (Jauhariyah et al., 2021; Prayogi & Verawati, 2024). As a basic science that studies natural phenomena and fundamental principles, physics has a direct contribution to a number of global issues reflected in the 17 Sustainable Development Goals (SDGs). These contributions, among others, are evident in SDG 7 (Clean and Affordable Energy) through renewable energy innovation; SDG 9 (Industry, Innovation, and Infrastructure) through advances in materials, optics, and electronics technology; and SDG 13 (Addressing Climate Change) through studies of the greenhouse effect, radiation, and climate change (Khosla et al., 2024; Olabi et al., 2023).

Geophysical and earth phenomena offer a rich context for bridging physics learning. Energy concepts can be linked to the use of renewable energy sources such as geothermal, solar, and wind; wave concepts can be studied through earthquakes and tsunamis; and the laws of thermodynamics can be analysed in the context of global climate change. Thus, physics learning based on earth phenomena not only strengthens conceptual understanding but also raises students' awareness of environmental sustainability and ecosystem responsibility (Fauza et al., 2023). Geophysical phenomena provide authentic and contextual learning resources because they represent natural processes that are closely related to students' daily lives and involve the application of multiple physics concepts simultaneously (Faryuni et al., 2025). For example, earthquakes and volcanic eruptions illustrate principles of mechanics, elasticity, wave propagation, heat transfer, and fluid dynamics, while climate change and renewable energy systems involve concepts of thermodynamics, radiation, and energy conversion (Posadas et al., 2021). Presenting these phenomena as learning contexts enables students to connect abstract physics concepts with observable environmental events, thereby promoting conceptual understanding and scientific reasoning (Hemtasin et al., 2026). Furthermore, contextual learning based on real-world phenomena encourages students to recognize the contribution of physics to understanding environmental issues and supports the development of sustainability-oriented perspectives in science education (Ashlan & Firayani, 2025).

In Indonesia, ESD has begun to be implemented through programs such as Adiwiyata and environment-based. However, the integration of ESD into science learning, particularly physics, remains limited, and students' understanding of global sustainability issues is relatively low (Adriyanto et al., 2020; Suryani et al., 2025). Although various innovative learning models, such as STEAM, PjBL, inquiry-based learning, and other contextual approaches, have been widely implemented in physics education to improve students' critical thinking and scientific literacy (Mahyuna et al., 2025), these studies primarily focus on instructional strategies and learning outcomes. Few studies have systematically connected authentic geophysical phenomena with fundamental physics concepts while explicitly aligning them with the Sustainable Development Goals (SDGs).

Furthermore, there is still limited literature that proposes a comprehensive framework to guide teachers in integrating geophysical contexts into sustainability-oriented physics learning. Previous studies have reported various strategies for integrating sustainability into science education through project-based learning, STEM or STEAM

approaches, inquiry learning, and contextual learning (Luthfi et al., 2026). However, most studies focus on improving learning outcomes or environmental awareness without systematically demonstrating how core physics concepts can be connected to specific geophysical phenomena and explicitly aligned with the Sustainable Development Goals (SDGs). In addition, there is still limited literature that provides a conceptual framework for selecting environmental phenomena as learning contexts while simultaneously mapping the relationships among physics concepts, sustainability competencies, and SDG targets. Addressing this gap is important to support teachers in designing physics learning that is scientifically meaningful, contextually relevant, and aligned with the objectives of Education for Sustainable Development (del Río-Rodríguez et al., 2026).

Despite the growing interest in integrating sustainability into science education, limited attention has been given to the systematic integration of geophysical phenomena within physics learning as a means of achieving Education for Sustainable Development (ESD) objectives. The novelty of this study lies in the development of a conceptual framework that combines three complementary components: (1) the identification of key geophysical and Earth phenomena relevant to physics education, (2) the systematic mapping of these phenomena to fundamental physics concepts and the Sustainable Development Goals (SDGs), and (3) the formulation of a contextual learning framework that supports the implementation of ESD in physics classrooms. Rather than focusing solely on instructional models or learning outcomes, this study emphasizes the relationship between authentic environmental phenomena, core physics concepts, and sustainability competencies. This integrated framework is expected to provide both theoretical and practical contributions by serving as a reference for educators in designing contextual physics learning that enhances scientific literacy, systems thinking, and sustainability awareness.

Based on this background, this article aims to analyse the integration of Education for Sustainable Development (ESD) into physics learning by using geophysical and Earth phenomena as contextual learning resources. Specifically, this study identifies geophysical phenomena that are relevant to physics education, maps their relationships with fundamental physics concepts and the Sustainable Development Goals (SDGs), and proposes a conceptual framework to support the implementation of sustainability-oriented physics learning. The proposed framework is expected to assist educators in designing contextual learning experiences that strengthen scientific literacy, sustainability awareness, and students' ability to address environmental challenges at both local and global levels. Specifically, this study identifies relevant geophysical phenomena, maps them to fundamental physics concepts and the Sustainable Development Goals (SDGs), and proposes a conceptual framework that supports the implementation of sustainability-oriented physics learning. It is expected that this framework will contribute to strengthening scientific literacy, sustainability awareness, and students' capacity to understand and respond to both local and global environmental challenges.

METHOD

This study employs a qualitative conceptual review design integrated with a structured literature analysis framework. Because this manuscript is a conceptual review rather than empirical field research, this study follows a transparent and systematic

approach to maintain methodological credibility. Our framework consists of: literature screening, quality appraisal, thematic data analysis, and conceptual model synthesis.

We began by searching Scopus and Google Scholar for relevant literature published over the last decade, specifically targeting the period leading up to 2026. The search strategy combined several core terms using Boolean operators: ("SDG" OR "Sustainable Development Goals") AND ("ESD" OR "Education for Sustainable Development") AND ("physics education" OR "contextual physics") AND ("geophysical phenomena" OR "earth science"). To build a credible foundation, we limited our inclusion criteria to peer-reviewed journal articles, official UNESCO policy documents, and standard physics education textbooks that explicitly tie physics concepts to sustainability goals or earth-based contexts. Conversely, we excluded opinion pieces, non-peer-reviewed conference abstracts, and undergraduate theses.

To ensure the validity of our findings, we cross-verified the selected literature by focusing on peer-reviewed papers from Scopus-indexed or nationally accredited (SINTA) journals, as well as institutional UN/UNESCO releases. We also double-checked the mapped connections between physics laws (such as thermodynamics and wave mechanics) and specific SDG indicators against established physics curricula to guarantee conceptual accuracy.

For the data analysis, we adopted a thematic approach. We extracted and categorized discussion points regarding ESD competencies and geophysical events based on their underlying physics principles. This process allowed us to systematically map eight core earth phenomena against their corresponding physics concepts and specific SDG targets (including SDGs 6, 7, 11, 13, 14, and 15). Finally, we integrated these synthesized themes into a practical pedagogical framework. This framework translates our findings into actionable learning outcomes across three core domains: cognitive (conceptual understanding), affective (sustainability awareness), and psychomotor (simulations and practical skills), providing a clear blueprint for educators.

RESULT AND DISCUSSION

The systematic literature review and conceptual analysis conducted in this study successfully formulate a matrix that integrates Education for Sustainable Development (ESD) into the physics curriculum. Based on the analysed textbooks, journals, and UNESCO documents (UNESCO, 2020b), the integration is structured into three main interconnected pillars: the establishment of a conceptual framework, the contextual mapping of eight core earth phenomena, and the academic implications across the cognitive, affective, and psychomotor domains.

ESD Integration in Physics Learning: A Conceptual Framework

The integration of Education for Sustainable Development (ESD) into physics learning aims to connect understanding of scientific concepts with the real challenges facing society in achieving sustainable development (Leonita et al., 2025a). Physics, as a fundamental science that studies natural phenomena, plays a crucial role in explaining processes occurring on Earth while also providing solutions to environmental and social problems. Through ESD, physics learning goes beyond mastering theories and formulas, but also aims to foster critical awareness, a caring attitude, and skills in applying

knowledge to maintain the sustainability of ecosystems and the quality of human life (Permanasari & Dwi Pursitasari, 2021).

One form of ESD integration in physics is the concept of energy. Students can learn the laws of conservation of energy and energy transformation by relating them to renewable energy issues. For example, the concepts of latent heat and the laws of thermodynamics can be studied through the case of geothermal energy utilization, while Faraday's law can be related to the conversion of wind energy to electricity. Through this context, students understand that global energy needs cannot continue to rely on fossil fuels, necessitating sustainable solutions based on physics (Pratama et al., 2026).

The concept of waves is also an important entry point for ESD integration. Seismic wave analysis not only teaches the principles of elastic wave propagation within the earth but also helps students understand how science is used in earthquake and seismic hazard (Miftahuddin et al., 2020). This understanding is particularly relevant in Indonesia which is lying on plate boundaries triggering earthquakes. It encourages students to connect theory with life-saving strategies and disaster risk reduction .

Furthermore, the concepts of thermodynamics and heat transfer can be used to discuss global issues such as climate change and global warming. The Stefan-Boltzmann law and the greenhouse effect, for example, can be used to explain the increase in global temperatures due to the accumulation of greenhouse gases in the atmosphere. By integrating this topic into learning, students not only learn the abstract laws of physics, but also understand their implications for the environment, ecosystem sustainability, and human life (Arisa & Chusni, 2025).

Thus, the integration of ESD into physics learning through the concepts of energy, waves, and thermodynamics forms a holistic educational framework. Students not only master academic material but also develop social awareness, critical thinking skills, and a responsible attitude toward sustainability issues. This aligns with the primary goal of ESD, namely to prepare a. generation capable of systematic thinking, wise decision-making, and contributing to a more sustainable future.

The conceptual framework for integrating Education for Sustainable Development (ESD) into physics learning requires a shift from conventional disciplinary approaches toward a more systemic and interdisciplinary perspective. Physics instruction has traditionally emphasized mathematical concepts and problem-solving, often with limited connection to real-world sustainability issues (El-Masri, 2026). As a result, students may develop strong analytical skills but have fewer opportunities to understand the relationship between physics concepts and environmental, social, and economic challenges. By positioning energy, waves, and thermodynamics as the main conceptual foundations, this framework enables physics learning to become more contextual and relevant, while supporting the development of systems thinking and sustainability awareness.

Contextual Approach through Geophysical and Earth Phenomena

A contextual approach to physics learning emphasizes the connection between theoretical concepts and real-world phenomena occurring in the surrounding environment (Hanifah et al., 2023). In the context of geophysics and earth sciences, frequent natural phenomena such as earthquakes, volcanic eruptions, tsunamis, geothermal energy, and climate change can serve as effective learning media (Ma & Mei, 2021). These

phenomena are not only rich in physics concepts to learn, but also relevant to students' daily lives, especially in disaster-prone areas like Indonesia. This makes physics learning more meaningful because students directly see the relevance of the knowledge they are learning to social and environmental realities. For example, earthquakes can be used to teach the concepts of force, energy, elasticity, and wave propagation. Teachers can relate Hooke's law to the deformation of rocks in the Earth's crust or Newton's laws to the release of energy during faults. Furthermore, seismic wave analysis can be learned through simple simulations, so students not only understand wave mechanics theory but also recognize its role in earthquake and tsunami disaster mitigation.

Geothermal phenomena also provide a rich context for physics learning. The concepts of thermodynamics, heat transfer, and the Carnot cycle can be explained through the use of geothermal energy as a renewable energy source. Several earth phenomena that can be incorporated into ESD-based physics learning are shown in Table 1. For example, students can be asked to calculate the efficiency of converting geothermal energy into electricity or compare the potential of this renewable energy with unsustainable fossil fuels. In this way, students not only learn thermodynamic concepts but also understand their implications for energy sustainability issues. Other phenomena such as tsunamis and fluid dynamics can be used as examples to explain Bernoulli's law, potential energy, and wave propagation speed. Teachers can use water simulations in test tanks to illustrate tsunami wave propagation and relate this to the importance of early warning systems in coastal areas. Similarly, climate change can be used as a context for learning about radiation, the greenhouse effect, and the Earth's energy balance.

Table 1
Geophysical and Earth Phenomena as an Advanced Context for ESD-Based Physics Learning

No.	**Geophysical/Earth Phenomena**	**Related Physics Concepts**	**Emphasized ESD values**
1.	Earthquake and seismic hazard	Newton’s laws, elasticity, Hooke's Law, mechanical wave propagation (P-waves & S-waves).	SDG 11: Sustainable Cities and Communities (Disaster mitigation & risk awareness).
2.	Tsunami	Fluid dynamics, shallow-water wave mechanics, gravitational potential energy, Bernoulli's law.	SDG 14: Life Below Water & Coastal Community Safety (Disaster preparedness).
3.	Volcanic eruption and magma dynamic	Fluid pressure, viscosity, heat transfer (conduction-convection), gravitational potential energy.	SDG 15: Life on Land & Environmental Risk Management (Ecological awareness).

4.	Geothermal energy	Laws of thermodynamics, thermal conductivity, fluid dynamics, energy conversion efficiency.	SDG 7: Affordable and Clean Energy (Resource sustainability & energy independence).
5.	Climate Change and Global Warming	Stefan-Boltzmann Law, blackbody radiation, electromagnetic waves, Earth's energy balance.	SDG 13: Climate Action (Global responsibility & ecological footprint awareness).
6.	Tectonic plate movements	Force, momentum, impulse, mechanical energy, magnetic field reversals.	SDG 4: Quality Education (Systems thinking & deep understanding of earth dynamics).
7.	Water Cycle and Precipitation Changes	Latent heat, phase transitions, conservation of mass, fluid dynamics, energy cycles.	SDG 6: Clean Water and Sanitation (Water conservation & natural resource management).
8.	Tropical Storms and Cyclones	Atmospheric pressure gradients, Coriolis force, torque, fluid dynamics, energy transfer.	SDG 13: Climate Action (Disaster preparedness & climate change adaptation).

Data Source: Synthesized by the authors (2026)

The eight phenomena presented in Table 1 provide a contextual framework for integrating physics concepts with environmental issues and the Sustainable Development Goals (SDGs). These phenomena enable students to connect fundamental physics principles with real-world situations, thereby promoting contextual understanding and sustainability awareness. Through this approach, physics learning extends beyond conceptual knowledge by encouraging students to recognize the relevance of physics in addressing environmental and societal challenges.

Tectonic processes provide meaningful contexts for learning mechanics, elasticity, wave propagation, and fluid dynamics. The movement of tectonic plates illustrates concepts such as force, stress, strain, and mechanical energy, while earthquakes demonstrate the release of elastic energy accumulated along geological faults (Jackson et al., 2021). The propagation of Primary (P) waves and Secondary (S) waves helps students understand the characteristics of mechanical waves and their interactions with different Earth materials. Similarly, volcanic activity introduces concepts related to fluid pressure,

magma viscosity, and heat transfer (Gómez-Arango et al., 2018). Integrating these phenomena into physics learning can improve students' understanding of natural hazards and disaster mitigation, supporting the objectives of SDG 11 (Sustainable Cities and Communities) and SDG 15 (Life on Land) (Alhusni et al., 2025).

Tsunamis provide an appropriate context for studying wave motion and fluid dynamics (Sruthi et al., 2019). Unlike wind-generated waves, tsunami waves behave as shallow-water waves because their wavelength is much greater than the ocean depth. The propagation velocity of tsunami waves is expressed by

$$v = \sqrt{gh}$$

where g is the gravitational acceleration and h is the water depth. As tsunami waves approach coastal areas, decreasing water depth reduces wave velocity while increasing wave height through the process of wave shoaling. This phenomenon enables students to apply concepts of wave propagation, hydrostatic pressure, and energy conservation to understand tsunami behavior and its implications for coastal disaster mitigation, thereby contributing to SDG 14 (Life Below Water) (Nik Effendi & Abdul Khanan, 2026).

Climate-related phenomena also provide valuable contexts for applying physics concepts to contemporary environmental issues. Tropical cyclones can be used to explain atmospheric pressure, rotational motion, fluid dynamics, and heat transfer in the atmosphere (Ito et al., 2020). By relating these concepts to climate change, students gain a better understanding of the physical processes responsible for extreme weather events and changes in water availability. Integrating these environmental contexts into physics learning supports the implementation of SDG 13 (Climate Action) and SDG 6 (Clean Water and Sanitation) while promoting scientific understanding of climate adaptation and sustainable water resource management (Bezen & Tanriöver, 2026).

By utilizing geophysical and earth phenomena as context, physics learning emphasizes more than just memorizing formulas, but also fosters critical awareness and a caring attitude toward the environment. Students are trained to connect physics concepts to real-world problems, seek creative solutions, and understand the link between science and sustainable development. This aligns with the ESD principle, which emphasizes the interconnectedness of scientific knowledge, sustainability values, and concrete actions in everyday life (Leonita et al., 2025b).

Implications for Physics Learning

The integration of Education for Sustainable Development (ESD) through geophysical and earth phenomena into physics learning has several important implications for the teaching and learning process. These implications can be seen across three main domains: cognitive, affective, and psychomotor. From a cognitive perspective, students gain a deeper understanding of physics concepts because learning is linked to real-world phenomena relevant to everyday life (Ariska et al., 2024). For example, when discussing the laws of thermodynamics in the context of geothermal energy, students not only understand the mathematical equations but are also able to explain how these principles are used in environmentally friendly electricity generation.

This approach fosters critical thinking skills, systems analysis, and the ability to connect science to sustainability issues (Siombone et al., 2022).

In the affective domain, the use of geophysical and earth phenomena fosters environmental awareness and awareness of disaster risks. Students learn that understanding physics concepts has a direct impact on human life, such as mitigating earthquakes or tsunamis. This fosters social empathy, a sense of responsibility, and motivation to contribute to environmental conservation and sustainable natural resource management. Meanwhile, from a psychomotor perspective, phenomenon-based learning allows students to conduct simple experiments, simulations, or problem-based projects. For example, students can create a simple model of tsunami wave propagation using water in a container, or simulate the cycle of a geothermal power plant through a heat transfer experiment. These activities not only hone practical skills but also strengthen student engagement in the learning process.

Overall, the implication of integrating ESD into physics learning through geophysical and earth phenomena is the creation of a more holistic, meaningful, and sustainability-oriented learning process. Physics is no longer viewed as an abstract science and far from reality, but rather as a science that contributes directly to addressing global challenges. Thus, physics learning has the potential to produce a generation that is not only academically intelligent but also socially conscious and committed to sustainable development. The integration of Education for Sustainable Development (ESD) into physics learning through geophysical and earth phenomena significantly contributes to the quality of learning. This approach not only strengthens mastery of physics concepts but also fosters critical awareness, environmental awareness, and students' practical skills in understanding and responding to natural phenomena.

Although integrating Education for Sustainable Development (ESD) into physics learning offers cognitive, affective, and psychomotor benefits, its implementation presents several pedagogical challenges. The transition from conventional teacher-centered instruction to inquiry-based and phenomenon-based learning requires teachers to adopt new instructional strategies and learning designs. One of the main challenges is balancing the achievement of physics learning objectives with the integration of sustainability issues without reducing the depth of either component (Nugroho et al., 2025). Therefore, effective instructional planning is required to ensure that physics concepts remain scientifically rigorous while maintaining their relevance to environmental and societal contexts.

Digital simulations, computational modeling, and virtual laboratories can support the implementation of this learning approach. Many geophysical phenomena, such as tectonic plate movement, volcanic activity, and atmospheric circulation, cannot be directly observed or experimentally reproduced in school laboratories . Interactive digital platforms, including PhET simulations, GeographicInformation System (GIS) applications, and simple computational programming, enable students to investigate these phenomena by manipulating relevant physical variables in a safe and controlled environment (Oktageri et al., 2025; Trolese et al., 2025). For example, students can simulate the effects of magma viscosity on volcanic flow or examine how changes in surface albedo influence the Earth's energy balance. These learning activities strengthen students' conceptual understanding while promoting scientific inquiry, problem-solving skills, and digital literacy.

The integration of ESD into physics learning also has implications for curriculum development and educational policy. Curriculum implementation should encourage learning experiences that connect physics concepts with real-world environmental problems and emphasize interdisciplinary thinking. In addition, assessment should not only measure conceptual understanding but also evaluate students' ability to analyze problems, apply scientific knowledge, and propose solutions related to sustainable development. Through this approach, physics education can contribute to the development of scientifically literate students who are able to understand environmental challenges and participate in achieving the Sustainable Development Goals (SDGs).

Geophysical phenomena closely related to people's lives, such as earthquakes, geothermal heat, tsunamis, and climate change, make physics learning more contextual and meaningful. The implications include cognitive (conceptual understanding), affective (caring and responsible attitudes), and psychomotor (practical and experimental skills). Thus, this integration aligns with the goal of ESD, namely to develop a generation that is not only knowledgeable but also aware of and committed to sustainability.

CONCLUSION

Integrating Education for Sustainable Development (ESD) into physics learning through earth-science phenomena effectively delivers a focused, sustainability-oriented education. Through this approach, students not only understand theoretical physics concepts but also relate them to real-world phenomena. This contextual approach, based on geophysical phenomena, has positive implications for students' cognitive, affective, and psychomotor domains. In the cognitive domain, students more easily grasp concepts through direct application to earth phenomena. In the affective domain, students develop a sense of care, responsibility, and awareness of the importance of sustainability. Meanwhile, in the psychomotor domain, students have the opportunity to practice skills through simple experiments, simulations, and problem-based projects.

Thus, the integration of ESD into physics learning not only strengthens academic competency but also shapes students' character, fostering scientific literacy, social sensitivity, and a commitment to sustainable development. This demonstrates that physics learning can be a strategic tool in preparing a generation capable of critical thinking, active participation in disaster mitigation, and contribution to renewable energy utilization and environmental conservation.

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