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Simulation Technologies in Physics Learning for Education for Sustainable Development

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ABSTRACT

Objective: *This study aims to systematically analyse how simulation technologies are integrated into physics education to support Education for Sustainable Development (ESD). The objective is to identify publication trends, thematic focuses, and pedagogical implications of simulation-based learning in fostering sustainability competencies and scientific literacy.* ***Method:*** *A Systematic Literature Review (SLR) approach was employed using data from Scopus and ScienceDirect databases covering the years 2007-2025. Thirty-five selected articles were analysed using bibliometric mapping in VOSviewer and thematic content analysis to identify research patterns related to the use of simulation in ESD-oriented physics learning.* ***Results:*** *The findings reveal that simulation technologies enhance students' conceptual understanding, digital competence, and sustainability awareness. Four main themes emerged: (1) simulation for conceptual understanding, (2) sustainability competency development, (3) teacher digital competence, and (4) equity in virtual learning. Publication trends show a steady increase since 2019, with the highest research output in 2023. Most contributions originated from countries with strong digital infrastructures, such as the USA, Indonesia, and Switzerland.* ***Novelty:*** *This study provides an integrated view of simulation-based physics education as a driver of sustainability competencies, highlighting its dual cognitive and affective impact. Unlike previous reviews, this work explicitly connects simulation technology with ESD frameworks, offering insights for future pedagogical models and sustainable digital learning practices.*

INTRODUCTION

In the era of rapid technological advancement and global sustainability challenges, education is expected to play a transformative role in shaping environmentally conscious, scientifically literate, and sustainability-oriented citizens (Chowdhury et al., 2020; Ariza et al., 2021; Batista et al., 2024; Hnatyuk et al., 2024; Kapelista et al., 2024). Physics, as a fundamental science, serves as a gateway for students to understand the principles underlying natural phenomena and technological innovation. The integration of Education for Sustainable Development (ESD) into physics learning is envisioned to cultivate learners' ability to connect scientific knowledge with real-world sustainability issues such as energy conservation, climate change, and responsible technology use (Ariska et al., 2024; Badiah et al., 2024; Novita et al., 2025; Rizki et al., 2024; Shobah et al., 2025). Ideally, students are not only expected to master physical concepts but also to apply them to address complex environmental problems through critical thinking, creativity, and systems thinking (Astutik et al., 2020; Saregar et al., 2020; Suharno et al., 2022; Lestari & Fitriyah, 2023). This expectation aligns with United Nations Sustainable Development Goal 4, which emphasises the importance of quality education in fostering sustainable futures (Haron et al., 2021; Hossain et al., 2023; Prabawati et al., 2024; Saini et al., 2023; Costa et al., 2024).