



Innovative Learning Paths in Biology Education

Integrating Educational Technology and Transdisciplinary Approaches in the Era of Industry 5.0

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ABSTRACT

This study explores the transformation of biology learning paths through the integration of educational technologies and transdisciplinary strategies within the context of Industry 5.0 and Society 5.0. Using qualitative and design-based methods, we developed learning frameworks incorporating both hard and soft technologies, including AI applications, big data, virtual labs, and STEAM-based projects. Results show that educational innovations not only enrich students' conceptual understanding but also cultivate 21st-century competencies such as analytical thinking, collaboration, and problem-solving. The study proposes a dynamic instructional model aligned with real-world issues and concludes that adaptive ecosystems in educational institutions are essential for preparing responsible and innovative future scientists.

Keywords

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Educational Technology
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Learning Path
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Transdisciplinary Learning

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Introduction

The transformation of biology education in the era of Industry 5.0 has gone beyond conventional methods. Traditional models that rely solely on textbook instruction and static classroom environments are no longer sufficient to prepare students for complex global challenges. The convergence of emerging technologies and interdisciplinary learning frameworks is redefining how students engage with biological concepts. The adoption of virtual simulations, artificial intelligence (AI), and collaborative digital tools provides new dimensions to conceptual learning in biology [1]-[4].

In response to societal and environmental complexities, educational paradigms must shift toward adaptive, personalized, and real-world-integrated learning paths. Industry 5.0, with its human-centered and sustainable principles, necessitates pedagogical approaches that empower students to think critically and solve authentic problems [2], [5]. Learning paths in biology education now emphasize not only scientific knowledge but also the development of analytical thinking, digital literacy, and ethical responsibility. This requires institutions to integrate both hard technologies (e.g., VR, robotics, simulations) and soft technologies (e.g., AI algorithms, online learning analytics) [3], [6], [7].

This paper explores how the fusion of educational technology and transdisciplinary strategies can deepen biology learning and enhance its relevance to real-world contexts. By adopting STEAM frameworks, integrating AI tools such as Foldit and PlanNet, and fostering transdisciplinary collaboration, students gain more than academic content; they acquire competencies necessary for navigating a rapidly evolving world [4], [8], [9]. The investigation aims to highlight effective instructional designs that support dynamic learning ecosystems aligned with the principles of Industry 5.0 and Society 5.0.

Methods

This research employed a qualitative-descriptive approach with design-based research (DBR) to identify and formulate effective learning paths in biology. The data was collected through document analysis, teacher interviews, and observations of teaching practices. Case studies focused on STEAM-based biology learning scenarios. The analysis was conducted thematically to identify core pedagogical, technological, and interdisciplinary elements.

Results and Discussion

A. Integration of Hard and Soft Technology in Biology Education

The use of hard technology (e.g., virtual labs, 3D modeling, augmented reality) and soft technology (e.g., AI tools like DeepMind, Foldit platforms, and PlanNet) enables new dimensions of biology instruction. These technologies empower students to explore biological phenomena

that are otherwise invisible or inaccessible in traditional classrooms. For instance, virtual dissection labs and 3D cellular models allow learners to interact with biological structures with high precision, improving retention and conceptual understanding [3]-[5]. Furthermore, tools like DeepMind assist in decoding complex molecular interactions, offering valuable insights for both learning and research [4], [6].

The development of simulations to demonstrate cellular processes or molecular dynamics has significantly enhanced learning efficiency and accessibility. Simulation platforms provide a safe environment for students to experiment, visualize biochemical processes, and build hypotheses without resource limitations or ethical constraints. These tools also support differentiated learning by offering adjustable complexity and scaffolding to suit diverse learning needs [5], [6], [14]. Additionally, data generated from these simulations can be integrated with learning analytics to further personalize instruction and measure progress more accurately [6], [14].

Moreover, cloud-based tools and LMS-integrated systems are increasingly utilized to deliver adaptive content tailored to individual student progress. By collecting real-time performance data, educators can identify learning gaps and customize interventions effectively. Soft technology tools like Foldit gamify complex biological tasks, encouraging collaborative problem-solving and promoting citizen science [4], [13]. This intersection of hard and soft technologies not only bridges theoretical and practical learning but also equips students with the digital fluency necessary for future scientific endeavors [6], [13], [15].

B. STEAM-Based Learning Projects in Biology

Projects such as hologram-based refraction models and bottle-based filtration systems exemplify the fusion of science, technology, engineering, art, and math (STEAM). These hands-on activities promote active and creative engagement while reinforcing fundamental scientific principles [7], [8]. For instance, the use of recycled plastic bottles in constructing hologram pyramids not only introduces students to concepts of light refraction but also fosters environmental consciousness and creativity through upcycling.

These interdisciplinary activities allow learners to apply theoretical knowledge in meaningful contexts, thereby enhancing their understanding and retention. In the hologram project, students apply geometry and symmetry concepts while engineering stable structures capable of reflecting light in precise ways. Meanwhile, in the water filtration model, students simulate natural filtration processes using everyday materials, linking environmental science with engineering design [7], [8]. These types of projects embody the core of experiential learning and are aligned with the objectives of 21st-century skills development, including problem-solving and collaboration.

As depicted in Fig. 1, the example of the project results on light refraction demonstrates students' understanding of the concept through experimental visualization.

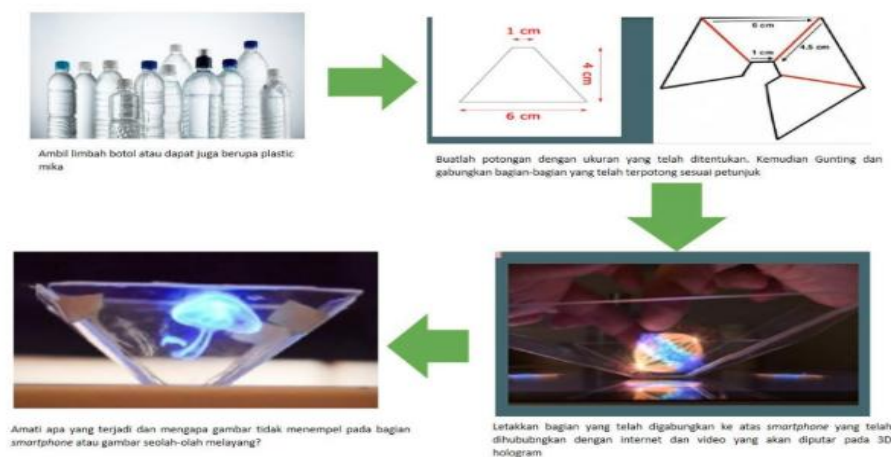


Fig. 1. Example of the Project Results on Light Refraction

Table 1 outlines the integration of STEAM domains in the project, highlighting how each area contributes to the understanding and visualization of light refraction using upcycled materials and holographic projection.

Table 1. The STEAM Description

STEAM Domain	Description
Science	Understanding of plastic waste and light refraction; transparent bottles chosen to allow light to pass with minimal distortion.
Technology	Smartphone as a light source and a hologram video to project light patterns onto plastic.
Engineering	Designing an optimally angled and stable pyramid to reflect light without distortion.
Art	Creative upcycling of waste and aesthetic selection of holograms to enhance learning.
Mathematics	Accurate geometry and symmetry calculations to ensure consistent hologram visuals.

Furthermore, integrating STEAM in biology education encourages innovation by connecting scientific inquiry with artistic expression and mathematical reasoning. The aesthetic element of designing visually appealing and functional prototypes instills a sense of ownership and motivation in students. Technology such as smartphone projection, sensors, and microcontrollers may also be introduced to enhance experimentation and data analysis. These interdisciplinary projects thus offer a scalable and inclusive strategy for implementing contextual learning in diverse educational settings [8], [9].

As illustrated in Fig. 2, the project results demonstrate students' ability to apply filtration principles through hands-on experimentation with common materials.



Fig. 2. Example of the Project Results on Filtration Principles

Table 2 presents the application of STEAM domains in the filtration project, demonstrating how students integrated scientific concepts, technological reuse, engineering design, artistic creativity, and mathematical precision to create effective and visually appealing water filtration models.

Table 2. The STEAM Description

STEAM Domain	Description
Science	Applies filtration principles using materials like charcoal, sand, and gravel to mimic natural soil filtering.
Technology	Reuses plastic bottles as simple, low-cost water filters to address environmental and clean water issues.
Engineering	Involves selecting and layering filter materials effectively and modifying bottles into functional filters.
Art	Uses creative design for material arrangement and bottle cutting to ensure both function and visual appeal.
Mathematics	Includes measuring material layers, bottle capacity, and filtration time to optimize system performance.

Table 3 summarizes two student projects that integrate STEAM domains, outlining their learning objectives and the educational technologies used. The Hologram Pyramid project focuses on light refraction and geometry using smartphones and video holograms, while the Bottle Filtration project addresses water purification through upcycled materials and simple sensors.

Table 3. Example of STEAM Integration in Biology Learning

Project Title	STEAM Domains	Learning Objectives	Educational Technology Used
Hologram Pyramid	S-T-E-A-M	Light refraction and geometry	Smartphone, video holograms
Bottle Filtration	S-T-E-A-M	Water purification and filtration systems	Upcycled materials, sensors

C. Development of Transdisciplinary Competencies

Modern biology learning must incorporate real-world challenges, requiring transdisciplinary skills that bridge science, technology, and societal needs. Projects involving environmental

conservation, public health, and digital biology cultivate responsibility, systems thinking, and innovation by encouraging students to explore connections between ecological processes and human behavior [9], [10]. These competencies are essential in developing holistic thinkers who can address sustainability challenges using integrative approaches.

Transdisciplinary education in biology not only merges content from various fields but also redefines the role of the learner as an active agent of change. Through inquiry-based learning and collaborative problem-solving, students learn to synthesize diverse perspectives and generate solutions with both scientific rigor and social relevance. For example, analyzing the impact of pollution on biodiversity engages students in environmental science, ethics, policy studies, and community advocacy [10], [11]. Such learning experiences promote empathy and civic engagement alongside academic competence.

Instructional design should align with ISD (Instructional System Design) principles to optimize these experiences by clearly defining learning objectives, aligning assessment strategies, and scaffolding interdisciplinary collaboration. Technology-enhanced transdisciplinary tasks, such as digital storytelling on ecological issues or using GIS tools to analyze habitat loss, further amplify the impact of these models [11], [12]. Thus, fostering transdisciplinary competencies in biology education is not only about content mastery but also about shaping adaptive, ethical, and innovative global citizens prepared for future uncertainties.

D. AI and Big Data in Adaptive Learning Pathways

AI-based tools such as PlanNet (plant identification), personalized LMS analytics, and adaptive testing represent cutting-edge developments in biology education. These technologies enable data-driven personalization and support inquiry-based learning models [13], [14]. AI allows educators to create dynamic learning environments by analyzing student interaction data and adapting content in real time. Tools like PlanNet, for instance, help learners identify plant species in the field using image recognition, bridging the gap between digital tools and real-world biological exploration [13].

Moreover, big data plays a pivotal role in constructing adaptive learning pathways by offering insights into learners' behavior, preferences, and performance. Through continuous monitoring and analysis, systems can recommend personalized resources, set appropriate difficulty levels, and predict learning outcomes [14]. LMS platforms with embedded analytics allow educators to track student engagement patterns and intervene proactively, ensuring that no learner is left behind. Such systems foster inclusive learning by accommodating diverse student needs and learning styles.

Additionally, the integration of AI into formative and summative assessments contributes to more equitable and efficient evaluation processes. Adaptive testing platforms adjust the

complexity of questions based on the learner's performance, providing immediate feedback and minimizing test anxiety [6], [14]. AI also supports intelligent tutoring systems that simulate one-on-one instruction, offering customized scaffolding and feedback loops [13], [14]. These innovations signal a paradigm shift in biology education, where personalized, data-driven instruction enhances student agency and academic success.

Fig. 3 presents how Pl@ntNet was applied as a digital tool to enhance students' understanding of plant biodiversity through interactive fieldwork.



Fig. 3. The Application on Biology Pl@ntNet

Table 4 highlights educational technology tools used in biology learning, detailing their functionalities, specific applications, and learner benefits. Pl@ntNet supports biodiversity classification through plant identification, enhancing field data accuracy, while DeepMind aids molecular biology understanding by simulating protein structures with realistic visualizations.

Table 4. AI Tools and Their Application in Biology Learning

Tool Name	Functionality	Biology Application	Learner Benefits
PlanNet	Plant identification	Biodiversity classification	Improved field data accuracy
DeepMind	Protein prediction	Molecular biology simulation	Realistic visualization

E. Toward an Adaptive Learning Ecosystem

Educational institutions must evolve into adaptive learning ecosystems to effectively respond to the dynamic demands of Society 5.0. This involves the integration of curriculum models that are flexible, responsive to global issues, and capable of equipping students with relevant future skills. By embedding digital tools and real-world problem-solving into the curriculum, institutions can promote interdisciplinary thinking and active student participation. Learning must become increasingly student-centered, leveraging technological innovations to foster autonomy, collaboration, and creativity [15], [16].

A critical factor in building such ecosystems is the alignment of institutional vision with pedagogical innovation. This includes not only providing infrastructure and digital access but also

encouraging experimentation and innovation at all levels of instruction. Faculty development programs must emphasize the use of AI tools, data analytics, and immersive technologies to support educators in redesigning their teaching strategies. Moreover, collaborative partnerships with industries, research centers, and community organizations can offer authentic contexts for students to apply their knowledge and skills [15], [16].

Sustainable transformation also requires systemic curriculum reform that is informed by both empirical data and forward-looking policies. Flexible learning pathways should be designed to accommodate diverse learner profiles and adapt to rapid technological shifts. Continuous feedback loops, supported by learning analytics, enable educators to refine their approaches and ensure learning remains effective and inclusive. By cultivating a culture of continuous improvement and innovation, educational institutions can become resilient, future-ready ecosystems that empower learners for lifelong success [15], [16].

Conclusion

The integration of educational technology and transdisciplinary approaches in biology fosters innovative and adaptive learning paths. Projects based on real-world issues and powered by technology prepare learners to become responsible global citizens with strong scientific literacy and 21st-century skills. Future directions include institutionalizing adaptive ecosystems and expanding the use of AI-driven tools.

Conflict of Interest

The authors declare that there is no conflict of interest.

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