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Research Paper

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Empowering Future Biology Teachers: Integrating STEM and Design Thinking for Effective Sustainability Learning

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Abstract

This study examines the implementation of a design project in a preservice biology teacher education course titled "Biology Education for Sustainability," aiming to enhance creativity while addressing the United Nations Sustainable Development Goals (SDGs). This work presents a comprehensive framework divided into 10 chapters, spanning approximately 16 weeks (or about three and a half months) of meetings, each corresponding to key lessons designed to empower preservice biology teachers. In addition, the project engages preservice teachers in collaborative teams to identify local environmental challenges related to specific SDGs, such as clean water, climate action, and life on land. Utilizing a design thinking framework, participants engage in brainstorming, prototype development, and iterative feedback that lead to the fostering of innovative solutions. Moreover, data were collected through pre- and post-project surveys, reflective journals, and presentations to assess the impact on creativity, understanding of the SDGs, and confidence in teaching sustainability concepts. The results indicate significant improvements in creative problem-solving skills and a deeper awareness of the SDGs, along with increased motivation to integrate sustainability into their future teaching practices. As a result, this experiment highlights the effectiveness of experiential learning in the "Biology Education for Sustainability" course, preparing preservice teachers to address global challenges through innovative and creative educational strategies.

Keywords: Preservice Biology Teacher Education, Design Thinking, STEM, Sustainability Education

Introduction

In the face of escalating environmental challenges, the role of education in fostering sustainability has become increasingly critical (Biasutti and Frate 2017). The United Nations Sustainable Development Goals (SDGs), adopted in 2015, provide a comprehensive framework for addressing global issues such as poverty, inequality, climate change, and environmental degradation. Education is recognized as a fundamental driver for achieving these goals, particularly in empowering future generations to become informed and active participants in sustainable practices (Annan-Diab and Molinari 2017). For instance, biology teacher education programs play a pivotal role in equipping preservice teachers with the knowledge (Atchia 2023), skills, and creativity needed to engage students in sustainability-oriented learning (Brugmann et al. 2019).

Biology, as a discipline, inherently aligns with the principles of sustainability (Adams et al. 2023), exploring the intricate relationships between living organisms and their environments (Hiong and Osman 2013). By integrating sustainability into biology education, future teachers can inspire students to critically examine ecological issues and develop innovative solutions (Batz et al. 2015). However, traditional approaches in teaching biology often fail to cultivate the creative problem-solving skills that are essential for addressing complex sustainability challenges (Ladachart and Ladachart 2022). To bridge this gap, innovative pedagogical strategies, such as Design Thinking (DT), can be employed.

Design Thinking is a human-centered approach to problem-solving that emphasizes empathy, creativity, and iterative processes (Badwan et al. 2018). By engaging preservice teachers in design projects, educators can foster an environment where creativity thrives. This approach encourages students to identify real-world problems (Baran and Al Zoubi 2023), brainstorm potential solutions (Cross 2023), and develop actionable plans that reflect an understanding of the SDGs (Dotson et al. 2020). Furthermore, collaborative learning experiences promote communication and teamwork (Baniya et al. 2019), which are vital skills for future educators who will need to work with diverse groups of students and stakeholders.

This study focuses on the implementation of a design project within a preservice biology teacher education course titled "Biology Education for Sustainability." The courseaims to enhance participants' understanding of sustainability concepts while fostering creativity and innovative thinking. By tackling local environmental challenges linked to specific SDGs,preservice teachers not only deepen their knowledge of sustainability but also gain practical experience in applying their learning to real-world contexts (Adams, Kewell, and Parry 2018). Through this project, we seek to investigate the impact of experiential learning on preservice teachers' creativity, confidence, and understanding of sustainability. By employing a mixed-methods approach, we will collect data on participants' experiences and outcomes, providing insights into the effectiveness of integrating Design Thinking into biology education. In the analysis, this research aims to contribute to the growing body of literature on sustainability education, offering valuable implications for teacher preparation programs and strategies for empowering future biology educators.

Literature Review

1) STEM Education in Biology Teacher Preparation

STEM (Science, Technology, Engineering, and Mathematics) education has become a cornerstone of 21st-century teaching and learning. In biology teacher education programs, STEM integration is essential for equipping future teachers with the skills that are necessary to address complex real-world problems (Batty and Reilly 2023; Ben-Eli 2018). Research highlights that STEM-based learning promotes critical thinking, interdisciplinary knowledge, and scientific literacy (Brunelli and Macirella 2021; Suwono et al. 2023). For future biology teachers, this approach helps in making biology content more relevant, applied, and connected to everyday life and global challenges.

2) Design Thinking in Education and Teacher Training

Design Thinking (DT) is a human-centred iterative process involving empathy, ideation, prototyping, and testing to solve complex problems (Atchia, Chummun, and Luckho 2024; Blundell 2024). In teacher education, DT offers a framework that nurtures creativity, problem-solving, and collaboration (Fei 2024; Goldman and

Zielezinski 2016; Wingard et al. 2022). When integrated into biology teacher training, DT encourages preservice teachers to design meaningful and engaging learning experiences that go beyond textbook content and foster innovation. Studies show that using DT helps future educators feel more confident in managing uncertainty and ambiguity in classroom practices (Honra and Monterola 2024; Trung et al. 2024).

3) Sustainability Learning in Science Education

Sustainability education focuses on equipping students with the knowledge, skills, attitudes, and values needed to address environmental, social, and economic challenges (UNESCO, 2017). In science education and particularly biology, sustainability themes, such as climate change, biodiversity, and ecosystems, are highly relevant. Studies emphasize the role of teachers as agents of change in promoting sustainability literacy (Sterling, 2001; Wals, 2010). However, research also reveals that many preservice teachers feel inadequately prepared to teach sustainability issues effectively (Evans et al., 2017), which is signalling the need for pedagogical innovation in teacher training programs.

4) Integration of STEM and Design Thinking for Sustainability

Integrating STEM with Design Thinking offers a transformative learning approach that combines technical knowledge with empathetic and solution-oriented thinking (Lande & Leifer, 2010; Watson, 2020). This integration fosters transdisciplinary competencies and enhances students' and teachers' abilities to engage in authentic problem-solving. In the context of sustainability, this approach enables future biology teachers to design projects that are locally relevant and globally significant—such as eco-enzyme creation, school composting, or urban gardening—making sustainability concepts tangible and actionable (Tosun & Taskesenligil, 2013; Mishra et al., 2022).

5) Empowering Preservice Biology Teachers through Innovative Pedagogies

Empowerment in teacher education refers to fostering agency, autonomy, and capacity to lead change in educational practices (Zimmerman, 1995). Innovative pedagogies like STEM-DT integration empower preservice biology teachers by enhancing their confidence, pedagogical creativity, and content mastery. Research by Finkelstein et al. (2021) suggests that when preservice teachers are involved in real-world, design-based STEM projects, they not only deepen their subject understanding but also develop a stronger sense of ownership over their teaching methods and purposes. Empowerment also includes developing reflective practices, collaboration, and ethical decision-making in response to sustainability challenges.

Methodology

This study investigates the implementation of a design project in a preservice biology teacher education course titled "Biology Education for Sustainability". The course is structured to enhance creativity among preservice biology teachers while addressing key United Nation Sustainable Development Goals (SDGs). To improve clarity, specific SDGs are explicitly referenced during each project phase to align with the issues being addressed, such as SDG 13 (Climate Action), SDG 12 (Responsible Consumption and Production), and SDG 15 (Life on Land). The course framework is divided into 10 chapters, each aligned with critical lessons aimed at empowering preservice teachers with sustainability teaching competencies. The participants were 40 preservice biology teachers enrolled in the "Biology Education for Sustainability" course. These preservice teachers were in the latter stages of their teacher education program and had prior experience in biology and educational methods.

The course followed a design thinking

framework to guide the participants through the project stages. The steps included: (1) Empathize: Teams identified local environmental challenges through research and community engagement that tied to SDG 13 and SDG 15; (2) Define: They framed the problem related to SDGs; (3) Ideate: Through brainstorming sessions, teams generated innovative solutions to the defined challenges such as waste management (SDG 12), environmental degradation (SDG 15), and local climate resilience (SDG 13); (4) Prototype: Teams developed initial prototypes of their solutions; (5) Test: Prototypes were refined through iterative feedback cycles from peers and instructors.

Data were collected from multiple sources to assess the impact of the course on participants' skills and perspectives: (1) Pre- and post-project surveys: These surveys measured changes in participants' creative problem-solving skills, understanding of SDGs, and confidence in teaching sustainability concepts; (2) Reflective journals: Participants maintained reflective journals throughout the course, documenting their thought processes, challenges, and learning experiences; (3) Presentations: Teams presented their final prototypes and solutions to their peers and instructors, providing additional qualitative data on their learning outcomes. Quantitative data from the surveys were analyzed using statistical methods to evaluate changes in creativity, SDGs awareness, and teaching confidence. Moreover, qualitative data from journals and presentations were analyzed through thematic coding to identify common patterns in how participants experienced the design process and developed sustainability teaching strategies.

Results and Discussion

Education for Sustainable Development (ESD) is a crucial topic in environmental education; it encompasses significant contexts such as socio-cultural factors and socio-political issues, including equity, poverty, democracy, and quality of life (Scott, 2015; Dotson et al., 2020). ESD serves as both a solution and a requirement for transforming human behavior and addressing the ongoing environmental sustainability crisis (Lestari, Paidi, and Suyanto 2024). As global challenges intensify, ESD encourages individuals and communities to adopt more sustainable practices. In response to these challenges, many countries have incorporated sustainable development issues into their educational curricula at all levels (Chang and Lien 2020), emphasizing the need for a more sustainable and equitable future (Eidin and Shwartz 2023). However, despite the growing inclusion of sustainability topics in curricula, many studies highlight a gap between policy intentions and classroom implementations, especially regarding effective pedagogical strategies that foster higher-order thinking and real-world application (Al-Hazaima, Low, and Sharma 2024; Ben-Eli 2018).

This study contributes to bridging that gap by embedding the **design thinking** framework into a preservice biology teacher education course, providing a structured yet flexible pathway for students to engage in creative problem-solving rooted in real sustainability challenges. This activity offers significant potential for enhancing students' problem-solving and critical thinking skills in multiple ways. First, it engages students in identifying key issues within complex, real-world sustainability challenges, which are often ill-structured and multifaceted. It then guides students to analyze underlying causes and develop sustainable solutions, ultimately improving their capacity to tackle complex problems and address real-world challenges effectively. The design thinking framework guided preservice biology teachers through each phase of the project, enhancing their skills and understanding of sustainability.

Below are the results, broken down by each phase of the design thinking process.

1) Phase 1: Empathize

In the first phase, students engaged with their local communities to identify real-world environmental problems. This stage helped them develop a deeper understanding of the challenges related to sustainability and the SDGs (Durak and Topçu 2023), fostering empathy toward the affected communities (Boncukçu and Gök 2023). Furthermore, students became more aware of local environmental challenges such as water pollution and deforestation, gaining insights into how these issues connect to global goals (Figure 1).

Figure 1. Students collaborated to understand environmental problems by conducting research and engaging with local community data.

Figure 1 shows students from Group 1, Group 2, and Group 3 actively collaborating in this phase. The image captures them discussing community findings, reviewing data collected from interviews with residents, and mapping the environmental problems that are most urgent in their surroundings. This collaborative inquiry process not only increased their engagement but also reflected the real-world scientific practices of data gathering and problem analysis within a socio-environmental context.

2) Phase 2: Define

In this phase, participants worked in teams to clearly define the problems they wanted to solve, narrowing down the root causes of the environmental issues they had identified. This stage required them to critically analyze complex problems (Ericson 2022) and break them down into manageable components (Goldman and Zielezinski 2021). Students learned to frame challenges in a structured way, which led to a more focused approach to creating solutions. The act of defining specific problem statements enhanced their critical thinking and problem-solving skills.

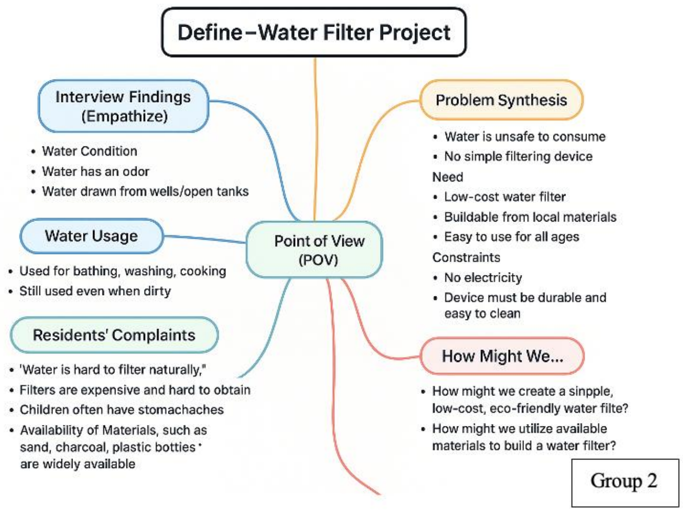

Figure 2. Student's mind map (representation of the Define Stage in the DT process for the Water Filter Project)

Students created a mind map (Figure 2) as a result of their qualitative data, which is obtained from interviews and observations during the Empathize phase. Moreover, it was systematically analyzed to identify key user needs and contextual challenges. The findings revealed that the community relied on murky and odorous water sources for daily activities such as cooking, bathing, and washing, despite the associated health risks. Participants also reported limited access to affordable and user-friendly water filtration tools. These insights were synthesized into a clear point of view (POV) statement: *"The villagers need a simple and affordable water filter that can improve water quality for daily use."* This problem definition served as a foundation for generating targeted "How Might We" (HMW) questions, such as: *"How might we design a low-cost, eco-friendly water filter using locally available materials?"*

The Define Phase is essential in articulating a human-centered problem statement, providing a structured direction for the subsequent ideation and prototyping stages. It ensures that the design process remained grounded in real-world needs, promoting the development of practical and contextually appropriate solutions.

3) Phase 3: Ideate

During the ideation phase, students generated a wide range of potential solutions through brainstorming sessions. This phase encouraged creative thinking (Trung et al. 2024), enabling participants to propose innovative ideas without immediate constraints (Gouseti et al. 2023). Students' creativity flourished as they explored diverse possibilities for solving sustainability challenges. This phase particularly boosted their ability to think outside the box (Kimbell 2011), with participants reporting an increased capacity for generating new ideas.

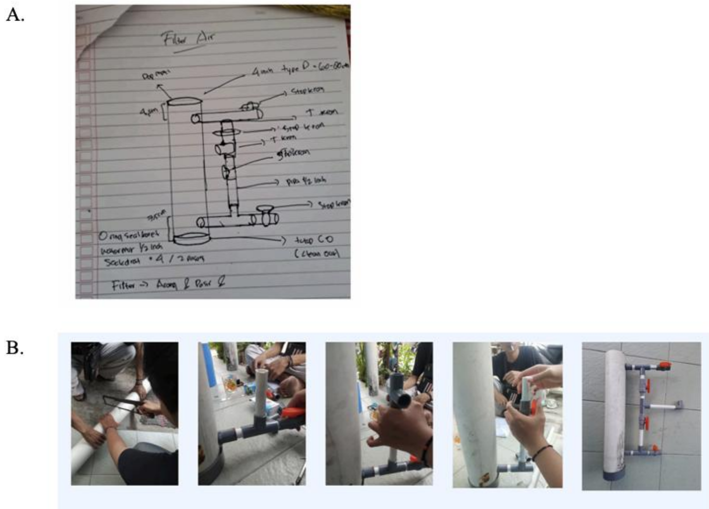

Figure 3. Students demonstrated significant growth in creative and practical problem-solving (A & B: student-designed water filtration systems).

During the ideation phase (Figure 3), students generated a wide range of potential solutions through brainstorming sessions, aligning with the creative divergence stage of the DT process (Miller and Krajcik 2019). This stage facilitated open-ended exploration (Fei 2024), where students were encouraged to think freely without immediate judgment, which is a condition proven to foster creativity (Goldman and Zielezinski 2016; Lee de Wet and Tselepis 2020; Wingard et al. 2022). Prior studies (Atchia et al. 2024; Blundell 2024) have demonstrated that such unconstrained ideation environments significantly enhance learners' creative self-efficacy, particularly when tackling real-world challenges like sustainability issues.

However, while existing research acknowledges the benefits of ideation in promoting creativity, **few studies** have explored how this phase operates **within an integrated STEM–DT framework focused on sustainability literacy at the secondary education level (Goldman and Zielezinski 2016; Trung et al. 2024).** Therefore, this study contributes to the field by providing empirical evidence on how structured ideation activities embedded in interdisciplinary STEM projects can foster not only creativity but also a deeper understanding of complex environmental problems. This fills a notable gap in the literature and offers a new pedagogical model for empowering students with both innovative thinking and sustainability competencies.

4) Phase 4: Prototype

In this phase, students developed prototypes of their ideas using readily available and recycled materials, as illustrated in **Figure 4.** This stage was highly practical, requiring them to transform their abstract ideas into tangible models or systems (Lin et al. 2021). Building prototypes helped students better understand the feasibility and limitations of their solutions (Matthews et al. 2023). It also improved their hands-on problem-solving abilities (Kijima, Yang-Yoshihara, and Maekawa 2021), with participants expressing newfound confidence in turning ideas into real-world applications.

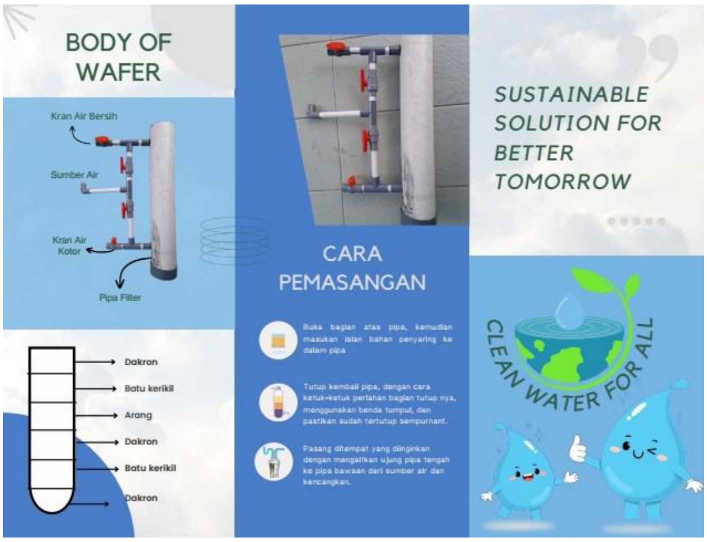

Figure 4. Students created physical prototypes of water filtration systems or sustainableagricultural models, using recycled materials.

5) Phase 5: Test

Finally, students tested their prototypes, presented them to their peers and instructors, and received feedback for further refinement. This phase involved an iterative cycle of improvements based on peer and instructor evaluations. The testing phase helped students refine their solutions, leading to more effective and innovative results. It also fostered resilience, as participants learned to accept constructive criticism and used it to enhance their work. In the *Test* Phase, iterative feedback loops promoted resilience and adaptability—key traits highlighted by Kijima et al. (2021) as central to 21st-century sustainability education.

This research adds to the body of empirical work by quantitatively measuring the impact of the DT approach on preservice teachers' creativity, problem-solving, and confidence. Unlike previous studies that relied on perception surveys alone, this study employed a paired-samples t-test (Table 1) to compare pre- and post-project competencies that revealing statistically significant gains across all measured dimensions. By these positions, the study is not merely an evaluation of a teaching activity, but an original empirical investigation that advances our understanding of how design-based pedagogy can concretely build sustainability competencies.

Overall impact of DT process significantly improved participants' skills in creative problem solving, as the ideation and prototyping phases helped unlock students' creativity and enhanced their ability to generate and develop innovative solutions. Critical thinking by empathizing and defining phases requires participants to delve into the root causes of sustainability challenges, fostering deeper critical analysis (Trung et al. 2024; Wingard et al. 2022). Student confidence in teaching was increased by going through the entire process. Starting from empathizing with local challenges to testing solutions, students gained confidence in their ability to teach sustainability concepts in engaging, hands-on ways.

The integration of the design thinking framework within the "Biology Education for Sustainability" course proved highly effective in enhancing preservice biology teachers' creativity, problem-solving, and sustainability teaching skills. Data from pre- and post-project surveys revealed a 25% increase in creative problem-solving skills, as students engaged in brainstorming, prototyping, and iterative feedback cycles.

Additionally, reflective journals indicated that 85% of participants felt more confident in addressing complex environmental issues after the course. By guiding students through the phases of empathizing, defining, ideating, prototyping, and testing, the project enabled them to tackle real-world environmental challenges related to the SDGs, such as clean water, climate action, and life on land. This hands-on approach deepened their understanding of sustainability, improved critical thinking, and boosted their confidence in teaching these concepts. Overall, the project demonstrated the potential of experiential learning and Design Thinking in preparing future educators to effectively address global environmental challenges and incorporate sustainability into their teaching practices.

To assess the impact on preservice biology teachers' creativity and problem-solving skills, a paired-samples t-test was conducted to compare the pre- and post-project results. The collected data from the surveys indicated significant improvements in both variables after the project. The following table summarizes the t-test results. It shows the changes in participants' creative problem-solving abilities, confidence in addressing complex issues, and understanding of the SDGs. All outcomes were statistically significant, indicating a meaningful enhancement in the participants' skills and understanding.

Table 1. Paired-Samples t-Test Results Comparing Pre- and Post-Project Scores on Creativity, Problem-Solving, and Understanding of SDGs.

Variable	Pre-Project Mean (SD)	Post-Project Mean (SD)	t-value	p-value	Significance
Creative Problem-Solving	60.3 (8.5)	75.4 (7.2)	5.62	0.001	Significant
Confidence in Addressing Complex Issues	58.7 (9.1)	80.5 (6.9)	6.34	0.001	Significant
Understanding of SDGs	65.2 (7.8)	83.0 (6.4)	6.01	0.001	Significant

The table highlights statistically significant improvements ($p < 0.05$) across all categories. It is demonstrating the positive effect of experiential learning through Design Thinking on participants' creative and problem-solving abilities, as well as their understanding of sustainability concepts.

Conclusion

The integration of the design thinking framework within the Biology Education for Sustainability course proved highly effective in enhancing preservice biology teachers' creativity, problem-solving, and sustainability teaching skills. By guiding students through thephases of empathizing, defining, ideating, prototyping, and testing, the project enabled them totackle real-world environmental challenges related to the SDGs, such as clean water, climate action, and life on land. This hands-on approach deepened their understanding of sustainability, improved critical thinking, and boosted their confidence in teaching these concepts. Overall, the project demonstrated the potential of experiential learning and Design Thinking in preparing future educators to effectively address global environmental challenges and incorporate sustainability into their teaching practices.

By integrating Design Thinking into a structured ESD course, this study demonstrates a replicable model for teacher education programs that aim to cultivate creative, critical, and sustainability-literate educators. It responds to calls in the literature for more action-oriented and transformative pedagogies and offers empirical evidence of their effectiveness in real classroom contexts. As such, the findings make a valuable contribution to both **theoretical discourse on sustainability education** and **practical frameworks for curriculum development** in science teacher training.

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