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Enhancing Biotechnology Learning Through PRA-Driven Hydroponic Technology

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ABSTRACT

This study aims to investigate the application of appropriate hydroponic technology as a learning tool in biotechnology education, focusing on its impact on students' theoretical understanding, practical skills, and collaborative abilities. The study employed socialization and mentoring based on Participatory Rural Appraisal (PRA) to actively involve students in the learning process. Data were collected through literature review and structured observations, then analyzed qualitatively to identify key outcomes and patterns. The results indicate that integrating hydroponic technology in biotechnology education effectively enhances students' comprehension of concepts while providing hands-on experience. Students demonstrated increased independence, improved peer collaboration, and the ability to implement environmentally friendly and efficient planting practices. Moreover, the approach facilitated the development of adaptive and sustainable problem-solving skills. These findings suggest that appropriate hydroponic technology can serve as an innovative and practical pedagogical tool in biotechnology education, fostering both cognitive and experiential learning. Future research is recommended to explore long-term impacts on student performance and to refine the integration of PRA-based methods in science curricula.

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INTRODUCTION

Technological advances have profoundly influenced human life, particularly in agriculture, where they have simplified daily activities and improved productivity (Bazargani & Deemyad, 2024; Chen, 2025). Agricultural technology, which encompasses the methods and techniques used to process inputs into useful outputs, has become increasingly critical for addressing food security and sustainable farming practices (Oliveira et al., 2025). Appropriate Technology emphasizes understanding local needs and resources to develop solutions that are practical, accessible, and environmentally friendly. By engaging communities in the design and implementation of technology, participatory approaches ensure relevance and acceptance, fostering sustainable solutions (Hernández-Ramos et al., 2021). In the context of education, introducing technological innovations can enhance students' understanding of science while equipping them with practical skills applicable in real-life agricultural practices. Therefore, integrating technologies such as hydroponics into learning is crucial. The combination of theoretical knowledge with hands-on applications allows students not only to learn concepts but also to contribute to sustainable practices (Malik & Zhu, 2023), ultimately addressing broader societal issues such as urban food production and environmental stewardship.

Despite the potential benefits of agricultural technologies, many communities and educational institutions face challenges in accessing and applying appropriate technologies effectively. Hydroponic farming, while offering high efficiency and sustainability, remains underutilized due to a lack of knowledge, resources, and practical training among students and teachers (Sánchez-García & Reyes-De-Cózar, 2025). Traditional soil-based agriculture often dominates curricula, limiting students' exposure to modern cultivation methods. Consequently, learners may lack essential skills for sustainable food production, and schools may fail to prepare students for contemporary agricultural challenges. Furthermore, urban areas with limited green space face constraints in promoting practical agricultural experiences. The need for adaptive and resource-efficient solutions highlights the importance of integrating technologies like hydroponics into educational programs (Lakhiar et al., 2025; Mahrous & Abd-Elkader, 2025). This study seeks to address this gap by exploring how appropriate hydroponic technology can enhance biotechnology education, providing students with both theoretical understanding and practical, hands-on learning opportunities, which is crucial for developing problem-solving and innovation skills.

Hydroponics, which allows plants to grow without soil using nutrient-rich water solutions, has emerged as a promising approach to sustainable agriculture. The method enables faster growth, higher yields, and efficient resource utilization, particularly in areas with limited arable land (Witjaksono et al., 2023; Azizah et al., 2023). Historically, hydroponics gained global recognition for high-tech agricultural applications and nutritional research, dating back to the 16th century, with modern developments expanding its use in urban environments. In Indonesia, Bob Sadino introduced hydroponic techniques to the public in 1980, initially popular among plant enthusiasts (Witjaksono et al., 2023). Today, hydroponics offers advantages such as easier maintenance, reduced labor, controlled growth conditions, and the possibility of cultivating plants out of season (Waluyo et al., 2021). In educational settings, hydroponics provides an interactive and engaging platform for students to observe biological processes, understand nutrient dynamics, and develop scientific thinking. Despite these benefits, many schools have yet to implement hydroponic systems systematically, limiting the potential for experiential learning in biotechnology education (Harfouche & Nakhle, 2020).

Previous research has highlighted the advantages of practical, technology-based learning approaches. Studies demonstrate that hands-on activities reduce verbalism, encourage active participation, enhance self-confidence, and foster critical and innovative thinking among students. Hydroponics, as a practical medium, has been shown to improve understanding of plant physiology, nutrient cycles, and sustainable cultivation methods (Yusril & Ramadhani, 2021). Moreover, integrating participatory methods such as PRA (Participatory Rural Appraisal) can increase student engagement and involvement in problem-solving activities, emphasizing students as active participants rather than passive learners. However, these studies often focus on technical outcomes or general educational benefits without fully exploring how combining hydroponics with participatory approaches can foster both cognitive and social learning in biotechnology. Additionally, research on hydroponic applications in school-based education is limited, particularly concerning adaptive and sustainable learning strategies tailored to local contexts.

While hydroponic techniques are well-documented in agricultural and nutritional studies, there remains a lack of research addressing their integration into biotechnology curricula in a systematic, participatory manner (Azizah et al., 2023; Waluyo et al., 2021). Previous studies often overlook student-centered approaches that combine technical practice with collaboration, problem-solving, and environmental consciousness. There is also limited evidence on how these methods impact students' independence, peer collaboration, and application of sustainable practices. This research aims to fill these gaps by exploring the effectiveness of appropriate hydroponic technology in promoting experiential learning in biotechnology education. By connecting practical hydroponic activities with participatory methods, the study contributes to understanding how technology can enhance both theoretical knowledge and applied skills, preparing students for sustainable agricultural practices while addressing the limitations of prior research (Ramdhani et al., 2024).

This study introduces a novel approach by combining hydroponic technology with Participatory Rural Appraisal in biotechnology education. Unlike previous studies that focus on either technology adoption or conventional hands-on learning, this research emphasizes student-centered, participatory learning, fostering independence, collaboration, and critical thinking. By applying appropriate technology principles, the study explores adaptive, resource-efficient, and environmentally friendly cultivation methods, which are crucial in addressing urban and resource-limited educational contexts. The approach also highlights the pedagogical benefits of integrating practical biotechnology education with sustainability and efficiency principles, creating a state-of-the-art model for modern science education that can serve as a reference for similar initiatives globally.

Based on the identified gaps, this study addresses the following research problem: How can the application of appropriate hydroponic technology, combined with participatory methods, enhance students' knowledge, practical skills, and collaborative competencies in biotechnology education? The study argues that integrating PRA-based hydroponics not only improves theoretical understanding but also promotes hands-on learning, independence, peer collaboration, and sustainable practices. By bridging technical cultivation techniques with participatory educational strategies, the research contributes to both pedagogy and applied biotechnology. The expected outcome is a replicable model for experiential learning that aligns with the principles of Appropriate Technology while addressing the challenges of limited resources, urban space, and student engagement in science education.

RESEARCH METHODS

This study employed a qualitative research design combining case study and literature review approaches. The case study approach was chosen to provide an in-depth understanding of the application of hydroponic technology in biotechnology education, while the literature review was conducted to explore existing knowledge on appropriate technology and its educational implications (Lai & Bower, (2020). The combination of these methods allows for both exploration and description, providing a comprehensive view of the phenomena under study. The qualitative approach was particularly suitable for capturing students' experiences, participation, and practical engagement with hydroponic systems, emphasizing their active role as subjects in the learning process rather than passive objects.

The research was conducted in an educational setting where hydroponic technology is applied in biotechnology learning (Khastini & Maryani, 2025). This location was selected due to its ongoing integration of appropriate hydroponic practices into the curriculum, allowing the researchers to observe real-life implementation and student engagement. Data collection techniques included a comprehensive literature review using scientific journals, articles, and books to provide a theoretical foundation, as well as structured interviews with teachers and students to obtain consistent and detailed information. The structured interview guide ensured that data collection covered relevant aspects of student participation, technology application, and learning outcomes.

Data analysis involved several stages, beginning with data coding and grouping to condense and reduce information into meaningful categories. The researchers then displayed the data systematically to identify patterns, relationships, and significant findings related to hydroponic technology in biotechnology education. Finally, data verification and interpretation were conducted by linking findings to relevant theories and concepts, allowing the researchers to provide a detailed description and explanation of appropriate hydroponic technology, its educational applications, and its benefits for student learning (Criollo-C et al., 2021). This systematic approach ensured the reliability and validity of the study's conclusions.

RESULTS AND DISCUSSION

Initially, students exhibited limited knowledge of appropriate technology and its application in biotechnology education. By incorporating hydroponic-based practical lessons, students were actively engaged in hands-on learning, which helped them understand theoretical concepts while developing practical skills (Oliveira et al., 2025). This finding aligns with previous studies showing that experiential learning enhances cognitive understanding, reduces verbalism, and promotes meaningful engagement with subject matter (González-Cortés et al., 2024). The integration of hydroponics into biotechnology lessons also fostered independence, critical thinking, and peer collaboration, emphasizing students as active participants rather than passive learners (Markula & Aksela, 2022). By applying participatory approaches, students were able to observe, manipulate, and analyze plant growth processes directly, bridging the gap between theory and practice in educational settings.

Figure 1. Seed Sowing Stage

Figure 1 illustrates the seed sowing stage, where students placed seeds into hydroponic growth media. This activity required precision, attention to detail, and collaborative work among students. The figure demonstrates how students were not only practicing technical skills but also engaging in observation and experimentation, reinforcing their understanding of plant physiology and nutrient absorption (Smith et al., 2022). The visual documentation of the seed sowing process highlights the hands-on learning element, providing evidence that hydroponics can be used as an effective tool for active student participation and skill development (Lavado-Anguera et al., 2024).

Figure 2. Hydroponic harvesting and packing

Figure 2 shows the hydroponic harvesting and packing process. Students were involved in retrieving mature plants, processing them carefully, and preparing them for further use or study. This stage emphasizes the efficiency, cleanliness, and organization inherent in hydroponic cultivation (Guo et al., 2020). It also demonstrates peer collaboration and the practical application of sustainable practices, such as careful handling and minimal waste. These observations confirm that hydroponics fosters both practical skill acquisition and social competencies, aligning with theoretical perspectives on participatory learning and Appropriate Technology principles (Sukacke et al., 2022).

The results of this study are consistent with literature indicating that hydroponics can accommodate a wide variety of plant species, including vegetables and ornamental plants (Yusril, 2021). Students successfully grew cabbage, lettuce, pak choi, and other crops in controlled hydroponic systems, which confirms the adaptability of the method in educational contexts (ref).

Unlike prior research focusing mainly on agronomic outcomes, this study demonstrates that hydroponics also provides educational benefits, including enhanced problem-solving, collaboration, and hands-on scientific inquiry (Meng et al., 2023). The theoretical implication is that combining practical cultivation with experiential pedagogy strengthens students' understanding of biotechnology concepts.

Although practical methods can face limitations, such as the need for specific equipment and unpredictable results (Papadopoulou et al., 2025), the hydroponic implementation in this study was cost-effective, feasible, and adaptable for classroom settings (Sánchez-García & Reyes-De-Cózar, 2025). By using affordable materials and reusing containers, students learned to apply principles of resource efficiency and sustainability, demonstrating how practical biotechnology education can be conducted even under constrained conditions (ref). These findings contribute to both theory and practice, showing that participatory, hands-on learning supports cognitive, social, and technical skill development.

The use of nutrient solutions further reinforced students' understanding of plant growth and hydroponic principles. Nutrients were selected based on solubility, contaminant-free quality, and their ability to provide multiple essential elements (Hernández-Ramos et al., 2021). Students' direct experience in preparing and applying nutrient solutions enhanced their comprehension of plant physiology and the role of nutrients in growth. This practical exposure demonstrates how hydroponic biotechnology education integrates technical competence with sustainability and efficiency principles, providing a model for effective experiential learning in schools (Jaganathan et al., 2024).

Overall, the study confirms that hydroponic biotechnology education enhances both theoretical knowledge and practical skills while fostering independence, collaboration, and environmental awareness. The activities allowed students to experience the entire cultivation process, from seed sowing to harvesting and packaging, providing a complete experiential learning cycle (Papadopoulou et al., 2025). By linking hands-on practice with participatory methods, the research contributes to the literature on educational technology, participatory learning, and sustainable agricultural practices, offering practical guidance for implementing hydroponics as a pedagogical tool in biotechnology curricula (Guo et al., 2020).

CONCLUSION

The study demonstrates that the application of appropriate hydroponic technology in biotechnology education significantly enhances students' theoretical understanding, practical skills, and collaborative abilities, highlighting the importance of hands-on, participatory learning for fostering independence, critical thinking, and sustainable practices. By integrating hydroponics with student-centered approaches, this research contributes to the scientific understanding of experiential learning in biotechnology, offering a practical model that bridges technical competence with environmental and efficiency principles. However, the study is limited by its focus on a single educational setting, which may affect the generalizability of the findings. Future research should explore the long-term impacts of hydroponic-based learning across diverse schools, investigate different crop types and cultivation systems, and assess measurable outcomes on students' problem-solving, innovation, and application of sustainability principles in broader educational contexts.

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