SEMARAK ILMU PUBLISHING

Semarak International Journal of STEM Education

Journal homepage: https://semarakilmu.my/index.php/sijste/index
ISSN: 3030-5152

Innovative STEM-based strategies for enhancing plant science education: a systematic literature review

Nordiana Md Khamis [1,*], Kamisah Osman[1] , Nurazidawati Mohamad Arsad[1], Muhammad Zulfadhli Kamarudin[2] , Norliza Ab Halim[3]

[1] STEM Enculturation Centre, Faculty of Education, Universiti Kebangsaan Malaysia,Selangor, Malaysia
[2] School of Education, Faculty of Social Science, University of Leeds, United Kingdom
[3] Kuala Kangsar Community College, Perak, Malaysia

ARTICLE INFO

Article history:
Received 27 January 2026
Received in revised form 19 February 2026
Accepted 23 April 2026
Available online 11 May 2026

Keywords:
STEM Education; Plant science education; Interdisciplinary learning; Educational strategies

ABSTRACT

The integration of innovative Science, Technology, Engineering and Mathematics (STEM)-based strategies in plant science education is increasingly recognized as vital for addressing contemporary educational challenges and global environmental issues. The complexity of plant science concepts, alongside the need to develop critical thinking, problem-solving, and sustainability-oriented competencies, highlights the importance of effective pedagogical approaches. This systematic literature review, guided by PRISMA framework, analyzed 50 empirical studies published between 2013 and 2024, retrived from Scopus and Web of Science. The review identifies key STEM-based stategies including technology-enhanced learning, experiental and inquirbased approaches, problem and project-based learning, collaborative methods and community engagement practices.Findings reveal three major contributions: (1) current trends and geographical distribution of plant science education research, (2) methodological patterns and dominant thematic areas, and (3) the transformative potential of STEM strategies in fostering deeper engagement and ecological literacy. Importantly, the review highlights significant research gaps in climate education, citizen science, and media-based pedagogy, offering directions for future work.

1. Introduction

In recent years, the swift progression of science and technology has mandated a fundamental shift in educational methodologies, particularly within the sphere of plant science education. As the world confronts urgent environmental challenges such as climate change, biodiversity loss, and food security, it has become increasingly imperative to equip students with the requisite knowledge and skills to comprehend and address these multifaceted issues [1]. Innovative Science, Technology, Engineering, and Mathematics (STEM) approaches offer the transformative potential to elevate plant science education by cultivating critical thinking, problem-solving, and interdisciplinary learning among students. Plant science, a discipline crucial to our understanding of life on Earth, spans a broad spectrum of topics, from plant physiology and genetics to

* *Corresponding author.*
E-mail address: nordianahlp2022@gmail.com

ecology and conservation [2]. Traditional pedagogical methods in plant science have often relied on rote memorization and passive learning, which can disengage students and fail to link theoretical knowledge with practical applications. In contrast, STEM-based strategies emphasize active learning, hands-on experimentation, and the integration of technology, rendering the study of plants more engaging and pertinent to students' lives. These strategies not only enhance students' comprehension of plant science concepts but also kindle a sense of curiosity and stewardship toward the natural world [3], [4].

A significant advantage of integrating STEM in plant science education is its capacity to promote interdisciplinary learning. By amalgamating principles from various scientific disciplines, students attain a comprehensive understanding of plant systems and their environmental interactions. For example, the study of plant genetics can be enriched by incorporating bioinformatics tools. In contrast, ecological studies can benefit from the use of Geographic Information Systems (GIS) to analyze spatial data. This interdisciplinary approach mirrors the intricacy of real-world problems, preparing students to think critically and innovatively [5]. Moreover, the utilization of technology in STEM-based plant science education plays a crucial role in enhancing learning outcomes. Technologies such as remote sensing, digital microscopy, and data analytics provide students with access to advanced tools and methodologies, enabling them to conduct sophisticated experiments and analyses. Virtual labs and online platforms also offer interactive learning opportunities, allowing students to explore plant biology in a simulated environment. These technological interventions make learning more accessible and engaging and also equip students with the technical skills required in contemporary scientific research and industry [6], [7], [8].

The integration of STEM-based methodologies in plant science education has the potential to significantly enhance diversity and inclusivity within STEM disciplines. By providing a rich tapestry of educational experiences, educators can foster an inviting atmosphere that inspires students from all backgrounds to embark on careers in plant science and allied fields. In essence, the implementation of cutting-edge STEM approaches in plant science pedagogy yields multifaceted improvements in student engagement and comprehension. As we endeavor to cultivate the next generation of scientific minds and environmental stewards, it is imperative that we embrace these innovative instructional paradigms. Such practices will ensure that botanical education remains not only relevant and dynamic but also profoundly impactful for generations to come. This systematic literature review is guided by two (2) research questions. These questions will focus on examining specific aspects of STEM-based strategies in plant science education. Thus, the systematic review presented in this article focuses on answering the following research question:

What are the current state and trends of educational research in the plant science education area?

The sub-objectives are then to find answers to the following questions:

What is the geographical distribution of research activity in plant science education?

What research methods were used?

What are the specific topics addressed in the plant science studies?

What are the innovative STEM-based strategies for enhancing plant science education?

These questions will be instrumental in directing the review's methodology, including the selection of relevant studies, data extraction, and the analytical framework employed to synthesize findings. They will ensure that the review comprehensively addresses the intersection of STEM education and environmental sustainability with a focus on plant science education.

2. Literature Review

Integrating STEM-based strategies into plant science education has demonstrated significant promise in enhancing student engagement, comprehension, and practical skills. A notable example is the study by [9], which emphasizes the role of experimental protocols involving photopigments and phycobiliproteins in biotechnological education. These protocols, developed for use with micro and macroalgae, provide students with hands-on experience that aligns with the Sustainable Development Goals (SDGs), particularly in relation to climate change and sustainable food systems. This innovative approach bridges theoretical knowledge and practical applications and also introduces students to the biotechnological implications of plant science, thereby fostering a deeper understanding and appreciation of the subject. In another study, [10] explored the impact of urban parks on preschool children's environmental perceptions. Their research highlighted the multifaceted dimensions of children's experiences in urban green spaces, encompassing physical, social, and affective aspects. Using walking interviews and thematic analysis, the study provided insights into how urban nature spaces can be effectively integrated into early childhood education to promote environmental awareness and literacy. This underscores the importance of experiential learning in natural settings as a means to enhance environmental education from a young age.

Further supporting the integration of sustainability into education, [11] examined the implementation of sustainable principles in kindergartens. Their findings revealed that children enrolled in ecological programs had a greater understanding of sustainability topics compared to those in language-focused programs. This study suggests that incorporating sustainability education at an early age can lay a strong foundation for future environmental stewardship and highlights the need for such topics to be embedded in early childhood curricula. Another innovative approach is discussed by [12], who developed an Artificial Intelligence of Things (AIoT) system for educational purposes. Their research showcased how AIoT can enhance learning experiences by providing real-time feedback on environmental conditions and student interactions with plant ecosystems. The use of smart dashboards and monitoring systems improves the learning environment and also engages students in interactive and data-driven educational activities. [13] explored the role of ecopedagogy in integrating chemistry, urban environments, and soil conservation into education. Their interdisciplinary approach aimed to challenge preconceived notions about urbanization and synthetic chemistry's impact on soil degradation. By conducting hands-on educational activities, the study demonstrated how scientific knowledge and practical skills can be combined to foster environmental consciousness and promote sustainable practices among students.

On the other hand, [14] developed a web application for observing flowering phenology, which proved effective in climate-related learning for elementary students. The use of time-lapse digital images to track seasonal changes in cherry blossoms helped students connect local environmental phenomena with broader climate change concepts. This participatory approach utilizing digital technology enhances students' understanding of environmental science and its real-world applications. In exploring the concept of "green schools, [15] assessed the integration of sustainability in European and Kazakhstani educational institutions. Their research highlighted the psychological aspects of environmental education and the importance of creating ecologically literate and culturally aware students. The study's findings emphasized the need for continuous environmental education throughout different educational stages to achieve meaningful and lasting impacts on students' environmental behaviors and attitudes. The role of free-choice learning environments in early childhood education was examined by [16]. Their study on plant diversity learning environments demonstrated how social and material interactions influence children's achievement of learning objectives. This research provides valuable guidelines for designing effective educational settings that encourage active engagement and intentional learning in young children.

Finally, [17] conducted a qualitative investigation on the impact of kitchen garden programs on grade 4 students' connection to nature and the development of ecoliteracy. The study discovered that regular interaction with the garden enhanced students' familiarity with and empathy for living organisms, fostering a deeper interest in the natural environment. This research underscores the importance of immersive, transdisciplinary learning experiences in cultivating environmental awareness and responsibility among young students.

3. Material and methods

3.1 Identification

The systematic review approach employed in this research comprised three distinct phases, each pivotal for the selection of pertinent literature. The initial phase focused on the identification of appropriate keywords. This was accomplished by utilizing resources such as thesauri, dictionaries, encyclopedias, and existing scholarly works to formulate comprehensive search strings. Subsequently, these search strings were applied to databases, including Scopus and Web of Science (WoS), as detailed in Table 1, ensuring a thorough retrieval of relevant keywords. This meticulous keyword selection process during the first stage of the systematic review yielded a total of 1586 papers from the aforementioned databases, contributing significantly to the body of literature analyzed in this study.

Table 1
Search string for Scopus and WoS

Scopus	TITLE-ABS-KEY (("environment* education" OR "science education" OR "STEM education" OR "nature based learn*") AND ("intervention" OR "strateg*" OR "approach" OR "program" OR "method") AND ("plant" OR "vegetat*" OR "flora" OR "green" OR "school garden")) Date of Access: July 2024
WoS	TS= ((“environmental education" OR "science education" OR "STEM education" OR "nature based learning") AND ("intervention" OR "strategy" OR "approach" OR "program" OR "method") AND ("plant" OR "vegetatation" OR "flora" OR "green" OR "school garden")) Date of Access: July 2024

3.2 Screening

During the screening phase, retrieved records were rigorously assessed for alignment with the research objectives. Content-specific criteria prioritized studies relevant to plant science and environmental education, while duplicate entries were removed. A total of 769 publications were excluded for irrelevance, duplication, or limited empirical focus. In the eligibility phase, 817 articles were evaluated against inclusion and exclusion criteria (Table 2). The review emphasized empirical research, excluding reviews, meta-syntheses, book chapters, and proceedings unless recent. Only English-language works published between 2014–2024 were considered. After eliminating 20 further duplicates, 50 studies fulfilled the criteria, forming the empirical basis of analysis.

Table 2
The selection criterion of searching

Criterion	Inclusion	Exclusion
Language	English	Non-English
Timeline	2013 – 2024	< 2013
Literature type	Journal (Article)	Conference, Review, Book, and proceeding
Publication Stage	Final	In Press

3.3 Eligibility

Following the PRISMA protocol, a total of 749 records were screened for eligibility. Titles, abstracts, and full texts were assessed against the inclusion criteria, leading to the exclusion of 699 studies that did not align with the review objectives. Ultimately, 50 articles met the eligibility requirements and were retained for full analysis (Figure 1). These studies constitute the empirical foundation of the review and underpin the synthesis presented in the findings.

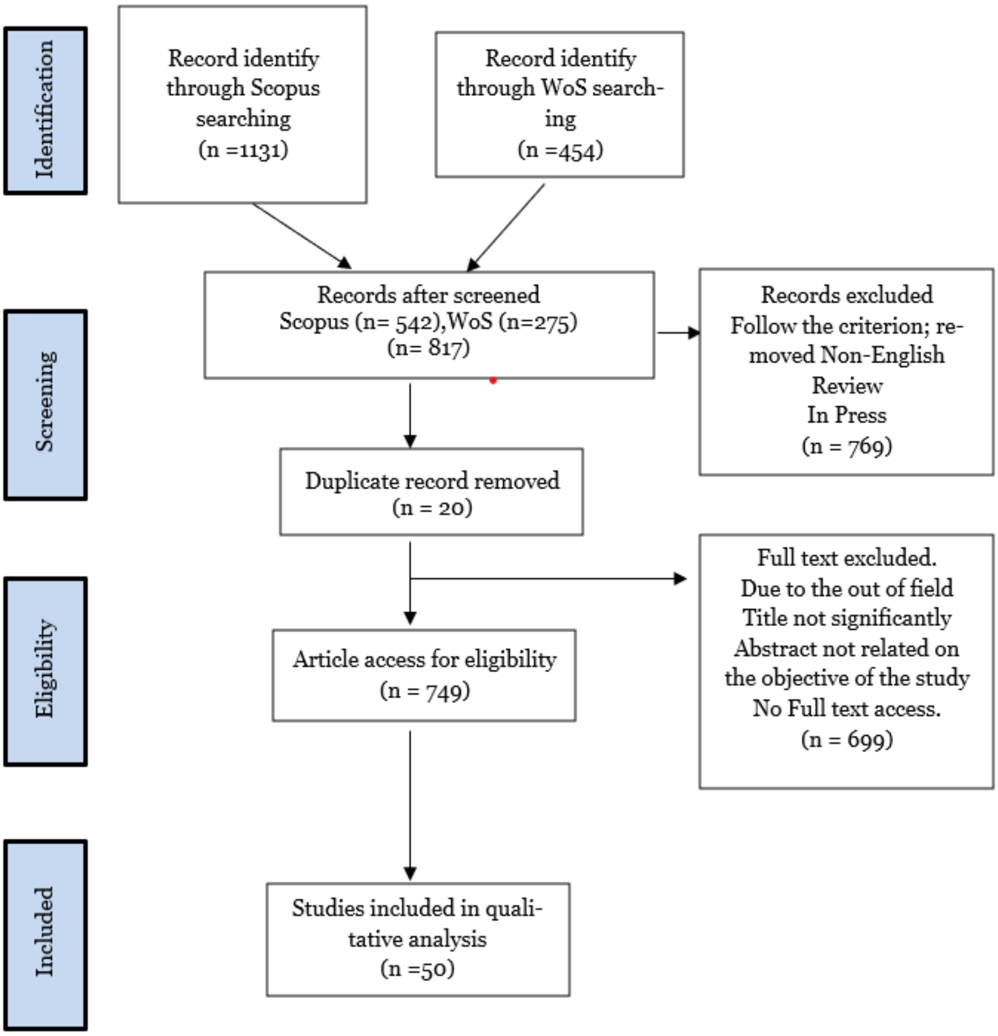

Fig. 1. Flow diagram of the proposed searching study [18], [19]

3.4 Data abstraction and analysis

This study employed an integrative analysis to evaluate and synthesize diverse research methodologies, including quantitative, qualitative, and mixed-methods approaches. The goal was to identify relevant themes and subthemes within the data. As shown in Figure 2, 50 selected publications were systematically reviewed for assertions and content related to plant science education. The analysis involved examining methodologies and findings, from which evidence-based themes were developed collaboratively among the authors. A log was maintained to track insights and facilitate interpretation. Finally, a comparative analysis was conducted to resolve discrepancies, and the themes were refined to ensure coherence and consistency across the findings. To validate the appropriateness of each subtheme, domain validity was established through the expert review by two specialists: one in plant science education and the other in STEM education, thereby reinforcing the methodological rigor and relevance of the derived themes.

4. Result

This section will delineate the principal outcomes gleaned from scrutinizing the selected publications. We commence with a synopsis of the findings from our quantitative descriptive analysis. The ensuing segments will explore the results of our qualitative evaluation, focusing on the essence and seminal discoveries within the analyzed articles.

4.1 State and trends of educational research

The field of plant science education has significantly transformed over the past decade, reflecting shifts in educational research priorities and global challenges, as charted in Figure 2.

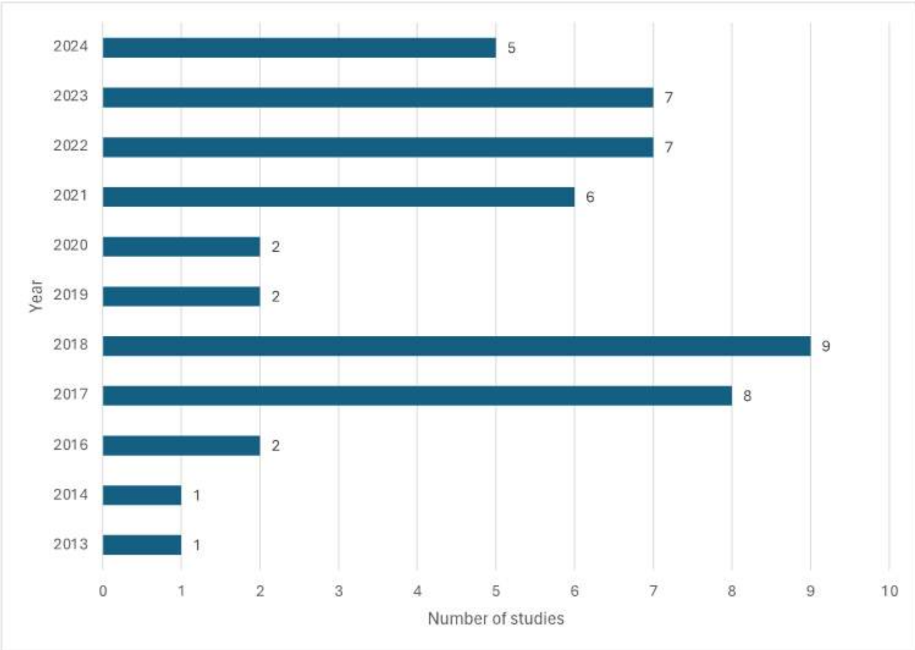

Fig. 2. The chart illustrates the yearly distribution of studies from 2013 to 2024

The chart in Figure 2 illustrates the yearly distribution of studies from 2013 to 2024, highlighting the research activity in plant science education over this period. In the earlier years, 2013 and 2014, there was minimal research activity, with only one study each, indicating either a nascent stage of development or different research priorities. Activity increased significantly in 2017 and 2018, with eight and nine studies, respectively, marking these years as peaks of interest and engagement in the field. Research output remained stable but lower in 2019 and 2020, each with two studies. The notable dip in 2020 can likely be attributed to the impact of the COVID-19 pandemic, which disrupted many research activities worldwide [20]. However, the subsequent years showed a resurgence in research, with 2021 recording six studies. This upward trend continued into 2022 and 2023, each with seven studies, reflecting a robust and sustained interest in plant science education. The year 2024, with five studies, maintains this trend of significant research activity, indicating ongoing engagement and investigation in the field. Overall, the data reveals a dynamic and evolving landscape in plant science education research, with periods of high activity over the years.

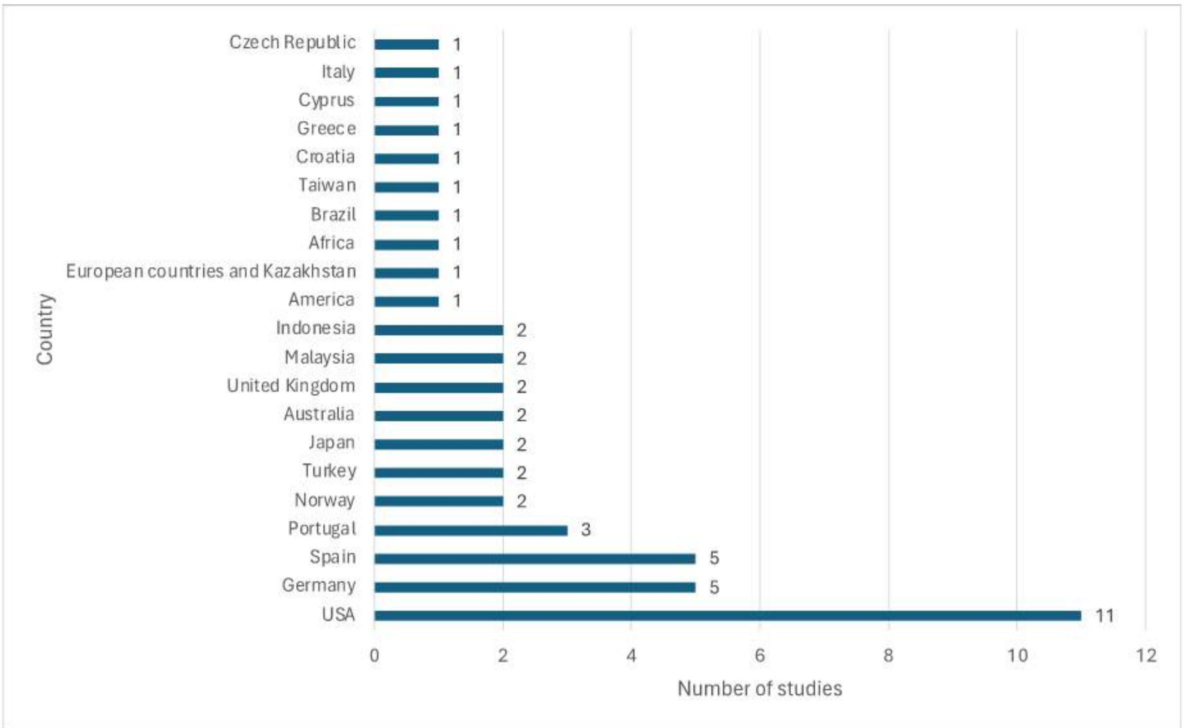

Fig. 3. The chart illustrates the geographical distribution of studies in plant science education across various countries

The chart in Figure 3 illustrates the geographical distribution of studies in plant science education across various countries. The United States leads significantly with 11 studies, highlighting a strong focus on this field. Germany and Spain follow, each contributing 5 studies, indicating notable research activity. Portugal has 3 studies, while Indonesia, Malaysia, the United Kingdom, Australia, Japan, Turkey, and Norway each have 2 studies, showing a moderate level of engagement. Several countries, including the Czech Republic, Italy, Cyprus, Greece, Croatia, Taiwan, Brazil, African nations, European countries, Kazakhstan, and America, each contributed 1 study, suggesting emerging interest or limited research activity in these regions. The diverse international representation in plant science education research underscores the global recognition of its importance. This widespread engagement highlights a shared understanding of the critical role plant science plays in addressing global challenges such as food security, climate change, and biodiversity conservation. The varying research intensity across different regions implies that while some countries lead in producing substantial research outputs, others are beginning to realize the field's potential and are increasing their contributions. This global diversity in research activities fosters a more comprehensive and inclusive understanding of plant science education, promoting innovative solutions and collaborative efforts to enhance educational practices worldwide. The implications for the future are significant, suggesting that as more countries invest in plant science education research, there will be a broader exchange of ideas and methodologies, ultimately leading to more effective and globally relevant educational strategies.

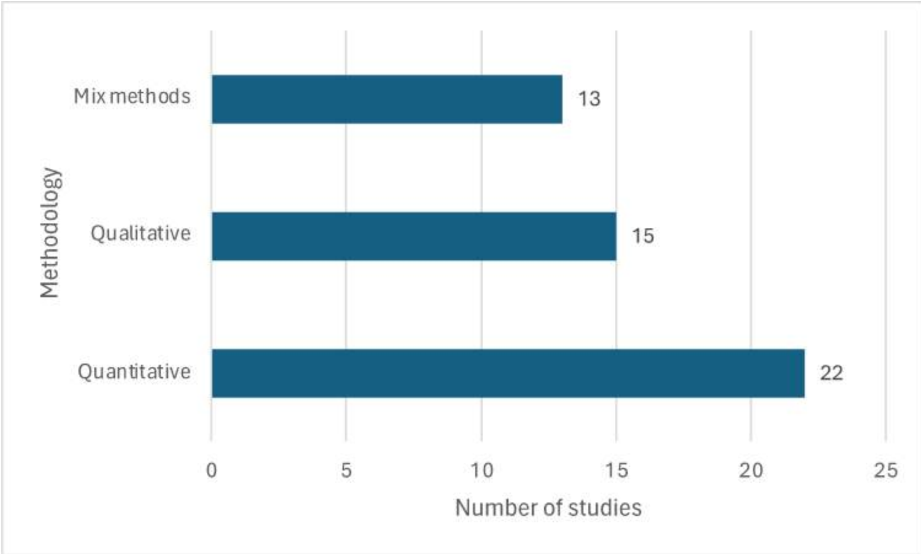

Fig.4. The chart presents the distribution of research methodologies employed in plant science education studies

The chart in Figure 4 presents the distribution of research methodologies employed in plant science education studies. Quantitative methods dominate, accounting for 22 studies, highlighting a preference for numerical data and statistical analysis in this field. Qualitative methods are also well-represented, with 15 studies focusing on non-numerical data and thematic analysis to explore experiences and perceptions. Mixed methods, which combine both quantitative and qualitative approaches, are used in 13 studies, reflecting a balanced approach to capturing comprehensive insights. This distribution underscores the diverse methodological approaches in plant science education research, emphasizing the value of both numerical data and in-depth qualitative insights to advance understanding in the field. The chart illustrates the distribution of research studies in plant science education across different educational levels.

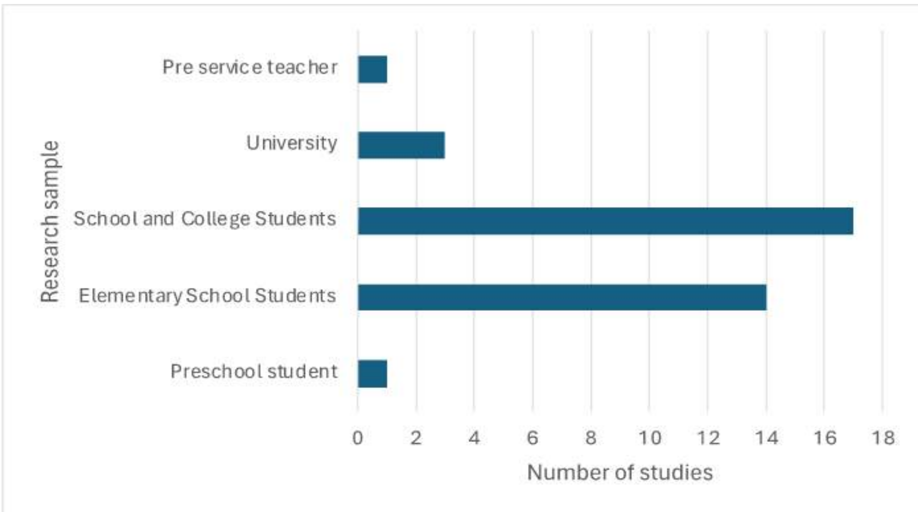

Fig.5. The distribution of research studies in plant science education across different educational levels.

The chart in Figure 5 illustrates the distribution of research studies in plant science education across different educational levels. The majority of studies focus on school and college students, with 16 studies indicating a significant emphasis on this demographic. Elementary school students are also a major focus, with 14 studies highlighting the importance of early education in plant sciences. University-level studies are less prevalent, totaling 4, while preschool students and pre-service teachers are the least studied groups, with 2 and 1 study, respectively. This distribution underscores the prioritization of middle to high school education in plant science research, reflecting an effort to engage students during critical learning phases.

4.2 Content Analysis

As illustrated in Table 3, the reviewed studies span several educational categories that collectively shape the field of plant science and environmental education. The largest proportion of research emphasizes experiential and inquiry-based learning (n=18), highlighting the value of school gardens, outdoor biodiversity projects, and authentic fieldwork in promoting engagement, critical thinking, and ecological responsibility. Another substantial cluster of studies is situated within environmental and sustainability education (n=12), focusing on the integration of green practices, ecoliteracy, and sustainable development goals into formal curricula.

Table 3
Overview of Educational Categories and Related Articles in STEM and Environmental Education

Category	Content (Examples from Articles)	Number of Articles Related
Environmental and Sustainability Education	Urban parks, school gardens, sustainability, ecoliteracy, eco-media, SDGs, environmental values, conservation	18
Plant and Botany Education	Plant biology, species identification, biodiversity, plant awareness, botanic gardens, hydroponics, ecological restoration, kitchen gardens	14
STEM and Science Education	Inquiry-based learning, science process skills, geoscience education, game-based learning, biotechnology (algae, photosynthesis, dyes), E-STEM pathways	10
Technology-Enhanced Learning in STEM/EE	Augmented reality, AI/IoT, digital tools, mobile applications, tablet-based learning, web-based inquiry, virtual vs in-person	9
Early Childhood and Primary Education	Preschool children, kindergarten sustainability, early childhood plant diversity, elementary science, children's drawings, family involvement	9
Community, Culture and Informal Education	Informal eco-media, cultural heritage (Maya, Indonesia), citizen science, summer camps, eco-attractions, social gardens, , community-based education	8
Higher and Teacher Education	Teacher self-efficacy, higher education nature-based learning, SciLG program (minority groups), professional development	5
Climate Education	Phenology and web applications, digitalization for climate adaptation	3

Technology-enhanced learning emerges as a rapidly growing area (n=12), with studies exploring the application of augmented reality, mobile tools, and AI/IoT to strengthen inquiry and collaboration in plant-related education. Research on community-based and informal education (n=9) demonstrates the role of citizen science, cultural heritage initiatives, and informal programs such as summer camps in fostering environmental awareness beyond classroom settings. Meanwhile, early childhood and primary education (n=4) and higher and teacher education (n=5) receive comparatively less attention, though they underscore the importance of early engagement with biodiversity as well as teacher preparation and professional development.

Notably, only a small subset of the reviewed articles explicitly foreground climate education (n=2), despite the critical role of plants in both mitigation and adaptation processes. This underrepresentation suggests that while plant science education is being enriched through experiential, technological, and community-oriented approaches, its integration with climate literacy remains limited. This gap highlights an urgent need for interdisciplinary efforts that more directly connect plant-focused curricula with climate change education, particularly in early schooling where foundational scientific understanding and pro-environmental attitudes are shaped.

4.3 STEM based strategies in plant science education

STEM-based strategies in plant science education encompass diverse approaches designed to enhance engagement and learning outcomes. These include technology integration, experiential and inquiry-based methods, problem-based and collaborative learning, as well as multidisciplinary and community-oriented approaches. Each strategy contributes distinctively, from leveraging digital tools to fostering hands-on practice and social learning. A structured synthesis of these strategies, with supporting examples, is presented in Tables 4–8 :

i) Technology Integrated Learning

Table 4
Technology-Integrated Learning Strategies and Their Characteristics in Environmental and Science Education

Category	Strategy	Characteristic of Strategy	Author
Technology-Integrated Learning	AIoT system implementation	• Provides real-time feedback on environmental conditions using smart dashboards	[12]
	Computer game	• Educational computer game (Ecoship Endeavour) based on ICMDCR framework • A digital game-based learning method to improve female students' critical thinking skills in elementary science	[21]
	Mobile application	• LOVE2GreenMY" mobile app for environmental education in Malaysian schools	[22]
		• Plant-O-Matic, a free iOS plant species identification • The app also offers additional species information like growth form, reproductive mode, flower color, and common name when available.	[23]
	Web application	• Web application for cherry blossom observation • Uses digital technology for phenological observations in climate education	[14]
		• Web-based inquiry (BearCam, Virtual Ecological Inquiry) • Web-based inquiry projects engage learners and enhance investigative practices in science education.	[24]
	Digital Tools	• ID- Logics tool for species identification • The ID-Logics tool has advantages in terms of enjoyment and learning about individual characteristics of plants.	[25]
		• Garden TOOLS program • Integrates technology into garden-based STEM learning, and improves teacher self-efficacy.	[26]
		• DPaCK-Model is useful for analyzing student projects from a subject didactic perspective.	[27]
	Augmented Reality (AR)	• Development of AR-based Interactive Learning Media through the Assemblr EDU application to increase interest in environmental education.	[28]

		• AR application for the ecological tour. Students adapted to learning with technology combined with traditional methods.	[29]
	Use of tablets and applications for content delivery	• Tablets in education. Results from the initiative ETiE, for teaching plants to primary school students	[30]

i) Experiential and Inquiry-Based Learning

Table 5
Experiential and Inquiry-Based Learning Strategies and Their Characteristics in Environmental Education

Category	Strategy	Characteristic of Strategy	Author
Experiential Learning	Exploration of urban park experiences	• Exploration of urban park experiences • Verbal expression of nature concepts	[10] [31]
	Nature-based learning	• Nature and outdoor learning	[32]
	Experiment	• At-home plant biology experiments • Simplifying the execution of experiments in educational settings	[33] [9]
	Year-long kitchen garden program	• Enhances ecoliteracy through year-long gardening activities	[17]
	School kitchen-garden project	• Hands-on gardening projects in schools	[34]
	Urban vegetable gardening, composting, workshops Social or community gardening	• Practical urban gardening with composting techniques • Combines gardening with social and community engagement	[35]
	Phenological observations	• Engages students in phenological studies to observe seasonal changes	[14]
	Free-choice learning environment on plant diversity	• Social and material interactions influencing children's learning	[16]
	Drawing activities	• Children's drawings reveal their perception of local biodiversity and limited understanding of the environment as a system based on analysis of natural, geological, and anthropic elements depicted	[36]
		• Children depict plants in their drawings, focusing on color choices to gain insights about plants	[37]
	Horticultural curriculum, summer camps	• Uses summer camps for horticultural education	[38]
	Eco-attraction-based education	• Uses eco-attractions for experiential learning	[39]
	Outdoor activity, inquiry-based activity, authentic field methods	• Uses inquiry-based methods to measure plant biodiversity	[40] [41]

	Coastal Roots Program, tree-ring science integration	• Integrates tree-ring science into environmental education programs	[42]
	Uses school gardens to facilitate inquiry-based learning	• School gardens as milieu for learning, aligned with Next Generation Science Standards	[43]

ii) Problem-Based, Collaborative, and Cooperative Learning

Table 6
Problem-Based, Collaborative, and Cooperative Learning Strategies and Their Characteristics in Environmental Education

Category	Strategy	Characteristic of Strategy	Author
Collaborative Learning	Integration of local values in environmental education curriculum.	• Evaluates sustainability understanding in kindergartens • Collaborative activities like planting gardens, recycling projects, and group discussions about the environment	[11]
		• Incorporates local cultural values into environmental education	[44]
		• Collaborative project and encompassed several activities and subjects, including garden creation, plant propagation and plant care, plant identification, the study of form function relationships, and lectures by plant researchers.	[45]
Cooperative Learning	Cooperative learning-based science education program with family involvement	• Engages families in cooperative science learning activities	[46]
	Environmental education with psychological methods	• The cooperative element between different educational institutions, sharing best practices, resources, and methodologies to achieve the goal of becoming "green schools”.	[15]
Problem-Based Learning	Simplifying the execution of experiments in educational settings	• Develops simplified protocols for conducting plant science experiments	[9]
	Kitchen gardens, ecoliteracy, transdisciplinary learning	• Enhances ecoliteracy through transdisciplinary learning	[17]
	Evaluation of species literacy, especially regarding local flora and fauna	• Assesses species literacy through interactive learning	[13]

iii) Mixed Methods and Multidisciplinary Approaches

Table 7
Mixed Methods and Multidisciplinary Approaches in Environmental Education: Strategies and Characteristics

Category	Strategy	Characteristic of Strategy	Author
Mixed Methods	Surveys, interviews, observations, concept mapping	• Utilizes concept mapping alongside traditional surveys and interviews	[13]
	Digital tools, plant identification	• Combines traditional and digital tools for species identification	[25]
	In-person and virtual nature-based environmental education	• Compares virtual and in-person nature-based learning experiences	[47]
	Drawing analysis, written questions, interviews	• Uses children's drawings and interviews to analyze perceptions	[16] [48]
	At-home plant biology experiments	• Simplifies plant biology experiments for remote learning	[17]
	Tree-ring research, geoscience education, fieldwork	• Integrates fieldwork and geoscience education	[42]
	AI, IoT, smart learning environments, environmental education	• Combines AI and IoT for smart learning environments	[12]

iv) Community Engagement and Social Learning

Table 8
Community Engagement and Social Learning Strategies in Environmental Education: Methods and Characteristics

Category	Strategy	Characteristic of Strategy	Author
Community Engagement	Urban vegetable gardening, composting, workshops, and community engagement	• Practical urban gardening with composting techniques	[35]
		• Focuses on sustainable resource use and community engagement	[49]
	The social garden	• Social or community gardening	[50]
	Citizen science	• Uses citizen science and international collaboration for phenological studies	[51]
	Environmental media	• Uses animated children's television programs and transmedia for environmental education	[52]
	Heritage curriculum	• Develops curricula based on cultural heritage and environmental education	[53]

By implementing these varied approaches, educators can create a more comprehensive and effective learning environment that addresses the multifaceted nature of plant science and its relevance to broader STEM fields.

5. Discussion

The systematic literature review on innovative STEM-based strategies for enhancing plant science education reveals numerous promising approaches and areas for future development. Environmental education in urban green spaces and garden-based learning emerge as significant focal points, with recommendations to incorporate these concepts into mandatory curricula. Technology integration, particularly augmented reality and digital tools, stands out as a crucial area for further research and implementation in environmental and science education. The importance of hands-on activities, fieldwork, and laboratory experiments is emphasized, especially in the context of teaching about environmental policies and conservation. Hence, improving teacher training in science education and botany is highlighted, along with the need for comprehensive guidelines for designing and evaluating learning environments, particularly in early childhood education. The review points to the necessity of addressing individual understanding of nature, incorporating animals and plants in higher education curricula, and promoting social justice through environmental education. Cooperative learning involving families, especially in preschool education, is suggested as an area for further exploration. The use of games, mobile applications, and web-based inquiry projects for biodiversity education is recommended for expansion. The long-term impacts of experiential environmental education on youth perceptions and actions regarding ecological crises require additional investigation. Consequently, the potential of social gardens and botanic gardens as educational tools is highlighted, with suggestions to explore their broader social impacts. The document also emphasizes the need for developing more at-home DIY experiments for remote teaching situations and improving initial teacher training in science education. Specific thematic topics such as overcoming environmental pollution, preventing global warming, and promoting wise use of flora and fauna are suggested for inclusion in educational programs. The integration of environmental education with psychology in a continuous educational process is proposed, along with guidelines for teaching digital literacy and further implementation of Education for Sustainable Development (ESD). The review also recommends examining instructional benefits across diverse learner groups and using tools like the GREEN Tool to operationalize school gardening components.

6. Conclusion

The comprehensive review of innovative STEM-based strategies for enhancing plant science education underscores the need for a multifaceted and integrated approach. Future research and educational practices should focus on seamlessly incorporating environmental education into mainstream curricula, leveraging technology for enhanced learning experiences, and promoting hands-on, experiential learning. Therefore, improving teacher training, developing comprehensive guidelines, and addressing individual understanding of nature are crucial steps for advancing plant science education. The review emphasizes the importance of interdisciplinary approaches, community involvement, and long-term impact assessment in shaping effective educational strategies. By implementing these recommendations, educators and policymakers can work towards creating more engaging, effective, and environmentally conscious plant science education programs that prepare students for the ecological challenges of the future. The focus on technology integration, particularly AR and digital tools, reflects the need to adapt educational methods to contemporary technological advancements while maintaining a strong connection to practical, hands-on learning experiences. Overall, these suggestions aim to foster a deeper understanding of plant science and environmental issues among students, potentially leading to increased ecological awareness and stewardship in future generations. The emphasis on diverse learning environments, family involvement, and social justice aspects of environmental education suggests a holistic approach to science education that goes beyond traditional classroom boundaries.

Acknowledgement
This research was funded by any grant.

Conflict of Interest Statement
The authors declare that there is no conflict of interest regarding the publication of this paper. No financial support, grants, or other forms of compensation were received that could have influenced the outcomes of this work. The research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Author Contributions Statement
Kamisah Osman and Nurazidawati conceptualized and designed the study, supervised the project, and reviewed the manuscript. Nordiana conducted data analysis, contributed to data interpretation and wrote the initial draft of the manuscript. Zulfadhli and Norliza contributed to manuscript revision, read, and approved the final version.

References

[1] Harper, R. *Toward Climate-Smart Education Systems: A 7-Dimension Framework for Action*. Washington, DC: Global Partnership for Education, 2023.

[2] Iriart, V., N. J. Forrester, T. L. Ashman, and S. E. Kuebbing. "The Plant Science Blogging Project: A Curriculum to Develop Student Science Communication Skills." *Plants People Planet* 4, no. 5 (2022): 485–498. https://doi.org/10.1002/ppp3.10287.

[3] Quave, C. L. *Innovative Strategies for Teaching in the Plant Sciences*. New York: Springer, 2014. https://doi.org/10.1007/978-1-4939-0422-8.

[4] Watson, J., S. Wright, N. Fitzallen, and B. Kelly. "Consolidating Understanding of Variation as Part of STEM: Experimenting with Plant Growth." *Mathematics Education Research Journal* 35, no. 4 (2023): 961–999. https://doi.org/10.1007/s13394-022-00421-1.

[5] Novo, A., I. Garrido, H. Lorenzo, and P. Arias. "Use of Geographic Information Systems (GIS) in Higher Education: Practical Geomatics Applications with Quantum GIS Software." In *2022 International Symposium on Computers in Education (SIIE)*, 1–6, 2022. https://doi.org/10.1109/SIIE56031.2022.9982364.

[6] Al Arefi, S. M. S. "Blended Learning for Remote Software Simulation Laboratory of a Solar Power System." In *47th Annual Conference of the IEEE Industrial Electronics Society*, 1–6, 2021. https://doi.org/10.1109/IECON48115.2021.9589652.

[7] Dudar, T. V., T. V. Saienko, M. M. Radomska, M. S. Lubsky, A. A. Yavniuk, V. V. Rozhko, and A. Y. Hay. "Innovation and Digitalization in Environmental Education: The Case Study of Climate Change Adaptation and Analysis of Land Surface Temperature." *Journal of Geology, Geography and Geoecology* 32, no. 4 (2024): 724–733. https://doi.org/10.15421/112363.

[8] Sypsas, A., and D. Kalles. "Virtual Laboratories in Biology, Biotechnology and Chemistry Education: A Literature Review." In *Proceedings of the 22nd Pan-Hellenic Conference on Informatics*, 70–75. New York: ACM, 2018. https://doi.org/10.1145/3291533.3291560.

[9] Geuer, L., N. Erdmann, M. Lorenz, H. Albrecht, T. Schanne, M. Cwienczek, D. Geib, D. Strieth, and R. Ulber. "Colorful Diversity: Modified Methods for Extraction and Quantification of Photopigments and Phycobiliproteins Isolated from Phototrophic Micro- and Macroalgae." *Journal of Chemical Education* 100, no. 2 (2023): 852–860. https://doi.org/10.1021/acs.jchemed.2c00899.

[10] Daskolia, M., and K. Chouliara. "Into the Park: Exploring Preschool Children's Experience in a Local Urban Park." *Environmental Education Research* 30, no. 1 (2024): 118–137. https://doi.org/10.1080/13504622.2023.2237707.

[11] Poje, M., I. Marinić, A. Stanisavljević, and I. Rechner Dika. "Environmental Education on Sustainable Principles in Kindergartens—A Foundation or an Option?" *Sustainability* 16, no. 7 (2024): 1–15. https://doi.org/10.3390/su16072707.

[12] Tabuenca, B., M. Uche-Soria, W. Greller, D. Hernández-Leo, P. Balcells-Falgueras, P. Gloor, and J. Garbajosa. "Greening Smart Learning Environments with Artificial Intelligence of Things." *Internet of Things* 25 (2024): 1–17. https://doi.org/10.1016/j.iot.2023.101051.

[13] Lombardi, D. S., S. Merola, and T. Celestino. "Chemistry, Urban Environments and Ecopedagogy: A Possible Dialog. Soil as a Case-Study Example for an Integrated Vision." *Ricerche di Pedagogia e Didattica* 18, no. 1 (2023): 87–114. https://doi.org/10.6092/issn.1970-2221/16127.

[14] Nakamura, K. W., K. Miyajima, A. Fujiwara, and K. Saito. "Development of a Web Application for Flowering Phenology Observation and Its Applicability to Climate-Related Learning in Elementary Schools." *Cogent Education* 10, no. 2 (2023): 1–16. https://doi.org/10.1080/2331186X.2023.2277045.

[15] Dlimbetova, G. K., S. U. Abenova, S. S. Sadykova, and A. I. Primbetova. "Integrating Sustainability into Education: An Exploration of the 'Green School - Green College - Green University' Approach." *European Journal of Contemporary Education* 12, no. 4 (2023): 1175–1184. https://doi.org/10.13187/ejced.2023.4.1175.

[16] Sáez-Bondía, M. J., E. Mateo, and J. Martín-García. "Science Learning in 3- and 5-Year-Old Children in the Same Free-Choice Learning Environment on Plant Diversity." *Learning Environments Research* 27, no. 1 (2024): 199–215. https://doi.org/10.1007/s10984-023-09475-9.

[17] Wallace, H. D. "Transdisciplinary Learning in a Kitchen Garden: Connecting to Nature and Constructing a Path to Ecoliteracy?" *International Research in Geographical and Environmental Education* 28, no. 4 (2019): 309–323. https://doi.org/10.1080/10382046.2019.1646013.

[18] Alias, N. A., N. K. Mahmud, A. S. Shafie, H. Ibrahim, S. L. Tan, R. Ghazali, M. A. Mustafa, et al. "Pap Smear Images Classification Using Machine Learning: A Literature Matrix." *Diagnostics* 12, no. 12 (2022): 1–16. https://doi.org/10.3390/diagnostics12122900.

[19] Moher, D., A. Liberati, J. Tetzlaff, and D. G. Altman. "Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement." *International Journal of Surgery* 8, no. 5 (2010): 336–341. https://doi.org/10.1016/j.ijsu.2010.02.007.

[20] Wicaksono, A., and J. A. T. da Silva. "Is COVID-19 Impacting Plant Science, and Is Plant Science Impacting COVID-19?" *Notulae Scientia Biologicae* 12, no. 3 (2020): 769–772. https://doi.org/10.15835/nsb12310778.

[21] Hussein, M. H., S. H. Ow, L. S. Cheong, and M. K. Thong. "A Digital Game-Based Learning Method to Improve Students' Critical Thinking Skills in Elementary Science." *IEEE Access* 7 (2019): 96309–96318. https://doi.org/10.1109/ACCESS.2019.2929089.

[22] Savita, K. S., N. A. Zainuddin, M. Muniandy, and M. Mehat. "A Mobile Based Application on Environmental Education for Primary School Children in Malaysia." *Journal of Theoretical and Applied Information Technology* 95, no. 22 (2017): 6300–6313.

[23] Goldsmith, G. R., T. A. Kursar, S. L. Roddy, A. C. West, J. N. Griffin-Nolan, M. K. Oliveras, D. B. Metcalfe, et al. "Plant-O-Matic: A Dynamic and Mobile Guide to All Plants of the Americas." *Methods in Ecology and Evolution* 7, no. 8 (2016): 960–965. https://doi.org/10.1111/2041-210X.12548.

[24] Webb, A. M., S. L. Knight, X. Ben Wu, and J. F. Schielack. "Teaching Science with Web-Based Inquiry Projects: An Exploratory Investigation." *International Journal of Virtual and Personal Learning Environments* 5, no. 2 (2014): 57–68. https://doi.org/10.4018/ijvple.2014040105.

[25] Finger, A., J. Groß, and J. Zabel. "Plant Identification in the 21st Century—What Possibilities Do Modern Identification Keys Offer for Biology Lessons?" *Education Sciences* 12, no. 12 (2022): 1–18. https://doi.org/10.3390/educsci12120849.

[26] Ingram, E., T. W. Hill, D. Harshbarger, and J. Keshwani. "Improving Elementary Pre-Service Teachers' Science Teaching Self-Efficacy through Garden-Based Technology Integration." *Education Sciences* 14, no. 1 (2024): 1–12. https://doi.org/10.3390/educsci14010065.

[27] Baumann, B., J. Groß, and M. Michelsen. "An App by Students for Students – The DPaCK-Model for a Digital Collaborative Teamwork Project to Identify Butterflies." *Frontiers in Education* 8 (2023): 1–15. https://doi.org/10.3389/feduc.2023.1190462.

[28] Safitri, D., A. Marini, A. F. Auliya, Sujarwo, and P. A. Wardhani. "Development of Augmented Reality-Based Interactive Learning Media to Increase Interest in Environmental Education." *Eurasian Journal of Educational Research* 2023, no. 106 (2023): 101–117. https://doi.org/10.14689/ejer.2023.106.007.

[29] Lo, J. H., Y. F. Lai, and T. L. Hsu. "The Study of AR-Based Learning for Natural Science Inquiry Activities in Taiwan's Elementary School from the Perspective of Sustainable Development." *Sustainability* 13, no. 11 (2021): 1–20. https://doi.org/10.3390/su13116283.

[30] Fokides, E., and P. Atsikpasi. "Tablets in Education. Results from the Initiative ETiE, for Teaching Plants to Primary School Students." *Education and Information Technologies* 22, no. 5 (2017): 2545–2563. https://doi.org/10.1007/s10639-016-9560-3.

[31] Jančaříková, K. "Czech Preschool Children's Conceptions about Nature." *Sustainability* 13, no. 19 (2021): 1–15. https://doi.org/10.3390/su131910962.

[32] Ameli, K. "Where Is Nature? Where Is Nature in Nature and Outdoor Learning in Higher Education? An Analysis of Nature-Based Learning in Higher Education Using Multispecies Ethnography." *Journal of Teacher Education for Sustainability* 24, no. 2 (2022): 113–128. https://doi.org/10.2478/jtes-2022-0020.

[33] Gya, R., and A. E. Bjune. "Taking Practical Learning in STEM Education Home: Examples from Do-It-Yourself Experiments in Plant Biology." *Ecology and Evolution* 11, no. 8 (2021): 3481–3487. https://doi.org/10.1002/ece3.7207.

[34] Petrou, S., and K. Korfiatis. "Transformations of Children's Environmental Conceptions through Their Participation in a School Kitchen-Garden Project." *Environmental Education Research* 28, no. 4 (2022): 524–544. https://doi.org/10.1080/13504622.2022.2051440.

[35] Vicente, M. M., R. Leitão, V. Quintino, P. Pombo, and A. M. Rodrigues. "Urban Vegetable Gardens as an Environmental Education Tool for Promoting Primary School Students' Engagement in EU Green Deal Strategies." *Visions for Sustainability* 2023, no. 19 (2023): 525–547. https://doi.org/10.13135/2384-8677/6994.

[36] Morón-Monge, H., S. Hamed, and M. del C. M. Monge. "How Do Children Perceive the Biodiversity of Their Nearby Environment: An Analysis of Drawings." *Sustainability* 13, no. 6 (2021): 1–19. https://doi.org/10.3390/su13063036.

[37] Ahi, B. "The World of Plants in Children's Drawings: Color Preferences and the Effect of Age and Gender on These Preferences." *Journal of Baltic Science Education* 16, no. 1 (2017): 32–42. https://doi.org/10.33225/jbse/17.16.32.

[38] Gillett, C., K. Fontenot, E. Bush, M. Walsh, and C. Johnson. "Summer Camp Garden Project: An Opportunity to Grow the Next Generation of Horticulturists." *HortTechnology* 27, no. 1 (2017): 114–120. https://doi.org/10.21273/HORTTECH03572-16.

[39] Dunkley, R. A. "Learning at Eco-Attractions: Exploring the Bifurcation of Nature and Culture through Experiential Environmental Education." *Journal of Environmental Education* 47, no. 3 (2016): 213–221. https://doi.org/10.1080/00958964.2016.1164113.

[40] Doup, M. L. "Using an Outdoor Activity on Local Plant Biodiversity to Teach Conservation Ecology and Promote Environmentally Responsible Behaviors." *American Biology Teacher* 80, no. 5 (2018): 359–364. https://doi.org/10.1525/abt.2018.80.5.359.

[41] Garip, G., M. Richardson, A. Tinkler, S. Glover, and A. Rees. "Development and Implementation of Evaluation Resources for a Green Outdoor Educational Program." *Journal of Environmental Education* 52, no. 1 (2021): 25–39. https://doi.org/10.1080/00958964.2020.1845588.

[42] Tucker, C. S., S. W. Leavitt, T. W. Swetnam, J. S. Dean, and C. A. Woodhouse. "Using Tree-Ring Research to Introduce Students to Geoscience Fieldwork." *Bulletin of the American Meteorological Society* 102, no. 6 (2021): 1275–1282. https://doi.org/10.1175/BAMS-D-20-0096.1.

[43] Williams, D. R., H. Brule, S. S. Kelley, and E. A. Skinner. "Science in the Learning Gardens (SciLG): A Study of Students' Motivation, Achievement, and Science Identity in Low-Income Middle Schools." *International Journal of STEM Education* 5, no. 1 (2018): 1–14. https://doi.org/10.1186/s40594-018-0104-9.

[44] Sarbaini, A. H. Hernawan, D. Darmawan, and M. Ali. "Environmental Education Based on Local Values: Its Integration in the Indonesian Elementary School Curriculum." *International Journal of Education and Practice* 10, no. 4 (2022): 322–333. https://doi.org/10.18488/61.v10i4.3174.

[45] Azevedo, H., I. Soares-Silva, F. Fonseca, P. Alves, D. Silva, and M. M. Azevedo. "Impact of Educational Gardens and Workshop Activities on 8th-Grade Students' Perception and Knowledge of Plant Biology." *Education Sciences* 12, no. 9 (2022): 1–16. https://doi.org/10.3390/educsci12090619.

[46] Ulutaş, A., and M. Kanak. "Effect of the Cooperative Learning with Family Involvement Based Science Education on the Scientific Process Skills of 5–6-Year-Old Children." *NeuroQuantology* 16, no. 11 (2018): 20–29. https://doi.org/10.14704/nq.2018.16.11.1263.

[47] Sprague, N. L., A. L. Sachs, and C. C. Ekenga. "Green vs. Screen: Exploring the Outcomes of an In-Person and Virtual Nature-Based Environmental Education Intervention for Low-Income Children." *Sustainability* 14, no. 19 (2022): 1–14. https://doi.org/10.3390/su141912600.

[48] Loureiro, J. de O., and R. André Dal-Farra. "Botany and Environmental Education in Elementary School in Brazil: Articulating Knowledge, Values, and Procedures." *Environmental Education Research* 24, no. 12 (2018): 1655–1668. https://doi.org/10.1080/13504622.2017.1343280.

[49] Birkinshaw, C., P. P. Lowry II, J. Raharimampionona, and J. Aronson. "Supporting Target 4 of the Global Strategy for Plant Conservation by Integrating Ecological Restoration into the Missouri Botanical Garden's Conservation Program in Madagascar." *Annals of the Missouri Botanical Garden* 99, no. 2 (2013): 139–146. https://doi.org/10.3417/2012002.

[50] Esteban-Ibáñez, M., and L. V. Amador-Muñoz. "The Social Garden as Strategy for Environmental Education." *Agricultura, Sociedad y Desarrollo* 17, no. 2 (2020): 321–347.

[51] Klütsch, C. F. C., R. K. Bayly, J. S. Fjeldsa, M. Gaigher, E. M. Maurer, J. R. Poulsen, J. R. Bøcher, et al. "Studying Phenological Phenomena in Subarctic Biomes with International School Pupils as Citizen Scientists." *Ecology and Evolution* 11, no. 8 (2021): 3501–3515. https://doi.org/10.1002/ece3.7122.

[52] Hawley, E. "Children's Television, Environmental Pedagogy and the (Un)Natural World of Dirtgirlworld." *Continuum* 32, no. 2 (2018): 162–172. https://doi.org/10.1080/10304312.2017.1347913.

[53] Baines, K., and R. K. Zarger. "'It's Good to Learn about the Plants': Promoting Social Justice and Community Health through the Development of a Maya Environmental and Cultural Heritage Curriculum in Southern Belize." *Journal of Environmental Studies and Sciences* 7, no. 3 (2017): 416–424. https://doi.org/10.1007/s13412-016-0416-3.