

ANALYSIS OF NATIONAL AND INTERNATIONAL EXPERIENCES IN IMPLEMENTING THE STEAM APPROACH IN BIOLOGY EDUCATION: THE CASE OF PLANT PHYSIOLOGY TEACHING

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Abstract. *This article analyzes national and international experiences in implementing the STEAM approach in biology education, with particular emphasis on teaching Plant Physiology in higher education institutions. The theoretical foundations of STEAM education and its role in enhancing interdisciplinary learning are discussed. The study examines the experiences of countries such as the United States, Finland, South Korea, and Singapore in integrating STEAM principles into biology education through project-based learning, laboratory activities, and digital technologies. In addition, current practices, challenges, and opportunities for implementing STEAM education in Uzbekistan's higher education system are explored. Special attention is given to the prospects of improving Plant Physiology teaching through interdisciplinary integration, virtual laboratories, and the development of students' research and innovation competencies. The findings highlight that the STEAM approach contributes to improving the quality of biology education and preparing competitive specialists capable of addressing contemporary scientific and technological challenges.*

Keywords: *STEAM education, biology education, plant physiology, interdisciplinary integration, higher education, digital technologies, virtual laboratories, project-based learning, research competence, innovation competence, educational modernization, teaching methodology, scientific inquiry, competency-based education, STEM integration.*

Introduction. In the twenty-first century, integrative approaches that promote the acquisition of knowledge through interdisciplinary connections have gained

increasing importance in education, replacing the traditional practice of teaching subjects in isolation. One such approach is the STEAM educational concept, which integrates Science, Technology, Engineering, Arts, and Mathematics within a unified learning environment. The theoretical foundation of this approach is based on the close relationship between knowledge and practice, the solution of complex problems through interdisciplinary perspectives, and the development of learners' creative and critical thinking skills.

The STEAM concept extends beyond the simple integration of individual disciplines and focuses on connecting the educational process with real-life situations. Within this approach, learning is organized not as the passive acquisition of ready-made knowledge but as a process involving observation, problem identification, experimentation, data analysis, and the development of practical solutions. From this perspective, STEAM education can be regarded as a contemporary interpretation of constructivist and competency-based approaches. Learners are viewed not as passive recipients of information but as active participants who create, apply, and transform knowledge in meaningful contexts.

Main Part. The integration of STEAM into biology education provides opportunities for a deeper understanding of natural processes and their analysis from multiple scientific perspectives. Since biological phenomena are closely interconnected with physical, chemical, mathematical, and technological factors, studying them within the boundaries of a single discipline is often insufficient. The STEAM approach expands opportunities for modeling biological concepts, conducting experimental investigations, utilizing digital technologies, and presenting results through visual representations. As a result, students not only gain a more comprehensive understanding of biological processes but also develop essential research skills that are fundamental to scientific inquiry and professional practice.

Plant Physiology is one of the branches of biological sciences distinguished by

its strong experimental nature. This discipline focuses on the study of complex physiological processes, including photosynthesis, respiration, water relations, mineral nutrition, growth, and development. Since most of these processes require quantitative measurements, laboratory experiments, and statistical analyses, they provide a favorable pedagogical foundation for the implementation of the STEAM approach. For example, the determination of photosynthetic intensity involves mathematical calculations, the investigation of light effects relies on physical principles, experimental data processing requires digital technologies, and the presentation of findings benefits from visual design elements. Consequently, Plant Physiology can be taught not merely as a body of theoretical knowledge but as a practice-oriented and research-based discipline.

Furthermore, the STEAM approach contributes to the development of students' competencies in the systematic analysis of biological objects, formulation of scientific hypotheses, interpretation of experimental data, and generation of innovative solutions to environmental challenges. The rapid advancement of modern agriculture, biotechnology, and environmental sciences increasingly demands specialists in Plant Physiology who possess not only biological knowledge but also technological and engineering thinking skills. Therefore, organizing the teaching of this discipline through the STEAM approach is considered one of the key factors in aligning the professional preparation of future biologists with the requirements of the contemporary labor market.

In developed countries, STEAM education is widely recognized as an important driver of innovation-based economies and knowledge societies. This approach promotes interdisciplinary thinking, complex problem-solving abilities, research skills, and creativity among learners. As a result, various countries have accumulated valuable experience in integrating STEAM elements into biology education, particularly in the teaching of Plant Physiology.

In the United States, the development of STEAM education originated from the

STEM concept and later evolved through the incorporation of arts and design components. Researchers such as G. Yakman [1, pp. 1–18] and M. Sanders [2, pp. 20–26] established the theoretical foundations of the STEAM approach, emphasizing that interdisciplinary integration enhances learners' ability to solve practical problems. In American universities, the teaching of Biology and Plant Physiology extensively incorporates laboratory investigations, Project-Based Learning (PBL), and digital technologies. Students study photosynthetic activity, transpiration processes, and plant responses to environmental stress factors using modern sensors and computer-based applications [3]. Such an approach not only facilitates the acquisition of biological knowledge but also promotes the development of practical research competencies.

The Finnish education system is distinguished by its high level of interdisciplinary integration. Since 2016, Finland has implemented the Phenomenon-Based Learning (PhBL) model, which organizes the learning process around real-life phenomena rather than isolated academic disciplines [4]. In biology education, topics such as plant growth, climate change, and environmental issues are studied simultaneously from the perspectives of biology, chemistry, physics, and mathematics. Students utilize statistical software and digital technologies to analyze experimental data. As a result, learners develop the ability to understand biological processes as interconnected and complex systems [5].

In South Korea, STEAM education is considered one of the strategically important directions supported at the national level. Since 2011, the country has been implementing the STEAM Education Initiative program [6, pp. 149-171]. The primary objective of this model is to increase students' interest in science and technology while preparing innovative and creative professionals. In biology education, including Plant Physiology, students are engaged not only in laboratory experiments but also in the development of engineering solutions. For instance, projects focused on designing automated irrigation systems and smart greenhouse

models are implemented while studying factors affecting plant growth [7]. Such activities facilitate the integration of biological knowledge with technological applications and engineering practices.

In Singapore, the STEAM approach has evolved in close connection with research and innovation. The national educational framework, known as “Thinking Schools, Learning Nation,” emphasizes the development of creative, independent, and lifelong learners as a primary educational objective [8, pp. 91–106]. In biology education, laboratory activities, scientific projects, and digital simulations play a significant role. During Plant Physiology courses, students participate in activities such as digital monitoring of plant growth dynamics, data modeling, and graphical presentation of experimental results [9]. This approach enables learners to integrate biological knowledge with technological and mathematical applications.

An analysis of international experiences demonstrates that laboratory investigations and project-based activities occupy a central position in STEAM-oriented Plant Physiology education. Instead of relying solely on traditional laboratory exercises, educational institutions increasingly employ open-ended experiments, problem-based tasks, and practical projects that encourage students to conduct independent research. Through these activities, students actively engage in identifying scientific problems, formulating hypotheses, conducting experiments, analyzing data, and drawing evidence-based conclusions [10].

One of the most innovative aspects of international practice is the extensive use of digital technologies and artificial intelligence tools in the study of biological processes. Modern educational laboratories increasingly incorporate sensor technologies, virtual laboratories, automated data-processing systems, and simulation software as integral components of the learning environment [11]. Furthermore, within the STEAM framework, biological knowledge is integrated with engineering projects, environmental investigations, and innovative technological applications. This integration contributes not only to the acquisition

of biological knowledge but also to the development of twenty-first-century competencies, including critical thinking, creativity, collaboration, and communication skills.

In recent years, reforms implemented in Uzbekistan's higher education system have been aimed at updating educational content in accordance with modern requirements, aligning it with international standards, and strengthening the practical orientation of the teaching and learning process. These transformations have also directly influenced biology education, creating a need for the application of innovative pedagogical technologies and integrative approaches in teaching. Within this context, the STEAM approach has emerged as an effective pedagogical tool that connects biological knowledge with practical activities, scientific research, and technological innovations.

One of the major directions in the modernization of biology education is the transition from the transmission of theoretical information toward students' independent inquiry and practical engagement. While traditional educational models primarily focused on the acquisition of ready-made biological knowledge, contemporary approaches emphasize students' ability to discover knowledge independently and apply it in real-life situations. Consequently, laboratory activities, small-scale research projects, field investigations, and digital educational resources are becoming increasingly important components of biology instruction. These developments are closely aligned with the fundamental principles of STEAM education and contribute to the development of future biologists' professional competencies.

The integration of STEAM elements into biological sciences is being implemented through various instructional practices in higher education institutions. In particular, there is a growing tendency to utilize mathematical analysis, information technologies, engineering thinking, and visual modeling tools in the study of biological processes. Activities such as statistical processing of

experimental data, the use of electronic databases, digital environmental monitoring, and the development of biological models enrich the content of biology education. At the same time, these practices enhance students' ability to connect biological knowledge with real-world challenges and practical applications.

Among biological disciplines, experimental fields offer particularly favorable conditions for STEAM integration. Research involving plants, microorganisms, and ecological systems requires observation, measurement, analysis, and prediction, all of which demand an interdisciplinary perspective. As a result, biology education increasingly incorporates research-based assignments, problem-oriented tasks, and project activities. Such approaches expand students' opportunities to connect theory with practice, develop scientific reasoning, and apply innovative solutions to biological and environmental problems.

Nevertheless, several challenges remain in the effective implementation of STEAM education within higher education. In some cases, the conceptual foundations and methodological potential of STEAM technologies are not fully understood, leading to their use merely as isolated interactive teaching techniques. In reality, STEAM should be regarded not as a single method but as a comprehensive educational model. Furthermore, the limited availability of interdisciplinary teaching materials and the unequal distribution of modern laboratory facilities and digital technologies across educational institutions continue to present significant obstacles to the successful implementation of STEAM-based instruction.

Another important issue is the need to further improve university instructors' methodological preparedness for organizing STEAM-based education. The development of interdisciplinary projects, the integration of technological tools into biology teaching, and the effective management of research activities require specialized competencies. Therefore, ensuring the continuous professional development of educators, expanding professional training programs related to STEAM pedagogy, and disseminating best educational practices remain among the

most pressing priorities.

Several promising directions can be identified for the further development of STEAM-based biology education. These include the establishment of virtual and remote laboratories, the wider implementation of digital platforms for modeling biological processes, the strengthening of collaboration with scientific research institutions, and the support of students' innovative projects. Such initiatives can significantly contribute to improving the quality of biology education. Furthermore, connecting biological content with real environmental and social challenges can enhance students' professional motivation and research engagement.

Contemporary trends in higher education increasingly require the integration of interdisciplinary learning, digital technologies, and research-oriented activities. Among biological disciplines, Plant Physiology possesses considerable potential for the effective implementation of the STEAM approach due to its theoretical depth and practical relevance. The physiological processes studied within this discipline are influenced by various natural and technological factors, making a comprehensive and interdisciplinary perspective essential for their proper understanding. Consequently, improving the teaching of Plant Physiology through STEAM-based instruction represents a promising strategy for enhancing both the quality and effectiveness of biology education.

One of the most important directions in this process is the strengthening of interdisciplinary integration. Physiological processes such as photosynthesis, respiration, water relations, mineral nutrition, and phytohormone activity are closely connected not only to biology but also to physics, chemistry, mathematics, and ecology. Therefore, the teaching of these topics should involve the integration of theoretical concepts from multiple disciplines within a unified problem-solving or project-based framework. Such interdisciplinary integration enables students to perceive biological phenomena not as isolated facts but as components of complex and interconnected systems. As a result, the practical significance and applicability

of biological knowledge are substantially enhanced.

Another promising direction for the advancement of Plant Physiology education involves the use of digital technologies and virtual laboratories. Modern information and communication technologies provide new opportunities for studying biological processes. In particular, the virtual simulation of physiological experiments, real-time monitoring of experimental outcomes, and statistical analysis of data can significantly improve the effectiveness of the learning process. Virtual laboratories also make it possible to conduct complex or time-consuming experiments in a safe and cost-effective environment. Moreover, they support individualized learning pathways, allow repeated experimentation, and facilitate students' independent analysis of research results.

Digital technologies further expand opportunities for monitoring plant growth and development, modeling the effects of environmental factors, and processing large volumes of biological data. Such activities help students master contemporary scientific research methodologies. At the same time, the introduction of innovative tools based on artificial intelligence, sensor technologies, and advanced data analytics is transforming Plant Physiology education and elevating the discipline to a new level of scientific and technological relevance[12; -B. 593-605.].

One of the most significant advantages of the STEAM approach is its contribution to the development of students' research and innovation competencies. A modern biology specialist should possess not only theoretical knowledge but also the ability to identify scientific problems, design research plans, conduct experiments, analyze results, and draw practical conclusions. Teaching Plant Physiology through the STEAM approach provides a favorable pedagogical environment for the development of these competencies. Students are engaged in independent inquiry through various projects, experimental tasks, and innovative activities, which enhance their scientific thinking and professional engagement[13; Pp. 1-5.].

Furthermore, participation in research and project-based activities enables students to develop teamwork skills, justify their ideas with evidence, approach problems creatively, and design innovative solutions. In particular, projects addressing contemporary challenges in agriculture, ecology, biotechnology, and food security help connect students' professional preparation with real-world needs. Such experiences contribute to the formation of competitive specialists capable of succeeding in both scientific and professional fields[14; -B.178-181.].

Conclusion. The application of the STEAM approach in biology education has become one of the priority directions of modern higher education, as it facilitates the integration of theoretical knowledge with practical activities, promotes interdisciplinary thinking, and supports the development of research competencies. By enabling students to analyze biological processes from multiple disciplinary perspectives, the STEAM approach contributes to the advancement of both the content and methodology of biology education.

The analysis conducted in this study demonstrates that in countries such as the United States, Finland, South Korea, and Singapore, STEAM education has become an essential component of biology instruction. Through the integration of laboratory activities, project-based learning, digital technologies, and engineering elements, these educational systems have successfully enhanced students' scientific and practical capacities. Their experiences indicate that STEAM-based instruction is highly effective in connecting biological knowledge with real-world challenges and fostering innovative thinking.

In Uzbekistan, meaningful progress has also been made toward the implementation of STEAM principles within the modernization of biology education. The incorporation of digital technologies, project activities, and research-oriented learning into biological sciences has contributed to improving students' professional preparation. Nevertheless, further efforts are needed to strengthen interdisciplinary integration, improve educational and methodological resources,

and enhance educators' STEAM-related competencies.

Plant Physiology possesses substantial potential for the effective implementation of the STEAM approach due to its interdisciplinary nature and strong experimental foundation. Strengthening interdisciplinary integration, expanding the use of virtual laboratories and digital technologies, and promoting project- and research-based learning can significantly contribute to the development of students' scientific, creative, and innovative competencies.

Therefore, the adaptation of successful national and international STEAM practices to the teaching of Plant Physiology can play a crucial role in improving the quality of biology education, enhancing students' professional competencies, and preparing highly qualified specialists capable of meeting the challenges of contemporary science and technology.

Foydalanilgan adabiyotlar

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