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Strategic Guidelines and Framework for Advancing Higher Education Programs in the Field of Biotechnology in Bosnia and Herzegovina

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Abstract

This document presents strategic guidelines and a development framework aimed at enhancing higher education programs in biotechnology within Bosnia and Herzegovina. It emphasizes the importance of aligning academic curricula, research capacities, and innovation ecosystems with global sustainable development goals (SDGs) and emerging scientific trends. Drawing on insights from the 2025 scientific-expert symposium "Next-Generation Biotechnologists – Skills of Future Educators," this work outlines key recommendations for modernizing educational approaches, strengthening interdisciplinary collaboration, and fostering the next generation of biotechnologists equipped to meet societal and technological challenges. The framework is intended for academic institutions, policymakers, and stakeholders committed to advancing biotechnology education and innovation in the region.

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Introduction

In Sarajevo, the Association of Biochemists and Molecular Biologists, in cooperation with the Academy of Sciences and Arts of Bosnia and Herzegovina, the Institute for Genetic Engineering and Biotechnology, the Faculty of Natural Sciences and Mathematics of the University of Sarajevo, and the Association of Geneticists of Bosnia and Herzegovina, organized a scientific symposium titled “Next-Generation Biotechnologists – Skills of Future Educators” from May 22–23, 2025.

Global goals for sustainable development, as outlined in the 2030 Agenda (United Nations, 2015), require revising social development strategies, including higher education and the economy, and implementing sustainable technologies. The symposium aimed to exchange knowledge and best practices in applying cutting-edge science to innovate production processes and technologies.

It provided a platform to discuss the importance of scientific and educational capacities that enable this transition. Participants included experts from the natural sciences, PhD students, and postdoctoral researchers from biotechnical, biomedical, and related fields. The target audience comprised academics, researchers, policymakers, and young entrepreneurs engaged in biotechnology, especially in sustainable agriculture and innovation.

Special emphasis was placed on developing innovative educational programs for training highly qualified professionals to address sustainability challenges in industry. The event was supported by the Federation of European Biochemical Societies (FEBS), the Ministry of Science, Education, and Youth of Sarajevo

Canton, and the Ministry of Education and Science of the Federation of Bosnia and Herzegovina. This article reflects two days of intensive discussion on biotechnology’s role in developing modern B&H society and educating future professionals, based on prior research involving all academic levels.

Methodological description

Prior to the symposium, a structured questionnaire was administered to participants (N = 50), comprising representatives from academic institutions, research organizations, and the biotechnology industry. The primary objective of the survey was to evaluate the current state of biotechnology education and to identify key competencies and reform priorities necessary for advancing this field. The instrument consisted predominantly of open-ended questions, allowing for the collection of detailed qualitative insights from respondents. The obtained data were processed through descriptive and basic statistical analyses to synthesize prevailing viewpoints and delineate the principal themes subsequently addressed during the symposium.

Biotechnology: definition, directions, and perspectives

Biotechnology is one of the most strategically important scientific fields, with immense potential for advancing healthcare, agriculture, industry, and environmental protection. Its essence (bios – life, logos – science, technos – skill) lies in applying knowledge of living systems to improve quality of life, promote sustainable resource use, and solve global challenges (OECD, 2009; WHO, 2021).

In healthcare, biotechnology has transformed disease diagnosis and treatment through innovations such as monoclonal antibodies, gene

therapy, and mRNA vaccines developed during the COVID-19 pandemic (Langer & Vacanti, 1993).

In agriculture, it has enabled genetically modified crops resistant to pests, drought, and diseases, improving productivity and food security, all crucial for a global population expected to double by 2100 (James, 2017).

Biotechnology also plays a key role in environmental protection. Through bioremediation, microorganisms remove pollutants from soil and water, while biodegradable materials and biofuels reduce reliance on fossil fuels and lower greenhouse gas emissions. Industrial biotechnology applies modified enzymes and microorganisms to produce goods more efficiently and sustainably, reducing energy and raw material consumption (Singh & Cameotra, 2004). Altogether, biotechnology is not only a scientific discipline but also a major driver of economic growth and sustainability. Its interdisciplinary nature and innovative potential make it vital for building a knowledge-based, resource-responsible future.

The importance of innovation in the field of biotechnology

Innovation is the capacity of an organization or company to use specific knowledge to create new production solutions and products. This ability, much like experience in production, develops through a process of "learning by doing" where innovation can be observed through the so-called learning curve (Luo et al., 2018).

In this process, it is important to understand that innovativeness is not solely the result of formal and/or informal knowledge and education, but also the accumulation of experience through daily activities at work and lifelong learning. Analyses

of patent data from the biotechnology industry have shown that the individual, a scientist or researcher, is the main bearer of innovation, while teamwork and previous shared experiences directly or indirectly increase productivity (European Commission, 2020a). On the other hand, the accumulated experience of the organization itself does not show a direct impact on innovation capacity, except when it overlaps with personal knowledge and mutual collaboration among employees. These insights are also related to the concept of absorptive capacity (Camisón & Forés, 2010) - the ability of an organization to recognize, absorb, and apply external knowledge. Absorptive capacity depends both on individual skills and the interconnection of different sources of knowledge within the organization. When this knowledge is properly connected, knowledge spillover occurs (Sharma & Tripathi, 2017), enhancing the potential of an innovative organization, where education and continuous learning of employees play a key role. Without the development of individual competencies, skills, and encouragement of collaboration, innovation cannot be sustainably developed. Literature data show that the most innovative organizations are those that stimulate the connection of different knowledge reservoirs (centers of excellence), both at the individual and organizational levels (Kafourous et al., 2012).

The role of education and lifelong learning in enhancing capacity in biotechnology

As knowledge and technological progress are the foundation of every modern society, education adapted to these needs represents a key pillar for the development and advancement of any

society, especially in the field of biotechnology.

This interdisciplinary field, which includes biology, genetics, other natural sciences, computer science, and engineering, as well as many other scientific disciplines, requires a high level of expertise and constant acquisition of new knowledge. Without clearly defined educational goals, a society cannot reach the level of competence required for successful research and innovation.

Education and continuous training enable the development of professional knowledge and skills necessary for work in laboratories, research institutes and centers, and biotechnological companies. Through formal education and informal learning methods such as workshops and online courses, scientists and professionals build a foundation for further professional development. As has been emphasized in many instances, individuals are the main bearers of innovative capacity in biotech companies, and their expertise and knowledge form the foundation of every successful innovation.

In addition, education enhances the development capacity of an innovative organization or company, and the ability to recognize, adopt, and apply new knowledge from the environment. This ability depends on previously accumulated knowledge, which means that without a well-educated workforce and ongoing education, the next generation of biotechnologists will not be able to utilize the available knowledge and innovative potentials emerging from academic or industrial settings.

A critical educational aspect is also the strengthening of teamwork and collaboration. Biotechnological innovations most often arise within multidisciplinary teams, where success is

largely conditioned by effective communication and integration of knowledge from various fields. Complementary knowledge and research experience within an organization or company form a realistic basis for innovation. Education that includes teamwork and task-sharing in projects directly contributes to enhancing the capacity of an innovative organization.

At a broader level, education lays the foundation for the development of a national innovation system. A well-educated workforce in biotechnology can drive positive changes in the development and advancement of university activities, research centers, entrepreneurial companies (start-ups), and industrial consortia. This helps build the infrastructure necessary for long-term and sustainable economic growth and development, as well as responses to major global challenges: climate change, the quality and availability of food and medicine, biodiversity preservation, discovery of new bioactive compounds (e.g., antibiotics), combating infectious diseases, and more.

Ultimately, the education of biotechnologists does not end with formal schooling, it continues through learning by doing. Quality formal education is only the starting point that enables focused and purposeful knowledge accumulation achieved through experimental and practical work, which serves as a solid foundation for any innovation system.

It is important to emphasize that education is not merely a means of transferring knowledge, or an activity in itself, but a key mechanism for developing innovative capacities in biotechnology. It guides and connects innovative individuals, teams, and organizations in a collective effort to transform knowledge into real, socially beneficial innovations.

New professional skills in basic and continuing education of the next generation of biotechnologists

In today's era of rapid development and knowledge acquisition, where technologies evolve at an relentless pace, traditional education models often cannot meet the growing and shifting demands of the labor market, especially in high-tech fields such as biotechnology. In this context, micro-credentials are becoming increasingly important as a modern, innovative form of education tailored to today's needs. They enable targeted, fast, flexible, and focused acquisition of specific knowledge and skills. Micro-credentials are defined as short, non-degree educational programs that provide mastery of concrete competencies or knowledge, most often delivered through online platforms and within a limited time frame (OECD, 2021a). Unlike traditional academic degrees, micro-credentials are focused, fast, and directly applicable. In the field of biotechnology, this could mean, for example, rapid and reliable mastery of tools for genetic/genomic analysis, basics of bioinformatics, techniques for working with CRISPR technology, or managing a research project or experiment.

One of the main advantages of micro-credentials as an educational model in biotechnology is their adaptability to the needs of industry. Biotechnological companies face rapid changes and technological advancements, which makes continuous professional development essential. Micro-credentials allow employees to quickly gain qualifications for new tasks and technologies without the need for years of formal education. According to the European Commission (2020b), micro-credentials increase employability, as they enable students and workers to acquire specific

skills that employers recognize and value. Furthermore, it is important to highlight that micro-credentials contribute significantly to the development of lifelong learning in biotechnology. In a sector where knowledge quickly becomes outdated, as is the case in biotechnology, the need for continuous and targeted learning has never been greater. Micro-credentials enable individuals to upgrade their knowledge in line with personal interests, technological changes, and professional demands. As noted in reports from the OECD (2021a), this approach to education allows faster adaptation to changes in the labor market and enhances the resilience of the workforce to technological disruptions. Another important aspect of micro-credentials is their role in educational inclusivity. Due to their online accessibility, they provide opportunities for acquiring knowledge and skills to those who are unable to attend traditional educational institutions, whether due to geographic, financial, or time constraints. Platforms such as Coursera, edX, and FutureLearn already offer a variety of micro-courses in the field of biotechnology, developed by prestigious global universities such as MIT, Stanford, and Cambridge. However, for micro-credentials to reach their full potential in the education and training of biotechnologists, standardization and institutional recognition of these qualifications are necessary. Therefore, micro-credentials must be adequately integrated into formal education and professional systems to ensure their credibility and transparency (European Commission, 2020b).

In conclusion, micro-credentials represent an efficient and adaptable tool for the modernization of education in biotechnology. They enable faster acquisition of practical knowledge, enhance expertise, support lifelong learning, and make

education more accessible to a wider population. In an era of rapid change, this very model of education can ensure that biotechnology professionals remain relevant and competitive on the international level.

Transversal skills and interdisciplinarity

Modern biotechnology, as a multidisciplinary and dynamic field, requires much more than just the technical proficiency of biotechnologists. Although knowledge in biology, genetics, biochemistry, informatics, and related areas forms the foundation of the profession, success in the biotechnology sector increasingly depends on so-called transversal skills, universal competencies that enable professionals to navigate complex, ever-changing, and cross-sectoral environments. Transversal skills, also known as soft or transferable skills, include abilities such as teamwork, critical thinking, problem-solving, time management, communication, digital literacy, and ethical awareness.

In biotechnology, collaboration between experts from different fields is fundamentally important and inevitable. Biologists, engineers, programmers, and economists work together on multidisciplinary projects that require a high level of coordination and communication. According to the OECD (2021b), effective interpersonal communication and the ability to work in teams are among the most in-demand skills across all science and technology professions, including biotechnology. Biotechnologists must be able to convey complex scientific information not only to their colleagues, but also to decision-makers, legislators, investors, and the general public, who may not necessarily have prior knowledge or formal education in the field.

Problem-solving and critical thinking are also key components of a biotechnologist's professional profile. Given the unpredictability of working with biological systems, it is essential for individuals to be able to analyze situations, interpret results, and make evidence-based, informed decisions. As noted by the World Economic Forum (2020), these cognitive skills are among the most important for the future of work, as they enable adaptation in rapidly changing environments. Considering that research and development projects in biotechnology are often conducted under pressure from time constraints, financial limitations, and regulatory demands, skills in organization, planning, and project management become indispensable.

Reports by the European Commission (2020a) highlight that the ability to manage tasks both independently and within a team is one of the foundations of competence for lifelong learning. Biotechnologists must know how to use resources efficiently, manage deadlines, and optimize work processes.

Digital literacy is another pillar of modern transversal competencies. Biotechnology increasingly relies on digital tools for data analysis, modeling, and visualization, and knowledge of programming languages and software solutions such as Python or R, as well as platforms like NCBI, Expasy, and Galaxy, is becoming indispensable. According to the Arregui et al., (2020), digital skills are no longer an added advantage, they are a fundamental requirement for work across nearly all segments of science and industry.

In a world where biotechnological innovations raise ethical questions, from genetic modification of organisms to the use of personal genetic information, moral responsibility and ethical

reasoning become just as important as scientific accuracy. It is essential that the education of future biotechnologists includes components that foster awareness of the ethical, legal, and social implications of their work. Transversal skills not only complement technical knowledge but also enable its effective application and adaptation in increasingly complex working conditions. In an era of profound societal transformation and global challenges such as climate change, food security, and pandemics, these universal competencies are precisely what make biotechnologists more resilient, innovative, and socially responsible.

Recommended directions for revising curricula in the field of biotechnologies

Given the dynamic development of biotechnology and its applications in industry, as well as the increasing integration of knowledge from various scientific fields in the development of new technologies, an adaptive revision of biotechnology curricula has become essential.

The goal of such a revision should not focus solely on expanding existing theoretical knowledge, but rather on a comprehensive modernization of the curriculum to address the real needs of contemporary society, while also taking into account the specific characteristics of the local industry (smart specialization) (Foray et al., 2021) and labor market. The first key aspect is the introduction of a culture of interdisciplinarity in research and innovation (Figure 1). Biotechnology today does not exist in isolation, it relies on (bio)informatics, artificial intelligence tools and technologies, automation, and nanotechnologies. Therefore, it is important that both basic and advanced educational programs incorporate foundations of computer science and programming (e.g., Python, R), big data processing, and the general use of digital tools. As stated in the OECD (2021b), digital skills and competencies in big data analysis must become an integral part of every technical discipline, including biotechnical sciences and biotechnology.

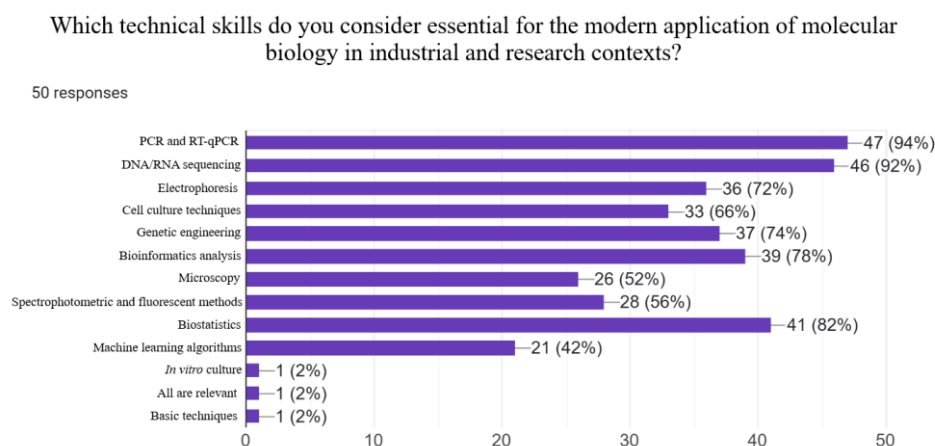


Figure 1. Essential technical skills for the modern application of molecular biology in industrial and research contexts (Questionnaire results)

The second important aspect of educating the next generation of biotechnologists is formal and continuous training in practical and laboratory skills that align with the demands of modern industrial production (e.g., the production of biosimilars, biosensors, development of new drugs, etc.) (Figure 2). This includes training students to work in accordance with GLP (Good Laboratory Practice), GMP (Good Manufacturing

Practice), and GCP (Good Clinical Practice), as well as developing their ability to use molecular biology techniques such as gene editing (CRISPR-Cas), PCR, nucleic acid sequencing (NGS), cell and tissue cultivation, and fermentation. According to recommendations from EASAC (2020), practical readiness of biotechnology students is becoming a key employability criterion both in the EU and globally.

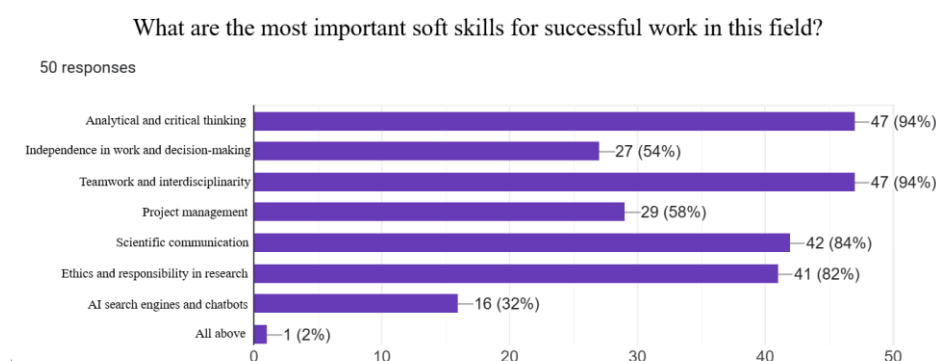


Figure 2. Soft skills in biotechnology field (Questionnaire results)

Alongside specialized knowledge, the revision of curricula must also encompass the development of transversal skills - communication, teamwork, project management, ethical reasoning, and entrepreneurship. Biotechnologists often work in teams and within the private sector, and they need not only to develop a product but also to position it in the market, understand relevant regulations, grasp market dynamics, and communicate with various stakeholders. Through curricula, it is necessary to nurture awareness of social responsibility and ethics, especially given sensitive topics such as genetic modification, the use of genetic data, and biosafety in the era of pandemics. Through case studies, interdisciplinary

discussions, and mandatory ethics modules, students must develop a critical perspective on the technologies they employ and their societal impact. Moreover, the revision must allow for flexibility and modularity in the program so that students can choose between academic and applied (industrial) tracks, with clearly defined learning outcomes and competencies for each. Full implementation and long-term sustainability require the continuous strengthening of links between universities, industry, and research centers. This includes internships, collaborative projects, and interdisciplinary supervision of diploma, master's, and doctoral theses. In this way, horizontal integration of theory and practice

is ensured, which, according to Arregui et al., (2020), is critical for developing the next generation of highly innovative biotechnologists.

Interaction between the education sector and industry in the field of biotechnology

Integrating industry into the development of biotechnology is crucial for any society, especially for Bosnia and Herzegovina—a country rich in natural resources and exceptional biodiversity, with significant educational potential in the natural sciences. Despite possessing a solid knowledge base, Bosnia and Herzegovina faces a historical disconnect between science and industry, a gap that has been further weakened between 1990 and 2020. While biotechnology has the potential to address issues such as food security and quality, environmental protection, public health improvement, and overall industrial modernization through the introduction of new technologies, it has yet to be strategically recognized as a priority sector in Bosnia and Herzegovina. One of the major challenges in the country's economic development is the lack of institutional support and financial instruments that would encourage companies to invest in biotechnology research and innovation transfer. Compared to EU countries, Bosnia and Herzegovina has limited public co-financing mechanisms for innovation, an underdeveloped venture capital fund, and weak tax incentives for research and development. To stimulate industry-academia collaboration, it is necessary to introduce national and entity-level incentive programs that would facilitate small and medium-sized enterprises in launching projects in cooperation with universities and research centers. Such models already exist in Slovenia and Croatia, where they have proven to increase the number of innovation projects (European Commission,

2020a). Bosnia and Herzegovina boasts a solid academic foundation, as universities in Sarajevo, Banja Luka, Tuzla, Mostar, and Bihać offer developed programs in biology, chemistry, pharmacy, and medicine. However, their interconnection, as well as their linkage with industry, is nearly nonexistent. Active efforts are needed to develop technology parks and bio-incubators where students and researchers can develop ideas in collaboration with the private sector (Vanjskotrgovinska komora BiH, 2022). This would include establishing "technology transfer offices" to assist in patenting, commercialization, and the launch of biotechnology or high-tech startups.

The BOOST project, funded by the EU and Germany, aims to support small and medium-sized enterprises in Bosnia and Herzegovina through academia-industry cooperation. The project will result in improved innovation levels and product quality for SMEs, strengthened capacities of academia and selected innovation hubs, and promoted knowledge exchange between the academic community and the private sector. Additionally, the University of Sarajevo and Bosnalijek signed an agreement on scientific and technological cooperation to improve research, development, innovation, and technology transfer in the fields of pharmacy, biotechnology, health, economics, and management. This collaboration aims to bring new opportunities for development, especially at the Institute for Genetic Engineering and Biotechnology. Furthermore, the RDBIH project, funded through the Erasmus+ CBHE program, aims to transform Bosnia and Herzegovina's research landscape by developing modern research and development strategies aligned with European standards, establishing six R&D centers across leading universities, and

creating a digital R&D network to facilitate collaboration and knowledge exchange. These initiatives represent significant steps toward bridging the gap between academia and industry in Bosnia and Herzegovina's biotechnology sector.

During the conference, it was emphasized that the exchange of knowledge among knowledge reservoirs, as well as skills within the educational sector of universities, could also give a stimulus to launching innovation in the field of biotechnology (Figure 3).

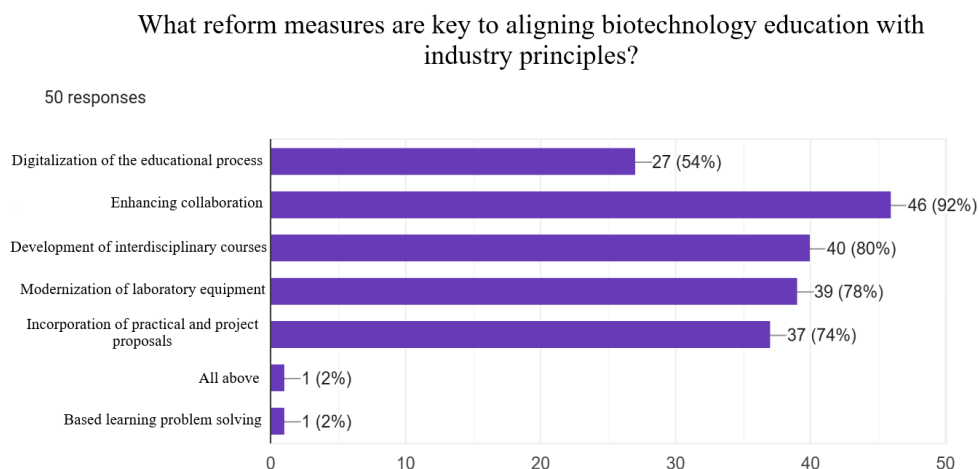


Figure 3. Key Reform Measures for Aligning Biotechnology Education (Questionnaire Results)

Additionally, BiH needs to develop a strategic framework for biotechnology development in the contexts of the green transition and the bioeconomy (aligned with the UNDP Agenda 2030), with clearly defined actors and objectives. At present, there is no national biotechnology development strategy, nor is this field precisely defined within the existing innovation, economic, or educational strategies. By creating a sectoral strategy at the state or entity level, it would be possible to define development directions (e.g., biopharma, agricultural biotechnology, biofuels, etc.) and purposefully channel resources and support.

A unique aspect of strategic orientation is the application of genomics and genomic technologies

in healthcare, particularly focused on sequencing the genome of a representative sample of the B&H population. Global trends increasingly demand the integration of genomics and the concept of precision (personalized) medicine, which, alongside other advanced engineering technologies such as imaging, big data processing, AI tools, and machine learning, relies primarily on the implementation of genetic and genomic analyses in medical diagnostics to determine therapeutic approaches more accurately and monitor the safety and efficacy of medical interventions.

Considering Bosnia and Herzegovina's bioethical and cultural specificities, the initiative, organization, and coordination of establishing a Human Genome Project in B&H and the reliable

application of genomic technologies must be central in national and comprehensive development strategies at all levels of government. Furthermore, the innovation ecosystem must include education and awareness-raising for the business sector. Many domestic companies are not aware that biotechnological solutions can be applied within their operations, such as in food and

beverage production, waste processing, livestock farming, viticulture and forestry, and the textile industry, among others. There is a need for seminars, workshops, and business symposia to concretely present these potentials and showcase regional best practices. In this domain, the academic community should play a leading role (Figure 4).

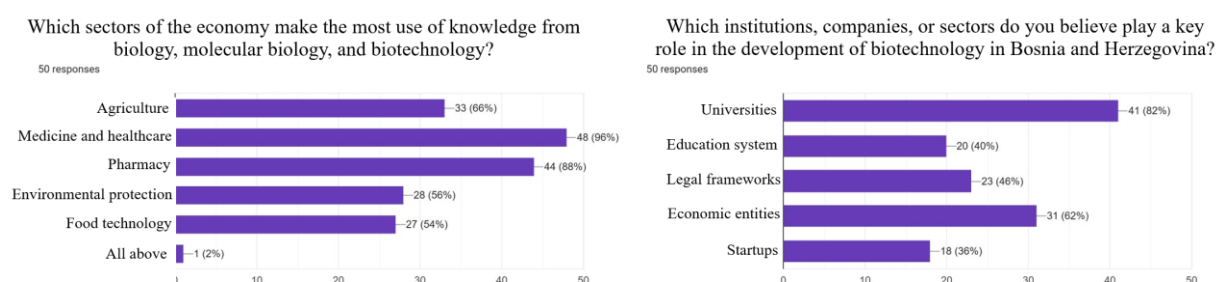


Figure 4. Economy sectors that make the most use of biological knowledge (left); Institutions, companies and sectors that play a key role in biotechnology development (right) (Questionnaire Results)

And finally, viewed from an international perspective, the initiative, expected to come from Bosnia and Herzegovina's government, implies the proactive and strategic use of international funding and collaboration programs, such as Horizon Europe, Interreg, and EU4Innovation. Participation in these programs enables domestic institutions and companies to engage in international biotechnology projects. This would open access to financial resources and advanced technologies, facilitate knowledge transfer, and enable the internationalization of local expertise.

Conclusion

The presented framework highlights the strategic importance of integrating biotechnology education with national and global priorities for sustainable development. By reinforcing interdisciplinary cooperation, updating curricula to reflect current

scientific and technological advances, and strengthening institutional capacities, Bosnia and Herzegovina can accelerate the formation of a skilled, innovation-driven workforce. The outcomes of the 2025 symposium underscore the need for continuous dialogue between academia, industry, and policymakers to ensure that biotechnology education remains responsive to emerging societal and economic challenges.

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