Biotechnology and its contribution to the agricultural economy: using microbes for increasing crop yields

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Abstract. The article analyses the significant role of biotechnology in the development of the agricultural economy, focusing on the use of microorganisms to increase crop yields. Biotechnology based on interaction with microbes represents an innovative approach that contributes to sustainable agriculture and optimization of production processes. The article elaborates on the various applications of microorganisms, including the use of nitrogen-fixing bacteria to increase soil nutrient content, phosphate-mobilizing microbes, and microorganisms involved in pathogen suppression and plant defense against diseases and stressors. Special attention is paid to biological fertilizers and biopesticides, which help to reduce the use of chemical agents, which in turn reduces harmful effects on the environment and human health. The prospects for using microbes to increase plant resistance to climate change, improve soil structure and quality, and optimize water use are discussed. The paper also analyses the economic benefits of microbial biotechnology in the agricultural sector, including reduced costs of chemical fertilizers and pesticides, as well as increased efficiency of agricultural production through increased yields. Successful examples of microbial technologies in agriculture and their contribution to global food security are highlighted. In conclusion, it is emphasized that the use of microorganisms in agriculture is a promising area that can not only increase yields and product quality, but also make a significant contribution to the sustainable development of the agro-industrial complex.

1 Introduction

Modern agriculture faces many challenges, including population growth, declining soil fertility, climate change and limited natural resources. These factors call for new solutions to improve the efficiency of agricultural production while minimizing environmental

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impact. In recent decades, the use of biotechnology has attracted considerable attention, offering innovative methods to address these challenges. One such method is the use of microorganisms, which play a key role in maintaining soil health and stimulating plant growth.

Microorganisms such as bacteria, fungi and other microbial communities can significantly improve agronomic processes. They can fix nitrogen, dissolve phosphate, suppress pathogens and improve soil structure, making them an important tool for increasing crop yields. These processes, called microbial biotechnology, are becoming an integral part of sustainable agriculture, offering environmentally friendly alternatives to chemical fertilizers and pesticides [1].

The application of microbial technologies can not only improve the efficiency of agricultural production, but also help to address global problems such as soil degradation and biodiversity decline. Given the significant potential of these technologies, research into their role in the agricultural economy and their contribution to increasing crop yields is becoming increasingly relevant.

The present work aims at analyzing the use of microbes in agriculture, reviewing the different methods of their application and assessing their contribution to the sustainability and productivity of the agro-industrial sector.

2 Materials and Methods

A number of research methods were applied in the process of writing the paper. Literature analysis and research reviews made it possible to study and systematize the existing scientific literature on the topic. The works of leading specialists on biotechnology, microbial processes in agriculture and their impact on crop yields were analyzed. The classification of existing microbiological technologies was also carried out and their application in agriculture was studied, which allowed structuring the materials and showing the differences between the methods used for different types of crops or agro ecosystems. The comparative analysis helped in comparing different biotechnological approaches such as the use of biofertilizers, biopesticides and other microbial technologies. The comparative analysis can compare their efficacy with traditional chemical means, assess the economic and environmental benefits of each approach, and identify optimal solutions for increasing crop yields.

3 Results

Biotechnology based on interaction with microbes is an innovative approach that contributes not only to sustainable agriculture but also to a significant optimization of production processes [2]. This method involves the use of microorganisms such as bacteria, fungi and other microbial communities to improve various agronomic parameters. Such microorganisms can stimulate plant growth, increase soil fertility, improve soil structure, and provide natural defense of plants against diseases and pests [3].

The use of microbes in biotechnology offers new opportunities to reduce dependence on chemical fertilizers and pesticides, thereby minimizing negative environmental impacts. It also contributes to the maintenance of biodiversity and sustainability of agro-ecosystems. This approach provides farmers with greener and more cost-effective solutions that can increase crop yields without compromising ecosystems.

Microbial-based biotechnology is thus becoming an important part of the strategy for transition to sustainable agriculture, contributing not only to increased production but also to the conservation of natural resources for future generations.

There are several methods of using microorganisms in agriculture that effectively utilize their unique abilities to improve soil quality, plant growth and disease protection. These methods include the use of different groups of microbes such as nitrogen-fixing bacteria, phosphate-mobilizing microorganisms and those that suppress pathogens. Let us consider them in more detail [4].

Nitrogen-fixing bacteria play a key role in maintaining and improving soil fertility, which directly affects plant growth and yields. Nitrogen (N) is one of the most important macronutrients required by plants as it is involved in the formation of proteins, nucleic acids and other vital molecules. Although the atmosphere is 78% nitrogen, it is not available in this form (N_2) to most plants. Nitrogen-fixing bacteria convert atmospheric nitrogen into ammonium (NH_4^+), which is readily assimilated by plants.

There are two main types of nitrogen-fixing bacteria used in agriculture - symbiotic bacteria such as *Rhizobium*, which form nodules on the roots of leguminous plants (peas, beans, soybeans, etc.), and free-living bacteria such as Azotobacter and Clostridium, which live in the soil and are able to fix nitrogen without symbiosis with plants.

The best known group of nitrogen-fixing bacteria is symbiotic bacteria of the genus *Rhizobium*, which form nodules on the roots of leguminous plants. This process starts with a chemical interaction between the roots of the plant and the bacteria. The roots release specific signaling molecules that attract *Rhizobium*, and the bacteria respond by synthesizing compounds that stimulate nodule formation [5].

In nodules, a biological nitrogen fixation process takes place in which bacteria convert atmospheric nitrogen (N_2) into ammonium (NH_4^+), which is then used by plants to synthesize amino acids and proteins. In return, bacteria obtain organic compounds from plants, such as sugars, which serve as a source of energy for the bacteria.

Consider the advantages of symbiotic nitrogen-fixing bacteria. For example, legumes with nitrogen-fixing bacteria can obtain up to 80% of the required nitrogen from the atmosphere, which significantly reduces the need for chemical nitrogen fertilizers. After the legume crop cycle is complete, the residual nitrogen in the soil can be utilized by subsequent crops, improving soil fertility for crop rotation. The introduction of nitrogen-fixing bacteria allows farmers to reduce the cost of purchasing nitrogen fertilizers and at the same time increase crop yields [6].

In addition to symbiotic bacteria, there are also free-living nitrogen-fixing organisms such as *Azotobacter*, *Clostridium* and *Cyanobacteria*. These microorganisms are able to fix nitrogen in the soil without entering into a symbiotic relationship with plants. They inhabit soils rich in organic matter and are most active under aerobic conditions. An example of the successful use of free-living bacteria is *Azotobacter*, which is used for soil and seed inoculation in various agricultural systems. This type of bacteria fixes atmospheric nitrogen and simultaneously stimulates plant growth by releasing phytohormones such as auxins, cytokinins and gibberellins, which accelerate the development of the root system and promote greater nutrient uptake [7].

Free-living nitrogen-fixing bacteria can be used not only on legumes but also on other plant species, which makes them more versatile. In addition to nitrogen fixation, some free-living bacteria secrete biologically active substances that stimulate plant growth and resistance to unfavorable conditions. Free-living nitrogen-fixing bacteria can function in a wide range of soil conditions and crop types.

The most traditional use of nitrogen-fixing bacteria occurs in legume crops, where symbiotic bacteria of the genus *Rhizobium* provide the main source of nitrogen for plants. The use of *Rhizobium* inoculants allows for sustainable growth of crops such as soybeans, beans and peas, resulting in higher yields and lower costs of chemical fertilizers.

Use of nitrogen-fixing bacteria in cereals and vegetable crops

In addition to legumes, nitrogen-fixing bacteria such as *Azospirillum* and *Azotobacter* are actively used for the treatment of cereals (wheat, maize, rice) and vegetable crops [8]. These bacteria help to improve nitrogen uptake, accelerate root growth and promote more efficient uptake of water and nutrients, leading to increased yields.

The introduction of legumes into rotations with other crops (e.g. cereals) improves the nitrogen balance of the soil. After legumes are harvested, nitrogen residues accumulated in the soil through the activity of *Rhizobium* bacteria become available to subsequent crops, increasing their productivity without additional fertilizer application.

Nitrogen-fixing bacteria are an effective solution for soil nitrogen enrichment, which makes them an important part of modern agro-technologies [9]. The use of both symbiotic and free-living bacteria can significantly reduce the use of chemical fertilizers, improve soil structure and fertility, and increase crop yields. This approach is particularly relevant for sustainable agriculture, where minimizing negative environmental impact and economic benefits are of key importance.

Considerable attention should also be paid to phosphate-mobilizing microorganisms. Phosphorus (P) is the second most important element after nitrogen for plant growth and development. It is involved in energy metabolism, formation of cell membranes and genetic material (DNA and RNA), as well as in the processes of photosynthesis and respiration. However, although soils may contain significant amounts of phosphorus, most of it is in a form that is inaccessible to plants, bound to minerals or organic compounds. This results in low phosphorus uptake and the need to apply large amounts of phosphorus fertilizer. However, these fertilizers are often inaccessible to plants due to their rapid binding to calcium, iron and aluminum in soils.

Phosphate-mobilizing microorganisms (PMMs), such as bacteria of the genera Pseudomonas, Bacillus, Penicillium, and Aspergillus, are able to solve this problem. They convert insoluble forms of phosphorus into plant-available phosphate, thereby increasing the efficiency of natural and applied phosphorus resources [10].

PMMs act through several biochemical mechanisms that ensure the transformation of phosphorus into available forms. Many phosphorus compounds in the soil are in organic forms that are not available for uptake by plants. PMMs secrete enzymes, such as phosphates, that break down organic phosphates into available inorganic forms.

In soil, phosphorus can be bound to calcium, aluminum and iron to form insoluble phosphates. PMMs secrete organic acids such as citric, lactic, and acetic and gluconic acids, which interact with these minerals to dissolve them and release phosphorus in a form available to plants. Microorganisms can release chelators, which are organic substances that bind to metals that block phosphates and release the phosphorus bound to them [11].

Some PMMs are able to secrete biosurfactants that reduce surface tension in the soil, improving phosphorus mineral dissolution and nutrient availability to plant roots.

The most widely studied groups of phosphate-mobilizing microorganisms are bacteria. In particular, genera such as *Pseudomonas*, *Bacillus*, and *Rhizobium* are actively used in agro-technologies to increase phosphorus availability. These bacteria are known for their ability to produce organic acids that convert insoluble phosphate into available forms. *Pseudomonas*, for example, can produce gluconic acid, which effectively dissolves calcium-phosphate in the soil.

Fungi of the genus *Aspergillus* and *Penicillium* also play an important role in phosphorus mobilization. These microorganisms are able to produce large amounts of organic acids, such as citric and oxalic acids, which are active against insoluble phosphorus compounds. Fungi are particularly useful in phosphorus-poor soils, where their activity can significantly increase the availability of this element to plants.

Mycorrhizal fungi such as *Glomus* create a symbiotic relationship with plants, helping them to absorb phosphorus that may be far beyond the reach of the root system. These fungi increase the area of contact with the soil and act as 'natural pumps', transferring hard-to-absorb nutrients, including phosphorus, to plants.

The main advantage of PMMs application is the improved availability of phosphorus to plants, which directly affects their growth and productivity. Phosphorus is essential for root development, flower and fruit formation, and general plant metabolism. The introduction of phosphate-mobilizing bacteria or fungi can optimize this process, especially in soils where phosphorus uptake is extremely low.

Modern agro-technologies often depend on the application of large quantities of mineral phosphate fertilizers, which quickly bind to soil minerals and become unavailable to plants. This is not only inefficient, but also harmful to the environment. The use of PMMs can significantly reduce the amount of fertilizer applied as the microorganisms make the existing phosphorus more available. This leads to cost savings on fertilizers and reduces their negative impact on ecosystems.

PMMs activity contributes to the improvement of soil microbiological activity and its structural characteristics. Organic acids produced by microorganisms can affect the solubility of other minerals, improving the overall soil condition. This improves soil water-holding capacity, aeration and overall biological activity, which creates favorable conditions for plant growth.

Phosphate-mobilizing microorganisms are actively used for seed treatment of cereal crops such as wheat, maize and rice. Inoculation of seeds with bacteria such as *Bacillus megaterium* and *Pseudomonas fluorescens* improves root development and access to phosphorus, which ultimately increases yields. Application of PMMs to vegetable crops such as tomatoes, potatoes and carrots also shows high efficacy. Incorporation of *Penicillium* and *Aspergillus* into the soil helps dissolve insoluble phosphate and improve phosphorus uptake by plants, which accelerates growth and improves product quality.

In organic agriculture, where the use of synthetic fertilizers is limited, phosphate-mobilizing microorganisms play an important role in maintaining soil fertility. The use of natural sources of phosphorus, such as bone meal, together with PMMs increases their efficiency and reduces costs.

Phosphate-mobilizing microorganisms represent an important tool to increase phosphorus availability and reduce dependence on mineral fertilizers in agriculture. Due to their unique biochemical mechanisms, PMMs efficiently convert insoluble phosphorus compounds into forms available to plants, resulting in improved crop growth and yield. The introduction of these microorganisms into agro-technologies contributes to sustainable agriculture, reduction of negative environmental impact and economic efficiency of production [12].

One of the most important problems of modern agriculture is the protection of plants from pathogenic organisms such as fungi, bacteria, viruses and insect pests. Traditionally, this task was solved using chemical pesticides and fungicides, which, although effective, can harm ecosystems, promote the development of resistant strains of pathogens and negatively affect human health. In this regard, the use of biological agents for plant protection, including microorganisms with antagonistic activity to pathogens, is becoming increasingly popular.

These microorganisms, including bacteria and fungi, not only inhibit the development of pathogens, but can also stimulate plant immune responses and improve plant resistance to stress factors. Key representatives of this group include bacteria of the genera *Bacillus*, *Pseudomonas*, and the fungi *Trichoderma* and *Gliocladium*. These microbes are actively used in biocontrol to suppress diseases, improve plant growth and increase resistance to unfavorable conditions [13].

Many beneficial microorganisms have the ability to directly inhibit the growth and reproduction of pathogens through the release of various antimicrobial substances. Some microorganisms produce natural antibiotics that inhibit the growth of pathogens. For example, bacteria of the genus *Bacillus* produce substances such as iturin, surfactin and phenazine, which act against a wide range of fungal and bacterial plant diseases.

Many microorganisms secrete enzymes that destroy the cell walls of pathogens. For example, the enzymes chitinase and glucanase destroy the cell walls of fungi, resulting in the death of pathogens.

Siderophores are low molecular weight compounds that bind iron in the soil and make it inaccessible to pathogens such as phytopathogenic fungi. Bacteria of the genus *Pseudomonas* and *Bacillus* actively synthesise siderophores, thereby inhibiting the growth of competing pathogens.

Beneficial microorganisms can also suppress pathogens by occupying ecological niches and competing for nutrients. This is particularly effective against soil and root pathogens such as *Fusarium* and *Phytophthora*. Beneficial bacteria and fungi can colonize the root zone of plants (rhizosphere), limiting pathogens' access to the resources needed for their reproduction.

Some microorganisms are able to activate the defense mechanisms of a plant, which increases its resistance to infections. This process is called induced systemic resistance (ISR). For example, the bacteria *Pseudomonas fluorescens* and *Bacillus subtilis* can stimulate the production of phytohormones and defense proteins, such as PR proteins (pathogenesis-related proteins), which help the plant to resist pathogen attacks more effectively [14].

Fungi such as *Trichoderma* and *Gliocladium* can act as hyperparasites by directly attacking pathogenic fungi. These microorganisms penetrate the mycelium of pathogenic fungi, destroy it and utilise it as a source of nutrients. For example, *Trichoderma* effectively suppresses phytopathogenic fungi such as *Botrytis cinerea*, *Rhizoctonia solani*, and *Sclerotinia sclerotiorum*.

4 Discussion

The prospects for the application of biotechnology and microorganisms in the agricultural economy are promising and cover a wide range of aspects including sustainable development, increased productivity, environmental safety and improved product quality. In the face of global challenges such as climate change, population growth and resource scarcity, the use of innovative biotechnologies may be the key to solving many of the problems facing agriculture.

Recently, there has been an active development and introduction of new bioproducts based on useful microorganisms. These products are able not only to protect plants from pathogens and improve their growth, but also to adapt to changing environmental conditions. For example, the development of microbial inoculants containing combinations of different microorganisms allows increasing the efficiency of application due to synergistic interaction between them.

Current research shows that combining different types of microorganisms can lead to significantly better results than using single strains. For example, the combination of mycorrhizal fungi and nitrogen-fixing bacteria can not only increase yields but also improve product quality by increasing nutrient content.

Genetic technologies make it possible to create new strains of microorganisms with improved properties, such as increased resistance to stress, higher productivity and nitrogen fixation capacity. Such advances open new horizons in the field of biotechnology and may become an important tool in the fight against global challenges in agriculture [15].

Organic farming actively uses microbial-based bioproducts to protect plants and improve their growth. These products are becoming increasingly popular as they help to comply with organic production standards and ensure that products are safe for human health and the environment.

The use of biotechnology and microorganisms in agrarian economies can significantly contribute to sustainable agricultural development. This is by reducing the use of chemical fertilizers and pesticides, improving soil structure and maintaining soil health, and increasing biodiversity in agro ecosystems [16]. The introduction of microorganisms that promote the growth and development of different plants can lead to increased biodiversity in agro ecosystems. This, in turn, strengthens the resilience of ecosystems to various stresses and pathogens, which is important for long-term food security.

The use of microbial-based biopreparations reduces the negative environmental impact of agriculture. This is due to the reduced use of chemical pesticides and fertilizers, which helps to reduce soil and water pollution, as well as improve the quality of products. The use of microorganisms and biotechnology can significantly increase crop yields. For example, inoculation of seeds with specific bacteria can increase both quantitative and qualitative yields, which is important to meet the growing demand for food [17].

The use of microorganisms such as mycorrhizal fungi and nitrogen-fixing bacteria can improve not only crop yields but also the nutritional value of agricultural products. This is particularly relevant in the context of increasing consumer interest in healthy eating and organic products.

The introduction of bioproducts can lead to lower production costs as they reduce the need for chemical fertilizers and pesticides, and promote more efficient use of resources such as water and land. This can make agriculture more economically sustainable and profitable.

The introduction of biotechnology in the agricultural sector can become an engine of economic development in rural areas. This is due to the creation of new jobs in the production of biopreparations, as well as an increase in farmers' incomes due to higher yields and product quality.

The development of biotechnology requires continuous education and research, which can lead to stronger co-operation between universities, research institutions and the agricultural sector to create new knowledge and technologies that will improve the agricultural economy [18].

Microbial technologies can be particularly useful for small and medium-sized farms that often face financial constraints. Biopreparations are usually more affordable than chemical agents and can be used to improve plant resistance and productivity, leading to improved economic performance of these farms [19].

The prospects for the application of biotechnology and microorganisms in the agricultural economy are promising and diverse. The introduction of these innovative approaches can be a key factor in addressing a host of pressing agricultural challenges, including increasing resilience to climate change, improving product quality and safety, and ensuring food security. These technologies open new horizons for the sustainable development of the agricultural sector, contributing to more efficient and environmentally friendly production systems that will be essential for future generations.

Biological fertilizers and microbial-based biopesticides represent an important step towards sustainable and environmentally friendly agriculture. Their use helps to reduce dependence on chemical agents, increase plant resilience to climate change, improve soil structure and quality, and optimize water use. In the face of global challenges such as climate change and a growing population, the application of these innovative solutions is becoming not only necessary but also strategically important for food security and environmental protection [20].

In recent years, the use of microbial technologies in agriculture has shown significant potential in increasing crop yields, improving product quality and resilience to climate change. The following are examples of the successful implementation of these technologies in different regions of the world, as well as their contribution to food security at the global level.

India, as one of the largest agricultural producers in the world, is actively using microbial technologies to improve the efficiency of the agricultural sector. In particular, the introduction of nitrogen-fixing bacteria such as *Rhizobium* and *Azospirillum* has helped farmers increase yields of pulses and cereals by 15-30%. In Uttar Pradesh, the introduction of microbial fertilizers led to a significant increase in pea production, improving both food security and income for local farmers. It has also helped to restore soil health, which is critical for long-term sustainable agricultural development [21].

In the United States, microbial technologies such as biopesticides based on the bacteria *Bacillus thuringiensis* (Bt) are actively used to control pests, including corn earworm and other insect pests. The introduction of Bt culture in maize production has reduced the use of chemical pesticides by 30-50%, which has not only improved environmental health but also reduced the cost of crop protection. It has also increased crop yields, which contributes to food security in the country.

In African countries such as Kenya and Uganda, farmers have started using mycorrhizal fungi to increase the resilience of staple crops such as potatoes and maize to unfavorable environmental conditions. Studies have shown that the use of mycorrhizal fungi can increase potato yields by 25-40 per cent under drought conditions. This is important for food security in regions where water scarcity is an ongoing problem [22].

As one of the leaders in agronomic innovation, the Netherlands uses precision farming systems that incorporate microbial technology to optimize fertilizer and pesticide use. Greenhouse complexes use microbial fertilization to help achieve high yields of tomatoes and cucumbers while keeping the use of resources to a minimum. This technology has enabled the Netherlands to become one of the largest exporters of fruit and vegetables, contributing significantly to Europe's food security.

Microbial technologies are helping to increase yields of staple crops, which is critical for global food security. With growing populations and a changing climate, this challenge is becoming increasingly urgent. The use of microbial technologies reduces dependence on chemical fertilizers and pesticides, which contributes to the environmental sustainability of agriculture. This is important for the long-term preservation of ecosystems and resources for future generations.

Microbial technologies tend to be more accessible to small farmers, thus improving their financial situation and increasing local food security. Adoption of such technologies helps small farmers to become more competitive in the market. Successful examples of microbial technology adoption in different countries emphasise the importance of international cooperation and knowledge sharing in agriculture. This allows best practices to be adapted to local conditions, thus increasing food security in different regions of the world [23].

The successful adoption of microbial technologies in agriculture demonstrates their significant contribution to food security at the global level. These technologies help to increase crop yields, improve product quality and reduce dependence on chemical inputs, making agriculture more sustainable and environmentally friendly [24]. With the growing challenges of climate change and increasing population, the application of microbial technologies becomes essential to create sustainable food systems that can meet the needs of humanity in the future.

5 Conclusions

The application of microbial technologies in the agricultural economy represents a revolutionary approach that promotes sustainable agriculture. The use of microorganisms, such as nitrogen-fixing bacteria and mycorrhizal fungi, can significantly increase resource efficiency, improving soil health and reducing dependence on chemical fertilizers and pesticides.

The introduction of microbial fertilizers and biopesticides leads to lower costs of chemical protection products and fertilizers, which is an important factor for farmers, especially in the context of rising agrochemical prices. These technologies help to increase the profitability of agricultural production by increasing yields and improving product quality.

Microbial technologies play a key role in food security, enabling increased food production against the backdrop of a growing population and a changing climate. Increasing crop yields and plant resistance to stresses such as drought and disease are important aspects for improving food availability.

The use of microbes to improve agronomic practices helps to reduce the negative environmental impact of agriculture. Reducing the use of chemical fertilizers and pesticides leads to improved ecosystem health, biodiversity conservation and better soil and water quality.

Given global challenges such as climate change and the need for sustainable development, microbial technologies have great potential for further development. Ongoing research and innovation in this field can lead to the development of new efficient bioproducts, enabling more efficient use of resources and adaptation to changing conditions.

Education and awareness-raising among farmers about the benefits of microbial technologies are important prerequisites for their widespread adoption. Educational programmes and initiatives aimed at teaching effective microbial practices will help accelerate the transition to more sustainable and environmentally friendly farming methods.

Overall, microbial technologies represent an important tool for transforming the agricultural sector, contributing to economic growth, food security and climate resilience. The application of these technologies not only meets the current challenges of agriculture, but also opens new opportunities for a safer and more environmentally sustainable food system in the future.

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