Nano fertilizers

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Abstract. In the context of global military conflicts and crises, the food habits and needs of the population are constantly growing. Global agricultural policy develops policies within the framework of the goals set by the UN. Sustainability strategies are part of the agricultural sector, setting requirements for the development of the sector in line with climate change, environmental approaches, and cost-effective tools for achieving sustainable agriculture. Against this backdrop, nano fertilizers could find their place as an element and tool for achieving the set sustainability criteria. By applying a descriptive-analytical approach and methods of analysis and synthesis, the aim of the study is to present the characteristics, application, and significance of nano fertilizers within the fertilizer market and the bioeconomy. Keywords: nano fertilizers, nanotechnology, sustainable agriculture, fertilizer market, bioeconomy.

1 Introduction

The widespread use of fertilizers in the last few decades has enabled a significant increase in global food production capacity. Recent studies by authors (J. Penuelas, F. Coello & J. Sardans, 2023) show the consequences of unbalanced and irrational use of fertilizers in individual countries. Their effect is characterized by disturbances in soil balance, inefficient food production, and damage to the environment.

Authors write that the agricultural system faces several challenges, the most important of which is the ability to feed the growing world population and mitigate climate change. In this context, improving the agronomic efficiency of fertilizers while reducing their costs and environmental impact is one of the biggest tasks [1]. In this regard, reviewing the scientific literature on innovative fertilizers, they define so-called "smart" fertilizers, indicating their varieties: a) ***nano-fertilizers***; b) ***composite materials***; and c) ***bioformulations***. Nano fertilizers are presented as smart fertilizers with a single number of nutrients for controlled release as an operational mechanism. Furthermore, nano fertilizers are an alternative to chemical fertilizers and an opportunity to achieve the goals of sustainable agriculture. In global agricultural policy, sustainability is a key tool and measure of effectiveness in individual areas. The environmental impact of using nano fertilizers would contribute to the achievement of sustainability strategy goals. This determines the ***relevance and interest*** of authors in the issue.

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2 Fertilizers market

2.1 Global market overview

The fertilizer market is a sector of the agricultural industry that produces and distributes fertilizers to farmers and other agricultural producers. Fertilizers are used to supplement the soil with essential nutrients such as nitrogen, phosphorus, and potassium, which are necessary for healthy crop growth. Fertilizers can be organic or synthetic and come in various forms, including granular, liquid, and gaseous. In recent years, the fertilizer market has seen an increase in demand due to the growing global population and the need to raise food production. As a result, the market is expected to continue growing in the coming years, according to forecast by Research and Markets (2025). Research by McKinsey & Company (2024) forecasts growth in demand for fertilizers of around 2.1% per year until 2027, and capacity growth of around 2.5%. Future demand for fertilizers will be influenced by consumer preferences, climate change, and technological developments. According to Mordor Intelligence (2025), the fertilizer market is estimated at US$402.5 billion in 2025 and is expected to reach US$541.2 billion by 2030, growing at a CAGR of 6.10% during the forecast period (2025-2030). Looking ahead, IMARC Group estimates that the market will reach US$246.6 billion by 2033, growing at a CAGR of 3.07% during the period 2025-2033.

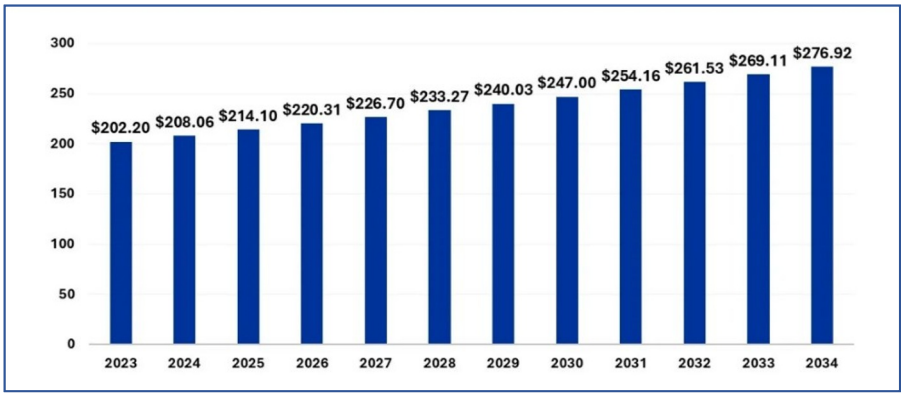

Fig. 1. Fertilizer Market Size 2023 to 2034 (USD Billion)

Source: Precedence Research, 2025. https://www.precedenceresearch.com/specialty-fertilizers-market

The Asia-Pacific region is the world's largest producer of agricultural products. Agriculture is crucial to the region's economy, employing around 20% of the total available workforce. The region is characterized by higher demand for food and a boost in the development of technology, research, and development (R&D). Together with rising incomes and government subsidies, these are factors that explain the market picture.

North America is the second largest cultivated region in the world. The need to meet growing demand for agricultural products due to population growth and changing dietary habits is driving the fertilizer market in the USA. Increasingly, precision farming techniques that optimize fertilizer use are also driving growth. Government initiatives, combined with subsidies, are encouraging farmers to strive for more sustainable food security while increasing demand for fertilizers. Organic farming is on the rise, and there will be greater demand for bio-based and organic fertilizers. Other advances in fertilizers include slow-release products and efficient nutrient content that ensure high crop yields while leaving

little residue that harms the environment. Some of the challenges are fluctuating raw material prices and regulatory pressure, but the answer to this is through creative innovation.

In 2024, the United States accounts for over 77.80% of the fertilizer market in North America. The fertilizer market also faces challenges related to rising energy prices, but this is offset by environmental innovations in fertilizers and government-supported research and development programs. Strategic cooperation with and investment in local production further strengthen the global position of the US fertilizer market.

The fertilizer market in Latin America is growing rapidly, with Brazil being the largest consumer in the region, consuming 41.1 million metric tons in 2022, according to the National Fertilizer Promotion Association. Latin America is strategically located and has export potential. It is therefore one of the important players in the global fertilizer market. The Middle East and Africa have become important geographical regions in the global fertilizer market. This is due to the region's huge natural gas reserves. These can be used cheaply to produce ammonia and urea, which are mainly used in the production of nitrogen fertilizers. The conflict between Russia and Ukraine disrupted traditional trade flows in the Black Sea, increasing demand for exports from the Middle East. Africa faces challenges in increasing production, but investments in fertilizer plants are underway, supported by international cooperation. Rising global prices have prompted African governments to prioritize fertilizer affordability. At the same time, the Middle East is a leader in export markets due to its strategic location and competitive production costs, making it an important player in the fertilizer supply chain.

Sustainability and technological innovation characterize the fertilizer market in Europe, which is a result of strict government policies. According to Eurostat data, approximately 8.9 million metric tons of nitrogen fertilizers were consumed in the region in 2022. Ammonia production became more expensive due to shortages caused by the conflict between Russia and Ukraine, so manufacturers sought more environmentally friendly alternatives. Europe is also investing significantly in research and development to produce innovative fertilizers that meet sustainability goals. Mature markets such as Germany and France are focusing on precision farming and nutrient efficiency, which ensures stable demand for fertilizers. These factors are increasing the demand for fertilizers and offering favorable prospects for the fertilizer market, according to IMARC Group (2024).

South America and the Asia-Pacific region are important markets for fertilizers, as they are characterized by an expansion of arable land in order to meet increased food needs. Where there is a shortage of nutrients, such as in Europe and North America, the effectiveness of specialized fertilizers is sought. These trends are set to drive the primary nutrient fertilizer market during the 2024-2030 period. (fig. 2):

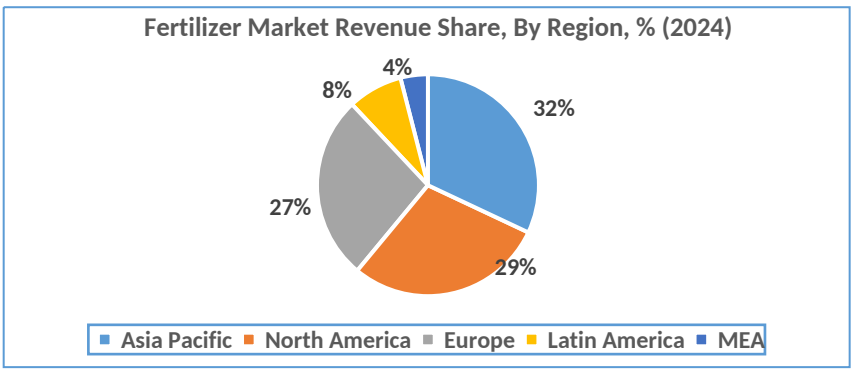

Fig. 2. Fertilizer Market Revenue Share, 2024. Source: Precedence Research, 2025, https://www.precedenceresearch.com/specialty-fertilizers-market

Precedence Research (2024) reports that the fastest growth is expected in the Middle East and Africa during the forecast period. With the significant increase in demand for organic products, organic farming practices are gaining pace in Middle Eastern countries. This, in turn, increases the demand for organic or biofertilizers to improve crop quality, thereby stimulating market development in the region.

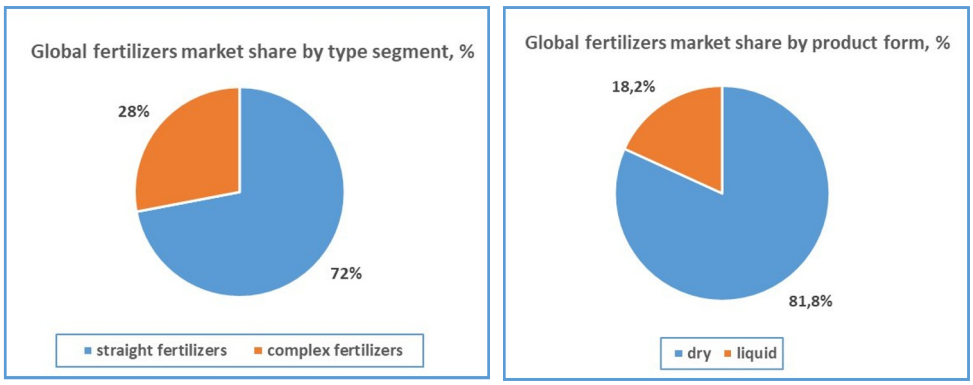

Fig. 3. Global Fertilizers Market Share, 2024. Source: Mordor Intelligence, 2025, https://www.mordorintelligence.com/industry-reports/fertilizers-market & IMARC Group, 2024, https://www.imarcgroup.com/fertilizer-market

Straight fertilizers, which include products with a single nutrient, such as nitrogen, phosphorus, or potassium fertilizers, are the leaders in the global fertilizer market. These fertilizers are widely used only when a deficiency of a specific nutrient is identified in the soil, allowing for targeted application to the crop. Taking into account local micro-conditions, soil conditions, and crop needs, precision farming practices are encouraged, allowing for direct fertilization with efficient and targeted nutrient supply. With the growing demand for food products and the need to optimize yields, direct-application fertilizers are becoming indispensable for farmers seeking to achieve higher productivity while maintaining soil health. Because these products are designed to meet specific nutrient needs, their use is expanding in regions where soil fertility is low or where nutrients are needed for optimal crop growth. These easy-to-use formulations, which have a direct impact on crop yields, make them popular among farmers in general, according to the IMARC Group (2024). Several factors determine the leading market positions in this segment: effective provision of essential nutrients for various crops, accessibility, and competitive prices compared to complex assortments. The strength of this segment is particularly evident in field crops, where precise nutrient management is critical. Straight fertilizers offer farmers flexibility in tailoring individual nutrient applications based on specific crop requirements and soil conditions, making them particularly valuable in precision farming practices. Strong results in the segment are also supported by their wide availability, established distribution networks, and growing concerns about nutrient leaching, which necessitates targeted nutrient application. Complex fertilizers are emerging as the fastest-growing segment of the global fertilizer market, which is expected to expand at a CAGR of approximately 6% from 2024 to 2029. This growth is due to increasing awareness of balanced crop nutrition and the segment's ability to provide multiple nutrients in a single granule. The compound fertilizer market is gaining popularity, especially in regions where modern agricultural practices are implemented, where convenience and efficiency in nutrient delivery make them increasingly attractive to farmers. The segment's growth is further stimulated by technological advances in fertilizer production, leading to improved nutrient release patterns and increased crop uptake efficiency. In addition, according to Mordor Intelligence (2025), growing demand for

specialized complex fertilizers for high-value crops and an increasing focus on sustainable farming practices are contributing to the segment's accelerated growth.

As IMARC Group (2024) reports, dry fertilizers dominate the market, with an 81.8% share in 2024. The widespread acceptance of dry fertilizers is due to the fact that they are easy to use and can be applied in significant quantities. Dry fertilizers are usually spread or directly imported into the soil. Dry fertilizers have a long shelf life and do not decompose easily under various environmental conditions, making them more reliable for farmers. Dry fertilizers are also suitable for places where transport and distribution logistics require the delivery of large quantities, as they can be delivered and stored in large quantities. The dry fertilizer market continues to grow as more global agricultural sectors adopt highly efficient farming practices, such as precision farming, which requires timely and efficient application of nutrients. The cost-effectiveness of dry fertilizers, combined with their availability, ensures continued dominance in the fertilizer sector.

According to data from IMARC Group, in 2024, the chemical fertilizer segment will lead the global fertilizer market, holding a significant 66.6% market share. The growth of this segment is mainly due to the increasing demand for food products, especially in regions where large-scale agricultural activities are carried out. Optimal crop growth and the restoration of essential nutrients in the soil are determined by the availability of chemical fertilizers. However, chemical fertilizers play a crucial role in meeting food security challenges in the context of a growing global population by increasing the productivity of existing arable land. Chemical fertilizers are also relatively inexpensive and provide immediate benefits, making them the preferred choice of farmers worldwide. Innovations in this segment are also being made with new formulations such as slow-release and controlled-release fertilizers to promote nutrient uptake, reduce harmful environmental impacts, and reduce application, contributing to continued market dominance (fig. 4).

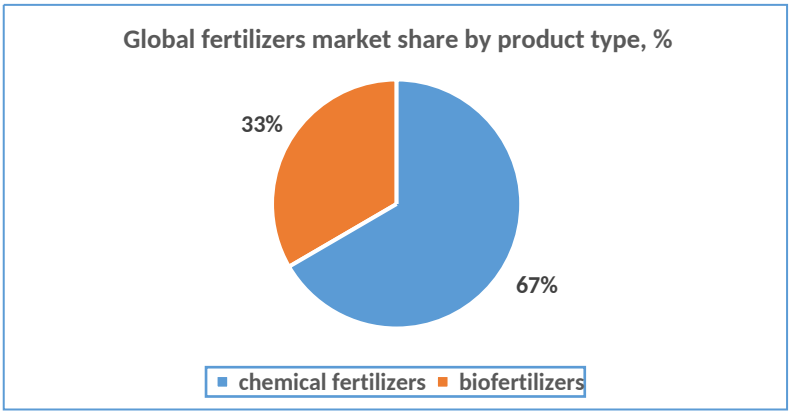

Fig. 4. Global Fertilizers Product Market Share, 2024. Source: IMARC Group, 2024, https://www.imarcgroup.com/fertilizer-market

According to forecasts by the European Fertilizer Association for 2024, consumption of the three nutrients (N, P, K) will increase for almost all field crops over the next 10 years. The forecast is for nitrogen consumption to increase for all major crops, except for fodder crops and grassland, where consumption will decrease by -3.0% and -0.4% respectively. Phosphate consumption is expected to increase for all major crops (with the largest increase for oilseeds, at +27.6%). Potash consumption is also expected to increase for all major crops (i.e., sugar beets by +24.5% and potatoes by +21.9%).

2.2 Trends in fertilizers industry

Like any market, the fertilizer market is influenced and affected by various factors. Leading market and marketing analysts mentioned above summarize and forecast the impact of these factors on the development and trends in the fertilizer industry. The driving forces that emerge and, in certain cases, limit and shape trends in the sector may be those listed in Table 1.

Table 1. Trends in fertilizers industry

Drivers	Impact
Urbanization and global food demand	According to the United Nations, the world population is expected to reach 9.7 billion by 2050, increasing food demand by 60% by mid-century. Demand for fertilizers to increase soil fertility and ensure sustainable production will continue to grow, stimulating market growth.
Government Initiatives and Subsidies	Similar rural development policies and programs boost the fertilizer market because they make fertilizers more accessible to farmers while also supporting agricultural productivity and sustainable practices. Policy changes, such as subsidies or penalties, can improve or hinder the use of certain fertilizers by changing market dynamics.
Economic Development and Increasing Incomes	Emerging markets and developing economies are contributing most to this growth, with average GDP growth of 4.2%, compared to 1.8% in developed economies. Economic growth raises living standards and changes dietary habits towards greater consumption of a variety of food products. This change in food consumption, such as increased meat consumption, requires more animal feed, which in turn requires fertilizers to grow raw materials. In addition, rising incomes allow farmers to invest in improved agricultural techniques, including fertilizers, to increase yields and improve quality.
Environmental policies and regulations	Environmental concerns and stricter regulations on chemical fertilizers are driving a shift toward bio-based fertilizers and specialty fertilizers that offer better nutrient efficiency and less environmental impact. Manufacturers are taking steps to produce more environmentally friendly and sustainable fertilizers.
Technology innovations	Innovations in fertilizer technology include slow-release fertilizers, controlled-release fertilizers, and microencapsulated fertilizers, which provide better nutrient delivery and reduced environmental impact. These technologies increase crop yields while minimizing nutrient waste, which is particularly beneficial for sustainable agriculture. Innovations such as nanotechnology improve the effectiveness and efficiency of phosphate fertilizers. These innovations reduce the amount of fertilizer needed to improve yields. Growing emphasis on smart farming and artificial fertilizers.

Source: adapted by the authors

As the population in developing countries grows, demand for agricultural products increases. The market is also stimulated by agricultural producers who recognize the role of fertilizers in yields and production, as well as their importance for plant growth and soil health. They improve soil fertility and replace nutrients in the soil that have been taken up by previous crops. Nitrogen, phosphorus, and potassium are important nutrients necessary

for plant growth. Therefore, as noted by Precedence Research (2024), the expansion of the agricultural ecosystem is leading to increased demand for fertilizers from India and China.

It is predicted that by 2050, the world's population will grow to around 9.7 billion people, which will have a serious impact on agricultural systems for food supply. The problem is complicated by the reduction in the amount of arable land due to increasing urbanization, which requires greater intensification of the available agricultural areas. The need for fertilizers is therefore becoming critical in order to increase crop yields and meet food needs. According to the FAO, global demand for cereals is expected to grow by more than 50% by mid-century, driven by increased consumption in developing economies. In addition, increasingly popular precision farming methods allow farmers to use fertilizers more efficiently, thereby minimizing losses. Although nitrogen fertilizers continue to be used most extensively in countries with staple crops such as corn, wheat, and rice, their use is also increasing in emerging markets such as Africa, as noted by the International Fertilizer Association (IFA). The African Union's Fertilizer Finance Facility in Africa aims to increase access to fertilizers for smallholder farmers by 50% by 2030 to help boost agricultural productivity levels. They emphasize the importance of fertilizers in meeting global food security challenges as population pressures and demand patterns change rapidly.

Industry trends can be influenced by certain ***limiting factors.*** For example, fluctuations in fertilizer prices depend mainly on the variability of raw material costs, which include the variability of natural gas, phosphate rock, and potash. Political tensions, trade policies, and the devastating effects of natural disasters can also disrupt supply chains, further exacerbating price volatility. Such situations make fertilizers inaccessible to farmers in developing countries, which affects global food production. Manufacturers face the challenge of stabilizing prices while maintaining profitability and ensuring consistent supplies for the growing needs of agriculture. Geopolitical tensions, high energy prices, and challenges to the global supply chain are causing fluctuations in the availability and prices of raw materials, which is hampering market growth and profitability. Governments around the world are imposing strict regulations on the use of traditional chemical fertilizers due to their negative impact on the environment, including soil degradation and water pollution. This creates obstacles for traditional fertilizer manufacturers, according to S&S Insider (2023). The use of chemical fertilizers has contributed to environmental concerns related to soil degradation, water pollution, and greenhouse gas emissions. Excess nitrogen and phosphorus compounds in fertilizers leach into waterways and cause eutrophication, which causes aquatic organisms in these waterways to die. Strict regulations on fertilizer use in most countries call into question the functioning of the market. Manufacturers are taking steps to produce more environmentally friendly and sustainable fertilizers. The transition to more sustainable practices is slow and costly, according to Research and Markets (2025).

Strict environmental regulations to reduce the impact of conventional fertilizers on soil and water pollution pose a serious threat to the global fertilizer market. As a result, both governments and environmental organizations point to the environmental problems associated with chemical fertilizers, including pollution of surface waters through runoff, soil depletion, and greenhouse gas emissions during production and as a result of their application. Consequently, a number of countries have introduced strict regulations limiting the use of nitrogen- and phosphorus-containing fertilizers. For example, to reduce nitrogen losses to surface waters, the EU's Common Agricultural Policy has introduced restrictions on nitrogen application rates. Compliance with these provisions requires costly changes to the production process, as well as research into whether it can be replaced by more environmentally friendly alternatives. The provisions are intended to promote better agricultural systems in the future, but at the same time they create additional difficulties in operation and reduce the profit margins of conventional fertilizer producers. Thus, S&S

Insider (2023) concludes that the industry is faced with the challenge of switching to bio-based fertilizers or specialty fertilizers that can comply with lending regulations.

Smart farming techniques enable the precise application of fertilizers based on data such as crop requirements and soil moisture content, thereby reducing nutrient losses for food security. This targeted approach helps to minimize fertilizer losses by optimizing their use. In addition, the growing focus on the production of artificial fertilizers from renewable resources creates enormous opportunities for market participants. Artificial fertilizers reduce environmental impact and improve soil fertility, according to Precedence Research (2024).

Against this backdrop, the use of **nanotechnology** could prove to be a step towards supporting the driving factors and reducing the impact of constraints on the fertilizer market, as well as achieving sustainable production and consumption in line with the industry's regulatory and environmental requirements.

3 Nano fertilizers

Excessive use of synthetic fertilizers causes economic burdens and increases soil, water, and atmospheric pollution. Nano fertilisers show great potential for sustainable use in increasing soil fertility and crop production with minimal or no environmental compromises. They are sub-microscopic in size, have a large surface-to-volume ratio, can encapsulate nutrients, and have greater mobility, thereby increasing plant access to nutrients and crop yields. Due to these properties, **nano fertilisers** are considered a ***"smart nutrient system"*** [2].

Ecosystem services and environmental quality are heavily impacted by the excessive use of chemical fertilizers in agricultural production systems to meet the food needs of a rapidly growing population. It is therefore necessary to develop an alternative mechanism for increasing agricultural production and environmental sustainability. Nano-hybrid structures, such as nano fertilizers (NFs), are an excellent alternative for overcoming the negative impact of traditional chemical fertilizers. NFs provide intelligent delivery of nutrients to plants and prove their effectiveness in terms of crop productivity and environmental sustainability compared to bulky chemical fertilizers. Plants can absorb NFs through their leaves or roots, depending on the application methods and particle properties. NFs increase plant resistance to biotic and abiotic stresses. They reduce production costs and mitigate environmental impacts. The many benefits of nano fertilizers open up new prospects for sustainable agriculture and mitigating the effects of climate change. However, excessive doses of NFs have a detrimental effect on crop growth, soil health and the environment. The widespread release of NFs into the environment and the food chain may pose a risk to human health and therefore needs to be carefully assessed. Hence, an in-depth review of the role of different NFs and their impact on crop growth, productivity, soil quality and the environment is needed, which would be useful for research on sustainable agriculture [3].

3.1 Nano technologies and fertilizers

Agriculture needs qualitative and quantitative improvement to achieve sustainability in the face of a constantly growing population and its food needs. Limiting fertilizer waste in the environment is one of the guidelines in this area, and nanotechnologies, with the advantages they offer, can be an effective alternative to conventional fertilizers [4].

Achieving higher quality through the application of environmentally friendly technologies requires a progressively new approach, such as nanotechnology, combined with financial stability and biological support. Nanotechnology offers a solution to overcome the limitations of conventional agriculture. That is why the latest developments in agriculture using nanoparticles (NPs) need to be thoroughly researched. The use of nanotechnology in agriculture is still in its infancy. However, it has the potential to transform new agricultural

systems, especially when it comes to issues related to fertilizer application. The impact of nano fertilizers on the production of various crops is related to their greater reactivity and solubility, better penetration through the cuticle, ensuring targeted delivery. As a result, improved growth and yield are reported, leading to targeted delivery. In addition, the authors also note a reduction in abiotic stress and heavy metal toxicity, which also means a reduction in fertilizer emissions. This improves the quality and efficiency of the nutrients applied [5].

The authors [6] explain that environmental protection, financial stability, and biological sustainability are more than noticeable consequences of nanoproducts that support plant crops. Reviewing the latest trends in the use of engineered nanomaterials (ENMs) in agriculture, they present the main applications of nano-fertilizers in the form of: nanoemulsions, nanogels, inclusion complexes, solid lipid nanoparticles (SLNPs), dendrimers, polymeric micelles, liposomes. Other researchers [7] consider nano fertilizers to be one of the most promising engineered materials being tested for both soil and foliar applications. According to the authors [8], the main purpose of applying NFs is to regulate the rate of nutrient release with high efficiency of nutrient uptake to meet the needs of crop growth and productivity. There are many different forms of nano fertilizers that can be made using many natural and synthetic materials. The nano-production of fertilizers can be classified into the following **categories**:

- ***Nano-supported fertilizers*** or nano-sized additives (bulk products with nano-sized additives): a type of fertilizer in which nanostructured materials can be applied as additives to regulate the release of fertilizers (e.g., entrapment nano fertilizer and adsorption nano fertilizer), nutrients included in nanocarriers;
- ***Nano-scale fertilizers*** or synthesized nanoparticles that refer to fertilizers made at the nanoscale, and
- ***Nano-coated fertilizers*** or nanoscale coatings or carrier materials (a product coated with a nano polymer or loaded with nanoparticles, where nano-coatings or coatings of nanomaterials are applied to contain conventional-sized fertilizers.

Nanotechnology has the potential to significantly increase crop yields and improve food production systems. This innovation could lead to more precise application of nutrients and savings in their use. The application of nanotechnology in the use of fertilizers has also been summarized by authors [9] who write that it has already been proven that better nutrient uptake is due to the increased surface-to-mass ratio of fertilizers. This is achieved by reducing particle size through physical or chemical methods. Thus, fertilizer application rates and costs are reduced, allowing for slow and targeted delivery of nutrients. As a result, the use, release, and absorption of nutrients are 20-30% more efficient when using nano fertilizers instead of conventional fertilizers.

According to the authors [10], the definition of nano fertilizers refers to their size characteristics. Nano fertilizers have the same functional purpose as conventional fertilizers, but are 1-100 nm in size, and their definition also includes bulk materials used in combination with nanoscale structures to create new products (e.g., fertilizer molecules coated with metal nanoparticles). Nano fertilizers have the ability to deliver nutrients to plants slowly and in a targeted manner, thereby increasing the efficiency of nutrient use and the rate of fertilizer application. Fertilizers produced using nanotechnology increase agricultural productivity. The authors emphasize that there is no single systematic classification of nanomaterials, specifying that nanomaterials can be classified into different types according to their size, morphological characteristics, physical and chemical properties. Their classification based on *composition and structure* is presented as: ***metal-based nanomaterials*** (nanosilver, nanogold, etc.); ***ceramic-based nanomaterials***; ***polymer-based nanomaterials***. According to their *application*, nano fertilizers are divided into four classes: **nano fertilizers with macro elements**, **nano fertilizers with microelements** (mainly in the form of oxides**), fertilizers enriched with nanomaterials - NEF** (they do not supply, but rather support the

effective absorption of nutrients – zeolites and chitosan in the form of nanoparticles are often used); **nanomaterials that stimulate plant growth** (graphene, nanotubes, etc.) [10]. Presenting the authors' summaries, Raimondi et al. [1] identify three main categories for classifying nano fertilizers: ***nanoscale fertilizers***—fertilizers whose size is reduced using physical, chemical, or biochemical methods; ***nanoscale additives***—added to bulk products as additives for secondary considerations; ***nanoscale coating materials*** or ***host materials***—materials for nanocoating (zeolites, other clays, and thin polymers) that are typically used to control the release of incorporated nutrients or as supporting fillers for forming nanocomposite structures that improve the thermal stability and mechanical properties of the bulk material.

Nano fertilizers are fertilizers produced using nanotechnology. They consist of nanoparticles containing micro and macro elements that are important for plant nutrition and food production, which are the basis of their growth, such as nitrogen, phosphorus, potassium, etc. Thanks to their nanoform, they are able to deliver these elements to plants in a regulated manner, either individually or in combination with nanoscale absorbents. The authors believe that the advantages offered by nano fertilizers, such as controlled release within the targeted delivery of nutrients, achieve the goals of sustainable agriculture [11].

As representatives of smart fertilizers, nano fertilizers represent a transformative approach to nutrient management in agriculture, using advanced technologies to optimize fertilizer application and increase crop yields while minimizing negative environmental impacts through mechanisms tailored to specific nutrient and soil needs through controlled delivery and release of nutrients to plants. New technological fertilizers support the rational use of resources, improve soil health and sustainability in agriculture by maximizing nutrient efficiency and reducing leaching and runoff. They also promise to mitigate the adverse effects of conventional fertilizers on water quality and greenhouse gas emissions, thereby supporting efforts towards a more environmentally friendly and sustainable agricultural system [12].

In this way, nano fertilizers are an expression of the bioeconomy within agricultural policy.

3.2 Nano fertilizers and bioeconomy

T. Turlakova (2021) provides a comprehensive summary of the scope of the bioeconomy. She points out that it is an innovative approach that integrates natural and labor resources, together with production capacities and scientific achievements in the field of innovation and technology. By combining material production with the transformation processes involved in it and energy, sustainability is achieved in specific areas – production, consumption, and economic development. This is due to the more efficient use of raw materials (organic and mineral sources), leading to the conservation of resources and the environment with a desired increase in the standard of living of the population.

According to Beluhova-Uzunova et al. (2019), agriculture is a key sector for the bioeconomy, which has emerged as a result of the challenges facing the global economy. The bioeconomy is a concept for achieving sustainability across all criteria within production, resource management, climate change mitigation and negative impact on nature, improving public health through integration for social and economic development. This is also confirmed by authors who summarize the elements of the bioeconomy as: core, partial, and indirect, where agriculture is a core element [13]. Agricultural and food systems represent the largest share of the global bioeconomy and therefore have enormous potential to deliver transformative solutions to many sustainable development challenges.

D. Kirechev & A. Petev (2021) summarize the complex and unpredictable challenges that require a consistent transition to food system sustainability, with policy changes at the

international, regional, national, and local levels. According to them, innovations support the achievement of the three pillars of sustainability in agriculture, as long as they are accessible, acceptable, and generate income for small farmers. Thus, nano fertilizers play a role in ensuring ecological and economic sustainability criteria through the objectives of the bioeconomy.

Access to affordable fertilizers can be seen as a major challenge to the viability of industrial agriculture and the realization of a bioeconomy based on this production system [14]. By investigating the effects of combined use of nano- and conventional fertilizers, authors reveal further research and field trials of nano fertilizers alone or in combination with conventional fertilizers are essential to fully reveal their benefits and establish their long-term effects, which may offer a path to more efficient and environmentally friendly crop nutrition. They show the benefits of growing crops like wheat, corn, and millet when using nano-N and nano-Zn. Adding them together with nitrogen fertilizers helps improve nutrient uptake. In addition, properties such as dehydrogenase activity and carbon biomass in the soil increase yields [15].

The conclusions of Beluhova-Uzunova et al. (2019) indicate that there are challenges associated with developing and implementing national and regional bioeconomy strategies that could ensure the development of smart specialization and green growth. Overall, more cooperation and coordination at international level is needed to promote the development of the bioeconomy and increase the potential of the concept. Global governance of the bioeconomy is very important and needs to be developed. On the other hand, cooperation and coordination between science and business are necessary to put the principles of the bioeconomy into practice.

Thus, improvements in the sector through the implementation of environmental policies, proclaimed by the requirements for a green economy within sustainable agriculture determine the industry's leading role in the field of fertilizers in achieving the goals of the bioeconomy.

4 Conclusions

The future belongs to nanotechnologies, which are a key tool for achieving the three dimensions of sustainability. Sustainable development strategies cover various sectors of the economy, and the agroecological approach determines the achievement of sustainable agriculture. The incorporation of nanotechnology into its framework is inevitable. Global agricultural policy requires compliance with constantly growing food needs. The implementation of appropriate policies in the sector leads to the application of environmentally friendly and economically viable ways to achieve sustainability, considering all factors that have an impact. Nano fertilizers are being scientifically studied for the purposes of sustainable development and the potential that agriculture could develop to support the implementation of sustainable agriculture strategies, respecting the possible advantages and minimizing any negative impacts.

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