BİLİM-TEKNOLOJİ-YENİLİK EKOSİSTEMİ DERGİSİ

JOURNAL OF SCIENCE-TECHNOLOGY-INNOVATION ECOSYSTEM

E-ISSN : 2757-6140 Cilt | Volume : 6 Sayı | Issue : 1 Yıl | Year : 2025

JOURNAL OF SCIENCE-TECHNOLOGY-INNOVATION ECOSYSTEM
BİLİM-TEKNOLOJİ-YENİLİK EKOSİSTEMİ DERGİSİ

JSTIE 2025, 6(1)

Bilim-Teknoloji-Yenilik Ekosistemi Dergisi (BİTYED) yılda İki kez (Haziran ve Aralık) yayınlanan uluslararası veri indeksleri tarafından taranan hakemli bir dergidir. Gönderilen makaleler ilk olarak editörler ve yazı kurulunca bilimsel anlatım ve yazım kuralları yönünden incelenir. Daha sonra uygun bulunan makaleler alanında bilimsel çalışmaları ile tanınmış iki ayrı hakeme gönderilir. Hakemlerin kararları doğrultusunda makale yayımlanıp yayımlanmaz kararı alınır.

Bilim-Teknoloji-Yenilik Ekosistemi Dergisi'nde yayınlanan makalelerde fikirler yalnızca yazar(lar)ına aittir. Dergi sahibini, yayıncıyı ve editörleri bağlamaz. Bu sayıda yer alan tüm çalışmalar başvuru anında ve yayın öncesi olmak üzere iki kez **iThenticate** uygulaması aracılığıyla benzerlik taramasından geçirilmiştir.

Bilim-Teknoloji-Yenilik Ekosistemi Dergisi (BİTYED)
Çanakkale Onsekiz Mart Üniversitesi, Bilim ve Teknoloji Uygulama ve Araştırma Merkezi (ÇOBİLTUM)
Terzioğlu Kampüsü, 17100 – Çanakkale – TÜRKİYE
Telefon: +90 (286) 218 00 18 Dahili: 24006, Fax: +90(286) 218 19 48
Web: http://bityed.dergi.comu.edu.tr / E-mail: bityek@comu.edu.tr

ISSN: 2757-6140 (Online)

JOURNAL OF SCIENCE-TECHNOLOGY-INNOVATION ECOSYSTEM
BİLİM-TEKNOLOJİ-YENİLİK EKOSİSTEMİ DERGİSİ

Volume 6 ● Issue 1 ● Year 2025 / Cilt 6 ● Sayı 1 ● Yıl 2025

JSTIE 2025, 6(1)

The Journal of Science-Technology-Innovation Ecosystem is indexed by the following data indices.
Bilim-Teknoloji-Yenilik Ekosistemi Dergisi aşağıdaki veri indeksleri tarafından taranmaktadır.

Certificates of Indexing / İndeks Sertifikaları

IPIndexing
Indexing Portal

CERTIFICATE FOR INDEXING (IPI Value 2023)

This Certificate is Awarded to

Journal of Science-Technology-Innovation Ecosystem

E-ISSN: 2757-6140

Evaluation of the above journal for the year 2023 has been accepted and indexed in IP Indexing.

IPI Value of the above journal for the year 2023

2024-07-01
Date of Issue

2025-06-30
Validity Date

IPI Value is valid for one year from the issuance of Certificate.

www.ipindexing.com

Evaluation Head

SCI

Certificate of Indexing

This is to certify that

Journal of Science-Technology-Innovation Ecosystem
ISSN: 2757-6140
is being indexed by Journament
Indexing stared on: April 15, 2024
Certificate issued on: December 17, 2024

Verification link: https://journament.com/journal/32508

Journament

Journal of Science-Technology-Innovation Ecosystem

(Bilim-Teknoloji-Yenilik Ekosistemi Dergisi)

OPEN ACCESS

JSTIE: MID1762025 | 2025, 6(1): 61-73 | e-ISSN: 2757-6140

New Approaches in Agriculture and Food Industry: Nanoparticles and their Potential Uses

Şehnaz Özatay[1]✉, Çağlar Kaya[2]

[1]Çanakkale Onsekiz Mart University, Ezine Vocational School, Department of Food Processing, Çanakkale, Türkiye
[2]Çanakkale Onsekiz Mart University, Faculty of Agriculture, Department of Horticulture, Çanakkale, Türkiye

Article History
Received: 24/01/2025
Accepted: 30/05/2025
Published: 07/06/2025
Review Article

Abstract: The aim of this study is to provide a comprehensive review of the innovative solutions offered by nanotechnology in the agriculture and food industry and the potential applications of nanoparticles. Nanotechnological materials, particularly in agriculture, have great potential to enhance the efficiency of pesticide use and enhance food safety. Due to their size and surface properties, nanoparticles allow the implementation of environmentally friendly practices, improve agricultural productivity, and ensure the effective release of agrochemicals. In addition to promoting plant growth and increasing soil fertility, nanoparticles have important antibacterial and antifungal properties in the food industry. These microstructures are used as an effective way of extending the shelf life of food products and preserving their nutritional value. However, the potential environmental and health risks associated with this technology should also be considered. To ensure the safe use of nanoparticles, research in this field must be carefully managed, and new strategies developed in line with sustainability principles. Therefore, given the significant potential of nanoparticles in agriculture and the food industry, research aimed at ensuring their safe and sustainable use needs to be intensified. National and international scientific studies in this area will improve the understanding of the environmental and health impacts of nanoparticles and maximize the effectiveness and safety of innovative applications.

Keywords: Agricultural sustainability, food safety, nanoparticles, nanotechnology

Tarım ve Gıda Sanayinde Yeni Yaklaşımlar: Nanopartiküller ve Potansiyel Kullanımları

Makale Geçmişi
Geliş: 24/01/2025
Kabul: 30/05/2025
Yayınlama: 07/06/2025
Derleme Makalesi

Öz: Bu çalışmanın amacı, tarım ve gıda endüstrisinde nanoteknolojinin sunduğu yenilikçi çözümleri ve nanopartiküllerin potansiyel kullanım alanlarını geniş çaplı ele alarak incelemektir. Nanoteknolojik materyaller, özellikle tarımda daha verimli pestisit uygulamaları ve gıda güvenliği konularında yüksek bir kullanım potansiyeline sahiptir. Nanopartiküller, boyutları ve yüzey özellikleri sayesinde, çevre dostu uygulamaların gerçekleştirilmesini sağlayarak tarımda verimliliği artırmak ve aynı zamanda tarım ilaçlarının etkili bir şekilde salınımını sağlamak için kullanılmaktadır. Nanopartiküller bitki büyümesini teşvik etme ve toprak verimliliğini artırma gibi avantajlarının yanı sıra, gıda endüstrisinde sağlık açısından önemli bir yer tutan antibakteriyel ve antifungal özelliklere sahiplerdir. Bu mikro yapılar, gıda ürünlerinin raf ömrünü uzatmak ve besin değerlerini korumak adına etkili bir yöntem olarak kullanılmaktadır. Ancak, bu teknoloji ile ilgili potansiyel çevresel ve sağlık riskleri de göz önünde bulundurulmalıdır. Nanopartiküllerin güvenli bir şekilde kullanılabilmesi için, bu alanda yapılan araştırmaların dikkatle yönlendirilmesi ve sürdürülebilirlik ilkeleri doğrultusunda yeni stratejiler geliştirilmesi gerekmektedir. Sonuç olarak, nanopartiküllerin tarım ve gıda endüstrilerinde sunduğu büyük potansiyel göz önüne alındığında, bu teknolojinin güvenli ve sürdürülebilir kullanımını sağlamak amacıyla yapılan araştırmaların artırılması gerekmektedir. Bu alandaki ulusal ve uluslararası alanda bilimsel çalışmalar, nanopartiküllerin çevresel ve sağlık üzerindeki etkilerini daha iyi anlayarak, inovatif uygulamaların etkinliğini ve güvenliğini en üst düzeye çıkaracaktır.

Anahtar Kelimeler: Gıda güvenliği, nanopartiküller, nanoteknoloji, tarımsal sürdürülebilirlik

✉ Correspondence (Sorumlu yazar): sehnazozatay@comu.edu.tr

Citation (Alıntı): Özatay, Ş. & Kaya, Ç. (2025). New approaches in agriculture and food industry: Nanoparticles and their potential uses. Journal of Science-Technology-Innovation Ecosystem, 6(1), 61-73.

Journal of Science-Technology-Innovation Ecosystem

(Bilim-Teknoloji-Yenilik Ekosistemi Dergisi)

OPEN ACCESS

JSTIE: MID1762025 2025, 6(1): 61-73 e-ISSN: 2757-6140

Introduction

In the context of global challenges, such as population growth, climate change, and resource depletion, sustainable agricultural practices assume paramount importance in ensuring food security and reducing environmental impacts (Amruddin et al., 2024). Agricultural production is confronted with environmental issues, particularly the degradation of soil quality, the depletion of water resources, and the excessive use of chemical fertilizers and pesticides (Adisa et al., 2024). Conventional agricultural methods have demonstrated limited efficacy in addressing these challenges, thereby necessitating the exploration of alternative solutions (Meydan, 2016). Technological innovations hold considerable potential to offer novel solutions to sustainability challenges in this field. Specifically, nanotechnology has emerged as a promising area in the agricultural sector, exhibiting significant potential to enhance environmental sustainability and improve agricultural productivity (Raliya, 2019; Sandhu et al., 2023).

The field of nanotechnology has emerged as a pivotal element in numerous applications, including the enhancement of plant growth, the reduction of pesticide usage, and the augmentation of soil health. This is achieved through the manipulation of materials at the atomic and molecular levels. The unique properties of nanotechnology, such as its high surface area, reactivity, and minute size, facilitate enhanced penetration of nanoparticles into plant root systems, thereby promoting enhanced nutrient absorption and augmented plant resistance to stress conditions (Zhao et al., 2020; Ochoa et al., 2025). In particular, applications employing nanoparticles have the potential to enhance productivity whilst concomitantly reducing environmental impacts. Nanotechnology has also precipitated significant advancements in areas such as pesticide control and fertilizer management, thereby leading to a substantial reduction in the use of chemical fertilizers and pesticides in agriculture, thus contributing to sustainable production practices (Atakan & Özkaya, 2018).

While nanotechnology offers opportunities in agriculture, it also faces several challenges that this new technology faces. Notably, uncertainties still exist regarding the environmental impacts of nanoparticles, their potential harm to ecosystems, and their effects on human health (Rana et al., 2024). Furthermore, the high production costs of nanotechnology-based products present a significant barrier, particularly for small-scale farmers in developing countries (Demirbilek, 2015). Nevertheless, for nanotechnology to be more widely adopted in agriculture, it is crucial to develop safety protocols, better understand the environmental impacts of these technologies, and provide training for farmers (Demir, 2024).

In the domain of food production, the utilization of nanoparticles has emerged as a groundbreaking approach, eclipsing conventional methodologies. This technological advancement has been identified as having considerable promise in domains such as food safety, preservation of nutritional value, and enhancement of sensory attributes (Nile et al., 2020). Nanotechnology has been demonstrated to be a highly effective instrument for enhancing the quality of food products, extending their shelf life, and reducing food wastage (Cushen et al., 2012). The use of nanoparticles has been demonstrated to enhance the bioavailability of food components, improve the effectiveness of additives, and prevent microbial contamination (Sharma et al., 2022).

The utilization of nanoparticles in food science has been shown to enhance the bioavailability of nutrients (Mallesham et al., 2025). The application of nano-carriers, in particular, has been demonstrated to facilitate the absorption of fat-soluble vitamins and minerals (Mallesham et al., 2025). These technologies ensure that dietary supplements are absorbed more efficiently by the body, while also allowing for the preservation of nutritional values. Notably, lipid nanoparticles have been shown to facilitate the delivery of vitamins and minerals to the body with greater efficiency (Afzia & Ghosh, 2025).

Another significant application of nanoparticles in the food industry pertains to active packaging systems,

where nano-coating technologies are employed to protect the surfaces of food products. These technologies create barriers against moisture, oxygen, and microorganisms, thereby contributing to the maintenance of product freshness (Prasad et al., 2024). The implementation of these smart packaging solutions has been demonstrated to enhance food safety, with the capacity to prevent foodborne illnesses by inhibiting microbial growth (Devipriya et al., 2023). Furthermore, the integration of nano-sensors within packaging materials facilitates the continuous monitoring of product freshness, thereby ensuring the provision of pertinent information to consumers (Raghavan, 2017).

In the context of food additives, the role of nanoparticles is of particular significance. The use of nano-carriers facilitates the regulated release of food preservatives, antioxidants, and other additives, thereby contributing to the prolongation of food product shelf life and the maintenance of product quality (Haris et al., 2023). This development signifies a substantial innovation within the domain of food safety, with the potential to reduce food waste. From a food safety perspective, nanoparticles are used for detecting and disinfecting pathogens microorganisms. The inhibition of microbial growth by nanomaterials has been demonstrated to enhance food hygiene and thereby reduce health risks (Chadha et al., 2022). The antibacterial properties of nanoparticles offer a significant advantage, particularly in food processing and storage. This study aims to explore the potential of nanotechnology in promoting sustainability within the agricultural and food industries. To enhance our comprehension of nanotechnology's contributions to enhancing productivity, reducing environmental impacts, and improving food safety, it is imperative to augment both national and international research in these areas.

Applications of Nanotechnology in Agriculture

Nanotechnology is a field of science that involves the design, production, and application of materials at the atomic and molecular level (Ormanoğlu et al., 2021). This technology has significant potential, particularly in sectors such as agriculture, where natural resources are limited and environmental pressures are high (Yonat & Kolören, 2022). Nanotechnology can enhance the properties of materials used in agriculture, improving plant health, increasing yields and productivity per unit area, and reducing environmental impact (Demirel, 2020). Additionally, this technology promotes efficient use of water and soil, offering innovative, micro-level solutions for sustainable agriculture. (Gökdemir et al., 2023).

Nanofertilizers and Plant Nutrition

Nanotechnology plays a crucial role in providing plant nutrition and optimizing the usage of fertilizers in agriculture. Conventional fertilizers dissolve quickly after being applied to the soil, and only a limited amount of nutrients are absorbed by plants (Dağhan, 2017). This leads to environmental pollution and loss of productivity over time. However, nanofertilizers have the potential to solve these problems by delivering nutrients to plants more efficiently (Demirci, 2023). Nanofertilizers produced using nanotechnology can reach plant root systems faster and more effectively. Nanoparticles slow down the dissolution process in the soil, allowing nutrients to remain in the soil for longer, allowing plants to absorb nutrients more efficiently (Ranjan et al., 2021). In addition, these fertilizers help to minimize the loss of essential nutrients such as nitrogen and phosphorus (Sedef, 2018).

Another advantage of nanofertilizers is their ability to increase agricultural productivity without harming the environment. Excessive use of traditional fertilizers can lead to contamination of water resources and excessive accumulation in the soil. In contrast, nano-enriched fertilizers deliver nutrients to plants with minimal environmental impact and without damaging soil structure. This contributes to improving the sustainability of agriculture while promoting environmentally friendly practices (Şahin, 2017). In addition, nano-fertilizers can be equipped with systems that control the rate at which nutrients are delivered to the soil and plants. As a result, plants receive the nutrients they need on a regular basis, improving crop health and quality (Dağhan, 2017).

Water Management and Irrigation Technologies

Nanotechnology includes various applications that ensure the efficient use of water resources (Kuhn et al., 2022). Water is one of the most important resources for agriculture, so its efficient management is crucial. Water filtration systems developed through nanotechnology help to ensure that water used for irrigation is cleaner, thereby contributing to more sustainable agricultural practices (Amdeha, 2021). By using nanofilters, contaminants in irrigation water can be effectively removed, protecting plants from harmful substances and allowing them to grow and develop in a healthy manner (Saleem & Zaidi, 2020). Nanotechnology also helps irrigation water penetrate the soil more effectively. Nanoparticles optimize the distribution of water in the soil,

reducing evaporation and promoting water conservation (Spanos et al., 2021).

Agricultural Monitoring with Biosensors

One of the most significant benefits of nanotechnology in agriculture is the development of biosensors (Kirsch, 2013). These sensors continuously monitor plant health and can detect disease or pest problems at an early stage. Nanobiosensors identify microorganisms and plant diseases in their early stages, preventing the spread of diseases and providing quick solutions for affected plants (Ghanbari et al., 2024). The sensing technologies provided by nanotechnology help to reduce the unnecessary use of pesticides while effectively maintaining plant health. In addition, these sensors monitor soil conditions and environmental variables, helping growers make more informed decisions (Nikolelis & Nikoleli, 2018). Nanotechnological biosensors can increase agricultural productivity and minimize the use of chemicals for pest control (Upadhyyay et al., 2024).

Pest Control with Nanomaterials

In agriculture, traditional pest control methods often require chemical pesticides, which can harm the environment and lead to imbalances in agricultural ecosystems (An et al., 2022). Nanotechnology offers effective alternatives to overcome this problem. Nanoparticles can target pests and have properties that can harm them (Cao & Wang, 2022). In addition, nanoparticles can attach to the bodies of harmful organisms and disrupt their biological functions, thereby reducing the need for pesticides. As this method is environmentally friendly, it helps to protect ecosystems (Jiang et al., 2024).

Quality Control in Agricultural Products with Nanotechnology

Nanotechnology is also used to improve the quality control of agricultural products (Mohammad et al., 2022). Nanoparticles can detect harmful pathogens on food products and prevent contamination (Samal, 2017). Antimicrobial nanoparticles prevent spoilage and ensure that food stays fresh for longer (Thiruvengadam et al., 2018). These innovative applications help reduce food waste and contribute to safer food supply chains. In addition, nanoparticles can be incorporated into the packaging of agricultural products, ensuring freshness while using environmentally friendly packaging materials (Sekhon, 2010).

Management and Recycling of Agricultural Waste with Nanotechnology

Agricultural production generates a large amount of waste, the efficient management of which is critical for environmental sustainability (Chandrika et al., 2018). Nanotechnology offers significant solutions for the recycling and management of agricultural waste (Pramanik et al., 2020). Nanoparticles can accelerate the biological degradation of agricultural waste and can be used to convert this waste into organic fertilizer. Similarly, nanoparticles play an effective role in wastewater treatment, making it suitable for reuse in irrigation, thereby contributing to water conservation (Giri et al., 2023).

Nanotechnology systems also offer significant opportunities for the reuse of organic waste. Nanoparticles accelerate the biological degradation of pesticides used in agriculture, preventing these harmful chemicals from contaminating the environment (Jha et al., 2011).

Compared to traditional methods of processing agricultural waste, nanotechnology offers much more efficient and effective properties. In particular, nanoparticles can act as carriers for enzymes or microorganisms that biodegrade organic waste at a faster rate (Ouda et al., 2023). By accelerating the degradation process, nanoparticles increase the biological degradation rates. Nanotechnological solutions are also being used to convert agricultural waste into energy. In the processing of biomass for biofuel production, nanoparticles improve the fuel production process, promoting the production of renewable energy. Nanotechnology increases the efficiency of the organic waste recycling process and reduces its environmental impact (Chellasamy et al., 2022).

The recycling of agricultural waste is not limited to biological processes; nanotechnology also plays an important role in the recycling of inorganic waste. Pesticides, chemicals, and other substances used in agriculture can contaminate soil and water sources. Nanomaterials can facilitate the safe handling of these chemicals (Corsi et al., 2023). Nanofilters and nanoparticles can effectively remove pollutants from water and soil, minimizing the environmental damage caused by agricultural waste. This application not only improves the sustainability of agricultural production but also helps to prevent environmental pollution (Goh et al., 2022).

Nanotechnology solutions can also enable the conversion of agricultural waste into valuable products. Organic agricultural waste can be transformed into biological fertilizer using nanotechnological methods. These fertilizers improve the nutrient content of the soil, resulting in healthier plants, while reducing the use of chemical

fertilizers. Nanomaterials speed up such conversion processes, allowing waste to be recycled quickly. In addition, the agricultural waste recycling reduces the need for resources in agricultural production, thereby increasing sustainability (Mustapha et al., 2024).

Reducing the Impact of Microplastics in Agriculture through Nanotechnology

Reducing the impact of microplastics in agriculture through nanotechnology. In recent years, microplastics have become a major concern due to their environmental pollution and harmful effects on ecosystems. The degradation of plastic materials used in agriculture, such as plastic sheeting, packaging, and agricultural tools, leads to the leaching of microplastics into soil, water, and the food chain (Sekar et al., 2024). The accumulation of microplastics in agricultural areas can disrupt the physical structure of the soil, reduce water quality, and adversely affect plant health. Nanotechnology has an important role to play in addressing this problem. Nanotechnological solutions are being used to limit the harmful effects of microplastics, prevent their accumulation in soil, and promote their biodegradation (Sharma et al., 2024).

One of the key contributions of nanotechnology in the fight against microplastics is the ability of nanoparticles to effectively remove these pollutants. In particular, nanoparticles can be used to prevent the accumulation of microplastics in soil and to remove them without harming the environment. Nanomaterials can adhere to the surfaces of microplastics, making it easier to collect and bind them. As a result, microplastics can be removed from environments such as soil and water before they accumulate (Das et al., 2024).

Recent studies on this topic have demonstrated the efficacy of magnetic nanoparticles in the collection of microplastics. The attraction of microplastics to the surface of magnetic nanoparticles facilitates their collection and removal from the environment. When placed in soil or water, magnetic nanoparticles adhere to microplastics, and by employing a simple magnetic field, they can be extracted from the environment (Sajid et al., 2023). This method has the potential to be an effective solution for environmental cleanup, especially in areas where microplastics are concentrated. In addition, certain nanoparticles have properties that can contribute to the biodegradation of microplastics. Nanoparticles can accelerate the biological processes of microorganisms or enzymes, helping microplastics to naturally decompose in an environmentally friendly way. The integration of nanomaterials with bacteria capable of altering the chemical structure of microplastics facilitates their biodegradation through natural processes (Nene et al., 2025). Such biological degradation processes contribute to the elimination of environmental damage caused by microplastics, while concurrently supporting the ecological balance of agricultural areas.

Microplastics in agricultural water can reduce irrigation water quality, which is critical for the growth of healthy plants and the safety of food production. Nanotechnology offers a promising solution to prevent microplastic contamination in irrigation water. (Liu et al., 2024). In particular, nanomaterials have been shown to play a key role in filtration processes that prevent microplastics from entering water sources.

The employment of nanotechnological filters has been demonstrated to yield a significantly enhanced level of effectiveness in the process of water purification when compared with conventional methodologies. The compatibility of nanoparticle size with microplastics allows for the efficient capture of these harmful pollutants from water. The utilization of these filters has been demonstrated to expedite the purification process whilst concurrently attenuating environmental impacts. Several nanofilters have been shown to remove microplastics from water while also eliminating heavy metals and other harmful substances, thereby contributing to improved water quality (Sekar et al., 2024). Such systems have the potential to enhance the efficiency of irrigation systems and promote the sustainability of agricultural production.

The accumulation of microplastics in the soil can disrupt soil structure and impede plants' ability to absorb essential nutrients. The application of nanotechnology can play a pivotal role in mitigating the accumulation of microplastics in soil, thereby preserving its quality. The use of nanoparticle-based solutions has been shown to be effective in preventing the accumulation of microplastics in soil and in the effective removal of existing microplastics (Kumar, 2023).

The ability of nanoparticles to separate plastics from the soil surface prevents damage to the soil structure. This approach prevents microplastics from penetrating deeper into the soil, thereby maintaining soil health. Furthermore, certain nanotechnological solutions have been shown to modify the chemical properties of microplastics in the soil, rendering them less susceptible to absorption by plants (Kumar, 2023). These approaches

are of particular significance in the context of preventing the accumulation of plastic materials utilized in organic farming (Sajid et al., 2023).

Agricultural Bioenergy Production with Nanotechnology

The potential of nanotechnology to transform bioenergy production from agricultural waste, biomass, and organic matter is significant (Arya et al., 2021). However, when bioenergy production processes are inefficient, these resources can be processed using unsustainable methods. The utilization of nanotechnology offers a number of advantages, including the potential for faster and more efficient conversion of biomass into energy, whilst concomitantly reducing environmental impacts and improving energy efficiency (Joshi and Arora, 2023). Biomass, which is derived from agricultural plants and animal waste, is a vital raw material for bioenergy production. However, the process of converting biomass into energy is often lengthy, costly, and complex (Chettri et al., 2024).

The application of nanotechnology has the potential to streamline these processes. The integration of nanomaterials enhances the effectiveness of enzymes or microorganisms employed in biomass processing, thereby facilitating a more expeditious and efficient conversion process. Nanoparticles interact with the cellular structure of biomass, thus enabling the more facile and efficient breakdown of organic materials. Nano-enzymes accelerate the hydrolysis of lignocellulosic biomass, which is particularly abundant in agricultural waste, by catalyzing the breakdown of cellulose and lignin components, thereby optimizing the bioenergy production process (Mehejabin et al., 2024).

This integration of nanotechnology into agricultural bioenergy production processes has the dual benefits of improving efficiency and supporting the development of more sustainable and environmentally friendly energy solutions.

Another advantage that nanotechnology offers in the field of biomass processing is its capacity to expedite the disintegration of chemical bonds within biomass. This is particularly significant for materials such as agricultural waste, which is characterized by elevated levels of lignin and cellulose. The utilization of nanomaterials in this context has been shown to facilitate the breakdown of these bonds, thereby accelerating the processing of biomass and, consequently, enhancing energy production. In addition, nanohydrogenation processes have been shown to enhance the efficiency of biomass in oil production (Hussain et al., 2024).

The role of enzymes and catalysts in this process is critical. The efficiency of enzymes is a critical factor in various bioenergy production processes, including fermentation of biomass, biodiesel production, and gasification. The potential of nanotechnology to enhance enzyme efficiency and thereby increase energy production is significant. The use of nanoparticles has been shown to enhance enzyme activity, thereby facilitating more efficient biomass processing. Additionally, nanocatalysts enable processing at lower temperatures and shorter durations, thus optimizing energy production (Patil et al., 2025).

Specifically, nanotechnological catalysts have the potential to be used in the anaerobic conversion of biomass into methane gas, thereby increasing the efficiency of biogas production. This process offers an environmentally friendly method of converting agricultural waste into energy. The acceleration of biochemical processes by nanotechnological catalysts has been demonstrated to enhance methane production efficiency. Furthermore, these technologies used in biogas production can improve energy conversion rates, significantly enhancing the efficiency of agricultural bioenergy production (Khan et al., 2022).

The application of nanotechnology has the potential to enhance the design of materials employed in the conversion of biomass into energy. The utilization of nanostructured materials can facilitate the efficient combustion or gasification of biomass. The properties of nanomaterials enable the effective conversion of biomass into energy. These materials possess the capability to conduct heat more efficiently, thereby increasing energy production during biomass combustion (Dehhaghi et al., 2019). Furthermore, these materials enable biomass processing at reduced temperatures whilst demanding less energy than conventional methods. The employment of nanotechnological materials in bioenergy production has been demonstrated to engender a reduction in environmental impacts. The greenhouse gases emitted during biomass combustion are minimized when nanotechnological materials are used, thereby enhancing environmental sustainability. Specifically, Nanofilters and nanocatalysts help reduce carbon emissions, making processes more eco-friendly. (Abdelsalam & Samer, 2018).

Nanotechnological Solutions for Climate Change Mitigation in Agriculture

Climate change is a phenomenon that significantly impacts the agricultural sector and will continue to manifest its effects in the future. Increasing temperatures, water shortages, extreme weather events, and changing rainfall patterns can negatively affect productivity, thereby threatening agricultural production and food security, as well as agricultural economies. Nanotechnology plays a crucial role in offering innovative solutions to combat these challenges. Nanotechnology can enhance agricultural productivity and offer sustainable solutions to climate change. (Dasgupta et al., 2017).

Nanotechnology can improve water management in agriculture by enabling more efficient use of water resources. The use of nanomaterials can ensure more effective water purification and more efficient use in irrigation systems. The employment of nanofilters can remove contaminants and harmful substances in irrigation water. Furthermore, nanotechnological materials that facilitate the retention of water in the soil for extended periods can reduce the necessity for irrigation, thereby conserving water (Hamad et al., 2020). This offers a substantial benefit, particularly in regions afflicted by drought, and assists in mitigating the repercussions of water scarcity on agricultural production. Additionally, nanotechnology is being employed to enhance the resilience of agricultural products to diseases and pests. Genetic interventions in plants or protective coatings enhanced with nanomaterials can improve plant resilience to environmental stresses (Pramanik et al., 2020). Furthermore, nanotechnological pesticides can be used in lower doses to combat targeted pests, providing effective control without harming the environment. Additionally, nanotechnological materials can reduce the water requirements of plants, enabling higher yields with less water.

The field of nanotechnology has also made significant contributions to the enhancement of soil health. A range of nanotechnological solutions has been developed to enhance the breakdown of organic matter in the soil and to facilitate more efficient nutrient uptake. The application of nanoparticle technology has been demonstrated to have the capacity to prevent soil degradation, enhance the soil's water retention capacity, and facilitate enhanced nutrient access for plants (Ahmed et al., 2024). This contributes to the enhancement of agricultural sustainability and the mitigation of deleterious effects associated with climate change, such as soil erosion.

The potential of nanotechnology in addressing climate change in agriculture is considerable. Solutions offered in areas such as water management, pest and disease control, soil health, and fertility can help make agriculture more resilient to the effects of climate change. Nevertheless, it is imperative to undertake further research to ascertain the applicability, safety, and environmental impact of these technologies. The widespread adoption of nanotechnological solutions has the potential to be a significant step towards sustainable agricultural practices (Wang et al., 2024).

Applications of Nanoparticles in Food Industry

In recent years, nanotechnology has gained significant importance in the food industry, particularly concerning food production, processing, preservation, and packaging. The application of nanoparticles has been shown to enhance product quality, extend shelf life, and ensure food safety (Biswas et al., 2022). The larger surface area of nanoparticles allows them to enhance the functionality of materials used in the food sector. The potential of nanoparticles in the food industry is extensive, ranging from enhancing nutritional value to ensuring food safety and generating positive health effects (de Sousa et al., 2023).

Nanoparticles are employed to enhance the efficiency of food processing. They function as carriers, facilitating the absorption of food materials and enabling nutrients to bind and be utilized more rapidly and efficiently in the body. Additionally, nanoparticles can enhance the effectiveness of food components, optimizing their nutritional value. For instance, nanoparticles can be employed to enhance the preservation and absorption of food additives, such as vitamins or minerals, thereby addressing nutrient deficiencies, a particularly salient issue in developing countries (Peidaei et al., 2021).

Additionally, nanotechnology holds considerable promise in ensuring food safety. Nanoparticles can be utilized to detect and disinfect pathogens in food products with high efficiency. Nanotechnological sensors can rapidly and accurately detect bacteria, viruses, or toxins on food products, thus contributing to food safety. Furthermore, nanotechnology can be employed in food packaging to assist in protecting foodstuffs from external factors. This can be achieved by nanotechnological food packaging that inhibits the growth of microorganisms, thus extending the shelf life of products. Consequently, this can result in a reduction of food waste and

enhancement of food safety (Gupta et al., 2022).

Another area of application for nanoparticles is the enhancement of the sensory characteristics of food products. Nanotechnological additives can modify sensory attributes such as taste, color, aroma, and texture. Furthermore, nanoparticles can balance the oil and water content of food products, thereby reducing their caloric content, thus aligning with contemporary trends in health-conscious eating. Furthermore, nanoparticles can enhance the appearance of food products, rendering them more visually appealing and aesthetically attractive (Neme et al., 2021). The enhancement of both the nutritional and sensory properties of food products by nanotechnology enables the creation of products that better meet market demands and improve consumer experiences (Babu, 2022).

The applications of nanoparticles and nanotechnology in the food industry are extensive, and they have the potential to shape the future of this sector. The impact of nanotechnological solutions on areas such as efficient nutrient delivery, enhanced food safety, extended shelf life, and improved sensory attributes of products is significant. However, continued research on the use of nanotechnology in the food industry is essential to gather more information on the safety and effects of these technologies (Onyeaka et al., 2022).

Nanoparticles in Food Packaging

The utilization of nanotechnology in the domain of food packaging represents a substantial advancement, not only in terms of prolonging the shelf life of products but also in enhancing food safety (Dobrucka, 2014). Nanoparticles can significantly enhance the functionality of packaging materials, with nanocomposites demonstrating particular efficacy in preserving food by protecting environmental factors such as oxygen, moisture, and light, thereby preventing food spoilage. The application of nanoparticle-based packaging has been shown to enhance the shelf life of food products by protecting them from external factors such as oxygen, moisture, and light (Aigbogun et al., 2018). Furthermore, the incorporation of nanoparticles with antibacterial and antifungal properties into food packaging can prevent the growth of microorganisms, which is particularly beneficial for perishable items such as fresh fruits, vegetables, and meat products. The efficacy of nanoparticles such as silver and zinc oxide in eradicating harmful pathogens has been well-documented (Dera et al., 2020), thereby ensuring food safety and preventing foodborne diseases.

Nanotechnology in Food Safety and Rapid Testing Systems

In the domain of the food industry, ensuring food safety is of paramount importance. In this regard, nanotechnology has emerged as a pivotal solution, offering advanced methodologies for detecting microbial contamination, toxins, and other harmful components in food products. The employment of nanotechnological sensors and testing systems has proven to be a rapid, precise, and reliable approach to ensure food safety. The surface properties of nanoparticles enhance their ability to bind to specific target components, making them an excellent tool for detecting pathogens in food products (Khan et al., 2025). Gold nanoparticles are commonly used in biosensors for pathogen detection, offering the ability to detect pathogens at very low concentrations, enabling rapid testing of food safety (Chadha et al., 2022). Furthermore, the use of nanoparticles in the detection of toxins and allergens serves to mitigate the potential health risks associated with food products.

Nanoparticles in Improving the Sensory Properties of Food Products

Nanotechnology also plays an important role in improving the sensory properties of food. Nanoparticles can change the color, aroma, texture, and flavor of food, making it more appealing and palatable. By balancing the fat and water content of food, nanoparticles enable the production of low-calorie foods. In addition, nanoparticles help to achieve better texture and appearance by ensuring the homogeneous distribution of food components. This is a significant advantage, especially for health-conscious consumers (Jagtiani, 2022).

Nanoparticles can also be used to ensure that food stays fresh for longer. Nanotechnology coatings form a protective layer on the surface of food, preventing oxidation and helping to keep food fresher for longer. These coatings can also reduce the loss of flavor and aroma, giving consumers a more satisfying experience (Berekaa, 2015).

Usage of Nanotechnology in Food Processing

Nanotechnology also has the potential to improve the efficiency of food processing. Nanoparticles can change the properties of materials used in food processing, enabling more efficient and sustainable production processes. Nanotechnological devices can reduce energy consumption by preserving the quality of food during

thermal processing. In addition, nanomaterials can improve the distribution of food additives during processing, thereby improving the overall quality of products (Ali et al., 2021).

Nanotechnology solutions can also reduce the use of harmful chemicals in food processing. This helps to minimize environmental impact and adverse effects on human health. For example, nanocatalysts enable efficient reactions at lower temperatures and pressures, which saves energy and ensures that food remains more natural and healthier (He et al., 2019).

Conclusion

The rapid development of modern technologies is shaping new approaches in agriculture and the food industry. In this context, nanotechnology has emerged as a significant tool that enhances sustainability, increases efficiency, and reduces environmental impacts of these sectors. The use of nanoparticles holds great potential in various areas such as improving agricultural productivity, combating plant diseases and pests, optimizing water usage, and enhancing soil health. Similarly, the application of nanoparticles in the food industry provides robust solutions for ensuring food safety, extending shelf life, enhancing nutritional value, and improving consumer experience. Nanotechnology offers innovative solutions in food processing and packaging, significantly contributing to reducing the environmental footprint of food production.

In agriculture, the use of nanoparticles has made significant progress, particularly in areas such as water conservation, pesticide application, and soil health improvement. Nanomaterials help reduce the water requirements of plants, ensure more efficient use of water, and accelerate the decomposition of organic matter in the soil, thus supporting the adoption of more sustainable production methods in agriculture. Furthermore, the targeted use of pesticides and fertilizers through nanoparticles reduces environmental pollution while increasing agricultural productivity. Nanotechnological materials also help plants become more resistant to diseases and pests, supporting biological control methods and reducing the reliance on chemical fertilizers and pesticides.

In the food industry, nanoparticles provide revolutionary solutions, especially concerning food safety and shelf life. Nanotechnological sensors and biosensors have the ability to quickly and accurately detect pathogens, toxins, and other harmful components in food products. Additionally, nanoparticle-based food packaging helps maintain the freshness of food for longer periods, preventing waste and inhibiting the spread of microorganisms with their antibacterial and antifungal properties. The ability of nanoparticles to optimize the transport of nutrients and enhance the nutritional value of food products provides a significant advantage in promoting healthy diets.

However, there are challenges that need to be addressed for nanotechnology to be widely implemented in agriculture and the food industry. Further research on the potential environmental and health impacts of nanoparticles is critical to ensure the safe use of these technologies. Additionally, the cost of nanotechnological products is a factor that needs to be considered before they can be integrated into industrial production processes. Moreover, these technologies must be properly monitored in terms of food safety, ethics, and regulatory compliance.

In conclusion, the potential of nanoparticles in agriculture and the food industry offers significant benefits in terms of sustainability, efficiency, and environmental responsibility. Nanotechnological innovations continue to develop important solutions to improve food safety, reduce environmental impacts, and enhance agricultural productivity. However, for the effective application of these technologies, further scientific research, regulatory development, and support for industrial-scale implementations are necessary. In the future, the role of nanotechnology in agriculture and food sectors is certain to strengthen, leading to significant changes in these fields.

Additional Information and Declarations

Authors' Contributions: The authors declare that they have contributed equally to the article.
Conflict of Interests: The authors declare that there is no conflict of interest among them.

Academic Editor: Dr. Abdul HADİ
Layout Editor: Dr. Baboo Ali

References

Abdelsalam, E. M., & Samer, M. (2019). Biostimulation of anaerobic digestion using nanomaterials for increasing biogas production. *Reviews in Environmental Science and Bio/Technology*, 18, 525-541.

Adisa, O., Ilugbusi, B. S., Adelekan, O. A., Asuzu, O. F., & Ndubuisi, N. L. (2024). A comprehensive review of redefining agricultural economics for sustainable development: Overcoming challenges and seizing opportunities in a changing world. *World Journal of Advanced Research and Reviews*, 21(1), 2329-2341.

Afzia, N., & Ghosh, T. (2025). Nanotechnology in food application: an introduction. In *Advancements in Nanotechnology for Food and Packaging* (pp. 1-31). Elsevier.

Ahmed, M. T., Ali, M. S., Ahamed, T., Suraiya, S., & Haq, M. (2024). Exploring the aspects of the application of nanotechnology system in aquaculture: a systematic review. *Aquaculture International*, 1-30.

Aigbogun, I., Mohammed, S., Orukotan, A., & Tanko, J. (2018). The role of nanotechnology in food industries-a review. *Journal of Advances in Microbiology*, 7(4), 1-9.

Amdeha, E. (2021). Recovery of nanomaterials from agricultural and industrial wastes for water treatment applications. *Waste Recycling Technologies for Nanomaterials Manufacturing*, 385-417.

Amruddin, A., Dinar, F., Sulandjari, K., Tanur, E. A., & Andriyani, L. Y. (2024). Sustainable agricultural practices and environmental stewardship: A global analysis of farmer adoption and impact. *Global International Journal of Innovative Research*, 2(3), 595-603.

An, C., Sun, C., Li, N., Huang, B., Jiang, J., Shen, Y., & Wang, Y. (2022). Nanomaterials and nanotechnology for the delivery of agrochemicals: strategies towards sustainable agriculture. *Journal of Nanobiotechnology*, 20(1), 11.

Arya, I., Poona, A., Dikshit, P. K., Pandit, S., Kumar, J., Singh, H. N., & Kumar, S. (2021). Current trends and future prospects of nanotechnology in biofuel production. *Catalysts*, 11(11), 1308.

Atakan, A. Y. D. I. N., & Özkaya, H. Ö. (2018). Fitopatolojide Nanoteknoloji. *Harran Tarım ve Gıda Bilimleri Dergisi*, 22(2), 296-303.

Babu, P. J. (2022). Nanotechnology mediated intelligent and improved food packaging. *International Nano Letters*, 12(1), 1-14.

Berekaa, M. M. (2015). Nanotechnology in food industry; advances in food processing, packaging and food safety. *International Journal of Current Microbiology and Applied Sciences*, 4(5), 345-357.

Cao, X., & Wang, Z. (2022). Application of nano-agricultural technology for biotic stress management: mechanisms, optimization, and future perspectives. *Environmental Science: Nano*, 9(12), 4336-4353.

Chadha, U., Bhardwaj, P., Selvaraj, S. K., Arasu, K., Praveena, S., Pavan, A., & Paramasivam, V. (2022). Current trends and future perspectives of nanomaterials in food packaging application. *Journal of Nanomaterials*, 2022(1), 2745416.

Chandrika, K. P., Singh, A., Tumma, M. K., & Yadav, P. (2018). Nanotechnology prospects and constraints in agriculture. *Environmental Nanotechnology: Volume* 1, 159-186.

Chellasamy, G., Kiriyanthan, R. M., Maharajan, T., Radha, A., & Yun, K. (2022). Remediation of microplastics using bionanomaterials: A review. *Environmental Research*, 208, 112724.

Chettri, D., Boro, M., Malik, A. A., & Verma, A. K. (2024). Nanotechnology for a greener future: sustainable energy and biofuel advances. *Biofuels*, 1-16.

Corsi, I., Venditti, I., Trotta, F., & Punta, C. (2023). Environmental safety of nanotechnologies: The eco-design of manufactured nanomaterials for environmental remediation. *Science of the Total Environment*, 864, 161181.

Cushen, M., Kerry, J., Morris, M., Cruz-Romero, M., & Cummins, E. (2012). Nanotechnologies in the food industry–Recent developments, risks and regulation. *Trends in Food Science & Technology*, 24(1), 30-46.

Dağhan, H. (2017). Nano gübreler. Türkiye Tarımsal Araştırmalar Dergisi, 4(2), 197-203.

Das, S., Ghosh, S., Bakshi, A., Khanna, S., Bindhani, B. K., Parhi, P. K., & Kumar, R. (2023). Nanotechnology and plant biotechnology: The current state of art and future prospects. *Biological Applications of Nanoparticles*, 101-120.

Das, T. K., Basak, S., & Ganguly, S. (2024). 2D nanomaterial for microplastic removal: A critical review. *Chemical Engineering Journal*, 152451.

Dasgupta, N., Ranjan, S., & Ramalingam, C. (2017). Applications of nanotechnology in agriculture and water quality management. *Environmental Chemistry Letters*, 15, 591-605.

de Sousa, M. S., Schlogl, A. E., Estanislau, F. R., Souza, V. G. L., dos Reis Coimbra, J. S., & Santos, I. J. B. (2023). Nanotechnology in packaging for food industry: Past, present, and future. *Coatings*, 13(8), 1411.

Dehhaghi, M., Tabatabaei, M., Aghbashlo, M., Panahi, H. K. S., & Nizami, A. S. (2019). A state-of-the-art review on the application of nanomaterials for enhancing biogas production. *Journal of Environmental Management*, *251*, 109597.

Demir, M. (2024). Atomik boyuttaki mühendisliğin adı "nanoteknoloji*". Euroasia Journal of Mathematics, Engineering, Natural & Medical Sciences*, 11(35), 34-42.

Demirbilek, M. E. (2015). Tarımda ve gıdada nanoteknoloji. *Gıda ve Yem Bilimi Teknolojisi Dergisi*, (15).

Demirci, M. A. (2023). Nanoteknoloji ve organik kimya. *Nanoteknoloji ve Organik Kimya*, 103.

Demirel, F. (2020). Bitki ve hayvan biyoteknolojisi; hücresel tarım ve nano-teknoloji. *Journal of Agriculture*, 3(2), 1-9.

Devipriya, C. P., Sumathi, B., Bamini, S., & Sabari, V. (2023). Polymers nanocomposite supercapacitors for water treatment and food packaging. *In Functionalized Nanomaterials Based Supercapacitor: Design, Performance and Industrial Applications* (pp. 473-501). Singapore: Springer Nature Singapore.

Dobrucka, R. (2014). Application of nanotechnology in food packaging. *Journal of microbiology, biotechnology and food sciences*, 3(5), 353-359.

Ghanbari, K., Jelvehzadeh, M., & Nejabati, F. (2024). Electrochemical biosensors available for identifying hazardous chemicals used in agriculture.

Giri, N. G., Abbas, N. S., & Shukla, S. K. (2023). Nanotechnology in agricultural practices: prospects and potential. *Applications of Emerging Nanomaterials and Nanotechnology*, 148, 252-275.

Goh, P. S., Kang, H. S., Ismail, A. F., Khor, W. H., Quen, L. K., & Higgins, D. (2022). Nanomaterials for microplastic remediation from aquatic environment: Why nano matters? *Chemosphere*, 299, 134418.

Gökdemir, F. Ş., Gündoğdu, M., Muftareviç, S., Sunar, A., & Eyidoğan, F. (2023). Nanopartiküllerin tarımsal bilimlerdeki önemi ve kullanım alanları. *Selçuk Üniversitesi Fen Fakültesi Fen Dergisi*, 49(1), 11-17.

Gupta, R. K., Guha, P., & Srivastav, P. P. (2022). Natural polymers in bio-degradable/edible film: A review on environmental concerns, cold plasma technology and nanotechnology application on food packaging-A recent trend. *Food Chemistry Advances*, 1, 100135.

Hamad, H. T., Al-Sharify, Z. T., Al-Najjar, S. Z., & Gadooa, Z. A. (2020). A review on nanotechnology and its applications on fluid flow in agriculture and water recourses. In *IOP conference series: materials science and engineering* (Vol. 870, No. 1, p. 012038). IOP Publishing.

Haris, M., Hussain, T., Mohamed, H. I., Khan, A., Ansari, M. S., Tauseef, A., & Akhtar, N. (2023). Nanotechnology–A new frontier of nano-farming in agricultural and food production and its development. *Science of the Total Environment*, 857, 159639.

He, X., Deng, H., & Hwang, H. M. (2019). The current application of nanotechnology in food and agriculture. *Journal of Food and Drug Analysis*, 27(1), 1-21.

Hussain, A., Parveen, F., Saxena, A., & Ashfaque, M. (2024). A review of nanotechnology in enzyme cascade to address challenges in pre-treating biomass. *International Journal of Biological Macromolecules*, 132466.

Jha, Z., Behar, N., Sharma, S. N., Chandel, G., Sharma, D. K., & Pandey, M. P. (2011). Nanotechnology: prospects of agricultural advancement. *Nano Vision*, 1(2), 88-100.

Jiang, X., Yang, F., Jia, W., Jiang, Y., Wu, X., Song, S., & Shen, J. (2024). Nanomaterials and nanotechnology in agricultural pesticide delivery: A review. *Langmuir*, 40(36), 18806-18820.

Joshi, A., & Arora, J. (2023). Recent trends and future prospects of nanotechnology for agro-waste valorization into biofuels. In *Agricultural Waste: Environmental Impact, Useful Metabolites and Energy Production* (pp. 559-582). Singapore: Springer Nature Singapore.

Khan, S. Z., Zaidi, A. A., Naseer, M. N., & AlMohamadi, H. (2022). Nanomaterials for biogas augmentation towards renewable and sustainable energy production: A critical review. *Frontiers in Bioengineering and Biotechnology*, 10, 868454.

Khan, W. S., Asmatulu, E., & Asmatulu, R. (2025). Nanotechnology emerging trends, markets and concerns. In *Nanotechnology Safety* (pp. 1-21). Elsevier.

Kirsch, J., Siltanen, C., Zhou, Q., Revzin, A., & Simonian, A. (2013). Biosensor technology: recent advances in threat agent detection and medicine. *Chemical Society Reviews*, 42(22), 8733-8768.

Kuhn, R., Bryant, I. M., Jensch, R., & Böllmann, J. (2022). Applications of environmental nanotechnologies in remediation, wastewater treatment, drinking water treatment, and agriculture. *Applied Nano*, 3(1), 54-90.

Kumar, R. (2023). Metal oxides-based nano/microstructures for photodegradation of microplastics. *Advanced Sustainable Systems*, 7(6), 2300033.

Liu, X., Sathishkumar, K., Zhang, H., Saxena, K. K., Zhang, F., Naraginiti, S., & Guo, X. (2024). Frontiers in environmental cleanup: Recent advances in remediation of emerging pollutants from soil and water. *Journal of Hazardous Materials Advances*, 100461.

Mallesham, P., Parveen, S., & Naik, R. (2025). Nano-bubbles: The next potential drive to advance technologies in food industry - A review. *ACS Food Science & Technology*.

Mehejabin, F., Musharrat, A., Ahmed, S. F., Kabir, Z., Khan, T. Y., & Saleel, C. A. (2024). Sustainable biofuel production utilizing nanotechnology: challenges and potential solutions. *GCB Bioenergy*, 16(10), e70001.Dergi ismi? Cilt (Sayı), Sayfalar.

Mohammad, Z. H., Ahmad, F., Ibrahim, S. A., & Zaidi, S. (2022). Application of nanotechnology in different aspects of the food industry. *Discover Food*, 2(1), 12.

Mustapha, S., Tijani, J. O., Elabor, R., Salau, R. B., Egbosiuba, T. C., Amigun, A. T., & Mohammed, A. K. (2024). Technological approaches for removal of microplastics and nanoplastics in the environment. *Journal of Environmental Chemical Engineering*, 112084.

Neme, K., Nafady, A., Uddin, S., & Tola, Y. B. (2021). Application of nanotechnology in agriculture, postharvest loss reduction and food processing: food security implication and challenges. *Heliyon*, 7(12), Sayfalar?

Nene, A., Sadeghzade, S., Viaroli, S., Yang, W., Uchenna, U. P., Kandwal, A., & Galluzzi, M. (2025). Recent advances and future technologies in nano-microplastics detection. *Environmental Sciences Europe*, 37(1), 1-21.

Nikolelis, D. P., & Nikoleli, G. P. (Eds.). (2018). *Nanotechnology and biosensors*. Elsevier.

Nile, S. H., Baskar, V., Selvaraj, D., Nile, A., Xiao, J., & Kai, G. (2020). Nanotechnologies in food science: applications, recent trends, and future perspectives. *Nano-micro Letters*, 12, 1-34.

Ochoa, L., Shrivastava, M., Srivastava, S., Cota-Ruiz, K., Zhao, L., White, J. C., & Gardea-Torresdey, J. L. (2025). Nanomaterials for managing abiotic and biotic stress in the soil–plant system for sustainable agriculture. *Environmental Science: Nano*. 12(11), 1037-1058.

Onyeaka, H., Passaretti, P., Miri, T., & Al-Sharify, Z. T. (2022). The safety of nanomaterials in food production and packaging. *Current Research in Food Science*, 5, 763-774.

Ormanoğlu, N., Emekci, M., & Ferizli, A. (2021). Böceklerle mücadelede nanoteknoloji. *Bursa Uludağ Üniversitesi Ziraat Fakültesi Dergisi*, 35(1), 181-202.

Ouda, M., Banat, F., Hasan, S. W., & Karanikolos, G. N. (2023). Recent advances on nanotechnology-driven strategies for remediation of microplastics and nanoplastics from aqueous environments. *Journal of Water Process Engineering*, 52, 103543.

Patil, P. M., Falke, V., Dar, M. A., & Dhanavade, M. J. (2025). Nanobiotechnology in biofuel production and implementation. In *Biofuels and Sustainability* (pp. 67-79). Elsevier Science Ltd.

Peidaei, F., Ahari, H., Anvar, A., & Ataei, M. (2021). Nanotechnology in food packaging and storage: A review. *Iranian Journal of Veterinary Medicine*, 15(2), 122-153.

Pramanik, P., Krishnan, P., Maity, A., Mridha, N., Mukherjee, A., & Rai, V. (2020). Application of nanotechnology in agriculture. *Environmental Nanotechnology Volume* 4, 317-348.

Prasad, J., Dixit, A., Sharma, S. P., Mwakosya, A. W., Petkoska, A. T., Upadhyay, A., & Kumar, N. (2024). Nanoemulsion-based active packaging for food products. *Foods and Raw Materials*, 12(1), 22-36.

Raliya, R. (Ed.). (2019). *Nanoscale engineering in agricultural management*. CRC Press, Taylor & Francis Group.

Rana, L., Kumar, M., Rajput, J., Kumar, N., Sow, S., Kumar, S., & Raigar, B. L. (2024). Nexus between nanotechnology and agricultural production systems: challenges and future prospects. *Discover Applied Sciences*, 6(11), 1-19.

Ranjan, A., Rajput, V. D., Minkina, T., Bauer, T., Chauhan, A., & Jindal, T. (2021). Nanoparticles induced stress and toxicity in plants. *Environmental Nanotechnology, Monitoring & Management*, 15, 100457.

Şahin, S. (2017). Antepfıstığında nanofiber bariyer yaprak gübresi, nanoteknolojik kalsit ve kaolin uygulamalarının verim ve bazı kalite özelliklerine etkisi, Harran Üniversitesi, ss, 49.

Sajid, M., Ihsanullah, I., Khan, M. T., & Baig, N. (2023). Nanomaterials-based adsorbents for remediation of microplastics and nanoplastics in aqueous media: A review. *Separation and Purification Technology*, 305, 122453.

Saleem, H., & Zaidi, S. J. (2020). Developments in the application of nanomaterials for water treatment and their impact on the environment. *Nanomaterials*, 10(9), 1764.

Samal, D. (2017). Use of nanotechnology in food industry: a review. *International Journal of Environment, Agriculture and Biotechnology*, 2(4), 238902.

Sandhu, Z. A., Raza, M. A., Farwa, U., Nasr, S., Yahia, I. S., Fatima, S., & Ashraf, H. (2023). Response surface methodology: a powerful tool for optimizing the synthesis of metal sulfide nanoparticles for dye degradation. *Materials Advances*, *4*(21), 5094-5125.

Sedef, M. (2018). Sıfır değerlikli nano demir sentezi ve sıfır değerlikli nano demirin bitkilerde demir gübresi olarak kullanımının araştırılması (Master thesis, Fen Bilimleri Enstitüsü), ss, 80

Sekar, R., Das, S., Shirin, S., Srinivasan, R., Marimuthu, P., Atchuthan, P., & Yadav, A. K. (2024). Nanobiomaterials-based environmental bioremediation: A special focus on microplastics. In *Bioremediation of Emerging Contaminants in Water. Volume 2* (pp. 163-187). American Chemical Society.

Sekhon, B. S. (2010). Food nanotechnology–an overview. *Nanotechnology, Science and Applications*, 1-15.

Sharma, A., Goel, H., Sharma, S., Rathore, H. S., Jamir, I., Kumar, A., & Kashyap, B. K. (2024). Cutting edge technology for wastewater treatment using smart nanomaterials: recent trends and futuristic advancements. *Environmental Science and Pollution Research*, 31(48), 58263-58293.

Sharma, A., Vijayakumar, P. S., Prabhakar, P. K., & Kumar, R. (Eds.). (2022). Nanotechnology applications for food safety and quality monitoring. *Academic Press.*

Spanos, A., Athanasiou, K., Ioannou, A., Fotopoulos, V., & Krasia-Christoforou, T. (2021). Functionalized magnetic nanomaterials in agricultural applications. *Nanomaterials*, 11(11), 3106.

Wang, Q., Shan, C., Zhang, P., Zhao, W., Zhu, G., Sun, Y., & Rui, Y. (2024). The combination of nanotechnology and potassium: applications in agriculture. *Environmental Science and Pollution Research*, 31(2), 1890-1906.

Yonat, H., & Kolören, O. (2022). Herbisit formülasyonlarında nanoteknolojinin rolü. *Turkish Journal of Weed Science*, 25(2), 134-144.

Zhao, L., Lu, L., Wang, A., Zhang, H., Huang, M., Wu, H., & Ji, R. (2020). Nano-biotechnology in agriculture: use of nanomaterials to promote plant growth and stress tolerance. *Journal of Agricultural and Food Chemistry*, 68(7), 1935-1947.