Exploring the Future of Agriculture through Nanotechnology- A Review

Abstract

Agriculture, as one of the oldest and most essential human endeavors, has constantly evolved through the integration of technology. In recent years, nanotechnology has emerged as a pivotal tool, redefining traditional agricultural paradigms. This comprehensive review delves into the multifaceted implications and applications of nanotechnology within agriculture, providing a holistic view of its past, present, and future roles. Historically, nanotechnology's initial foray into agriculture sought to tackle prevalent challenges, from pest control to soil fertility. Despite some early obstacles, this merger has since showcased myriad successful applications, underscored by targeted and efficient solutions that significantly enhance crop yield and food quality. The present-day agricultural landscape is punctuated by nano-fertilizers ensuring optimal nutrient uptake, nanopesticides targeting pests with minimal off-target effects, nanosensors enabling precision agriculture, nano-based food packaging enhancing shelf life, and nanomaterials aiding in disease diagnosis and treatment.However, with innovation come challenges. The environmental and health ramifications of introducing nanoparticles into ecosystems remain a concern. While they promise reduced chemical usage and waste, potential issues like nanoparticle accumulation, unknown long-term effects, and possible toxicity necessitate rigorous research and regulation. Economically, the nano-agri sector promises substantial yield increases, but it also requires significant investments. As the technology permeates the agricultural supply chain, ramifications on job markets, trade dynamics, and global competitiveness become evident.Looking forward, anticipated advancements include smart nanodevices, potent nano-bio interfaces, and self-repairing materials. Nanobots, soil health rejuvenation techniques, and advanced nano-encapsulation are among the many potential R&D avenues. The road ahead requires collaborative efforts from governments, research institutions, farmers, and the private sector. Public-private partnerships, in particular, could prove indispensable, merging public sector oversight with private sector innovation.

Keywords: *Nanotechnology, Efficiency, Environment, Economics, Innovation*

UNDER PEER REVIEW

Introduction

Agriculture has long served as the backbone of human civilization, feeding billions and acting as a primary source of employment, especially in developing countries. Throughout history, the sector has undergone immense transformation, largely due to technological advancements. From the rudimentary tools of ancient civilizations to the sophisticated machinery and biotechnologies of the modern era, each innovation has left an indelible mark on the way we cultivate, harvest, and process food. The history of agriculture is a testament to human innovation. The Neolithic

Revolution, around 10,000 B.C., marked the transition from nomadic hunting and gathering to settled farming, arguably the first significant agricultural innovation [1]. This shift allowed for the growth of civilizations as surplus food could be stored and trade began to flourish [2]. The subsequent centuries saw gradual improvements in tools and techniques. The Iron Age, for instance, brought about metal ploughs, replacing wooden and stone tools, leading to more efficient farming [3]. The invention of the seed drill by Jethro Tull in the early 18th century revolutionized seed planting, making it more systematic and efficient [4]. The 20th century, however, was a turning point. The Green Revolution in the 1960s and 1970s introduced high-yielding varieties of wheat and rice. Alongside the enhanced use of fertilizers and pesticides, these innovations led to a substantial increase in food production, especially in countries like India [5]. At the same time, mechanization transformed agricultural landscapes, with tractors and combine harvesters becoming commonplace in many parts of the world [6]. Nanotechnology, in its essence, is the manipulation of matter on a molecular or atomic scale, typically within the range of 1 to 100 nanometers [7]. Its emergence in the late 20th century has heralded a new era of technological advancement with implications across various sectors, from medicine to energy. In agriculture, the potential applications of nanotechnology are vast. Nano-fertilizers can increase nutrient uptake in plants, thereby enhancing their growth and yield [8]. Nanopesticides, on the other hand, can offer more effective pest control with reduced environmental impact compared to conventional pesticides [9]. Furthermore, nanosensors can monitor soil health, ensuring optimal conditions for plant growth [10]. Beyond the field, nanotechnology also promises advancements in food storage, packaging, and processing, with nano-packaging potentially extending the shelf life of produce [11]. This review seeks to provide a comprehensive overview of the role of nanotechnology in the future of agriculture. While technology has always been intertwined with agricultural evolution, the introduction of nanotechnology offers unprecedented opportunities and challenges. Through a detailed exploration of current applications, potential environmental, economic, and ethical impacts, as well as case studies, this review aims to shed light on the transformative potential of nanotechnology in agriculture. As nanotechnology is still a relatively nascent field in the context of agriculture, this review intends to stimulate dialogue among researchers, policymakers, and practitioners, fostering a collaborative approach to harnessing the full potential of this groundbreaking technology.

UNDER PEER REVIEW

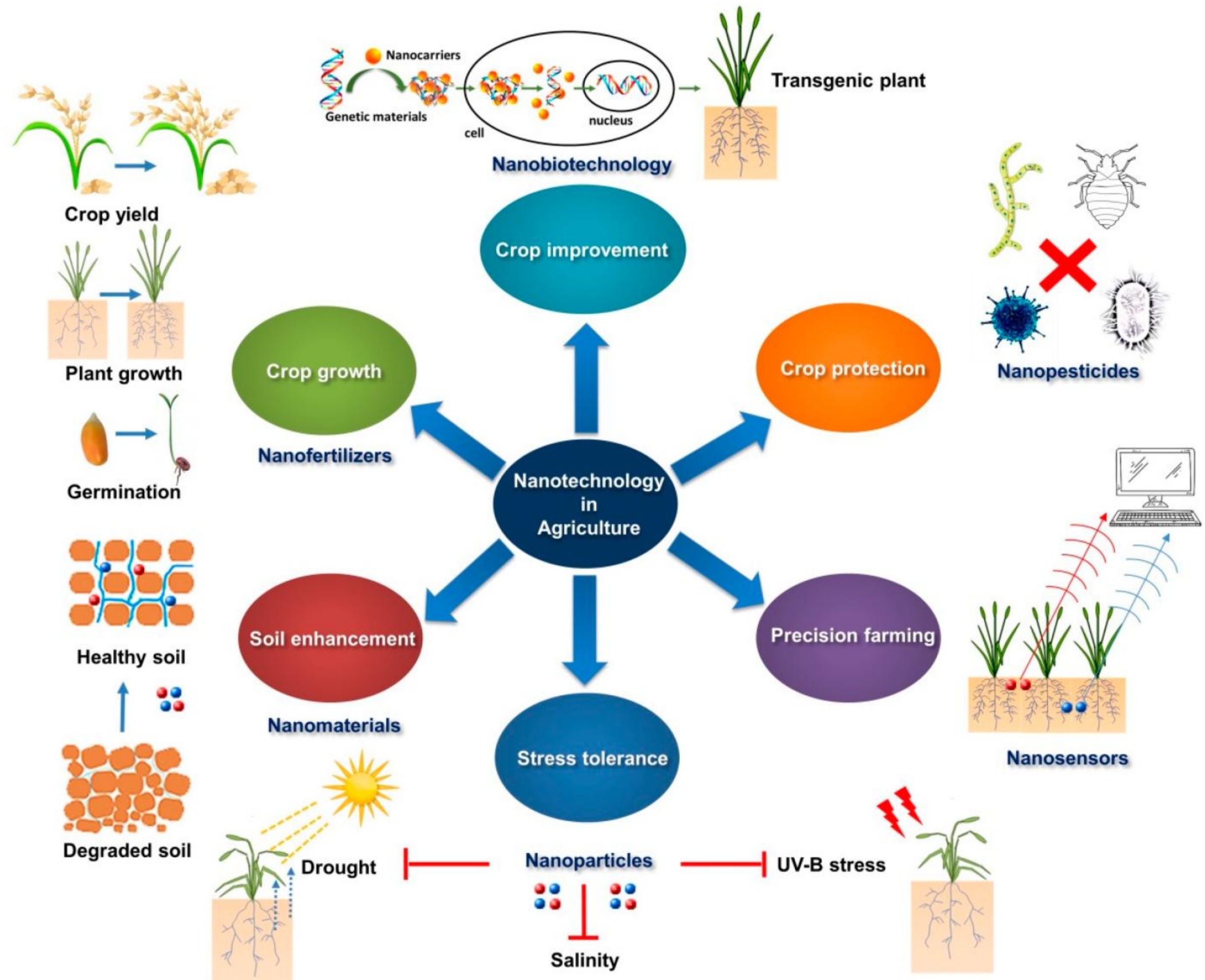

Figure 1. Applications of nanotechnology in agriculture (Source=https://www.mdpi.com/).

UNDER

Nanotechnology

Since its inception, nanotechnology has emerged as a frontier in the realms of science and technology, offering solutions and advancements across a myriad of sectors. Characterized by its manipulation of matter on an atomic and molecular scale, it holds promise and potential in altering the very fabric of conventional methodologies. Nanotechnology, as the name suggests, revolves around the nano scale. One nanometer is one-billionth of a meter, placing structures on this scale at dimensions between individual atoms and larger, more familiar materials [12]. At its core, nanotechnology is the study and application of unique properties and phenomena that matter exhibits at the nanometer scale [13]. Such properties can differ substantially from those observable at macro scales. The high surface-to-volume ratio of nanoscale materials often leads to increased reactivity [14]. Quantum effects can also become more pronounced, leading to distinctive optical, electrical, and magnetic properties [15]. The conceptual foundation of nanotechnology dates back to 1959 when physicist Richard Feynman delivered his famous lecture, "There's Plenty of Room at the Bottom," hinting at the potential for atomic-scale manipulation [16]. It was only in 1974 that the term 'nanotechnology' was first coined by Norio Taniguchi in his seminal paper discussing the precision of atomic level control. The 1980s marked significant advancements in the field. The invention of the scanning tunneling microscope (STM) by Gerd Binnig and Heinrich Rohrer in 1981 provided scientists the first real 'look' at individual atoms [17]. This breakthrough was swiftly followed by the development of fullerene (a molecule of 60 carbon atoms forming a closed cage) by Harold Kroto, Richard Smalley, and Robert Curl in 1985 [18]. The 1990s and early 2000s witnessed the proliferation of nanotechnology research globally, thanks to government and private sector investment. The National Nanotechnology Initiative (NNI) launched by the U.S. in 2000 catalyzed the establishment of similar programs worldwide [19].

UNDER PEER REVIEW

Present-day applications of nanotechnology across various fields

Today, nanotechnology has permeated various sectors, each leveraging the unique properties of nanomaterials:Medicine: Nanoparticles are being used to improve drug delivery, especially in cancer treatment, ensuring targeted delivery to malignant cells while minimizing damage to healthy tissues [20]. Additionally, nanoscale devices are aiding diagnostics and imaging.Electronics: The electronics industry has significantly benefited from nanotech. Transistors have been shrunk to incredibly small sizes, paving the way for faster, smaller, and more efficient electronic devices [21].Energy: Nanotechnology plays a role in enhancing alternative energy sources. Nanoscale materials improve the efficiency of solar cells and are utilized in batteries for higher energy storage [22].Textiles: The textile sector incorporates nanoparticles to design fabrics with unique properties, such as water and stain resistance, or enhanced strength and durability [23].Environment: Nanotech is employed to treat contaminated water and soil, offering solutions for environmental remediation [24].Aerospace and defense: Incorporating nanomaterials like carbon nanotubes can lead to stronger, lighter, and more durable materials, influencing the design of aircraft and spacecraft [25].

Historical Perspective on Nanotechnology in Agriculture

The synthesis of nanotechnology with agriculture has ushered in a new era, marked by enhanced efficiency, productivity, and sustainability. Over the decades, the amalgamation of these two fields has experienced numerous evolutionary leaps, shaping the trajectory of agricultural practices globally. Nanotechnology, a field that burgeoned in the late 20th century, found its roots in agriculture by addressing some of the pressing challenges of the time [26]. Initial forays into the agricultural realm were driven by the need to improve the delivery mechanisms for pesticides and fertilizers, with the primary. The advent of nanoscale carriers, such as nanoparticles and nano-capsules, paved the way for precision delivery, ensuring that nutrients and other agents reached targeted sites, like specific plant tissues or pests [27]. These advancements not only reduced the amount of chemicals and fertilizers required but also minimized off-target effects, leading to reduced environmental contamination [28]. As research deepened, the 2000s witnessed a surge in nanotech's applications in agriculture. Nanosensors emerged as a solution for real-time monitoring of soil health and crop conditions, offering farmers actionable insights into their fields' microenvironments [29]. Moreover, the development of nano-enhanced barriers, such as films and coatings, provided crops with protection from pests, diseases, and adverse climatic conditions [30]. Among the pioneering successes was the development of nano-encapsulated pesticides, which allowed for controlled release, thereby prolonging the efficacy and reducing the frequency of applications [31]. Additionally, nanobio-sensors, capable of detecting pathogens at an early stage, revolutionized plant disease management by facilitating timely interventions [32]. Nanotech also offered solutions for post-harvest management. Nano-composite films extended the shelf life of perishables by providing barriers against moisture, gases, and pathogens, thereby reducing post-harvest losses [33]. However, the journey wasn't devoid of challenges. The nascent nature of nanotechnology raised concerns about the environmental and health implications of introducing nanoparticles into the ecosystem [34]. Questions surfaced regarding their long-term effects, potential for bioaccumulation, and unforeseen ecological interactions [35]. Moreover, the high costs associated with developing and deploying nanotech solutions in agriculture initially posed hurdles for widespread adoption, especially in resource-limited settings [36].

UNDER PEER REVIEW

Current Applications of Nanotechnology in Agriculture

The marriage of nanotechnology with agriculture offers transformative solutions for an industry facing challenges from climate change, burgeoning populations, and resource constraints[1].Nano-fertilizers have reshaped the agricultural landscape by facilitating efficient nutrient delivery and uptake [37]. These fertilizers, designed at the nanoscale, allow for controlled nutrient release, ensuring that plants receive adequate nutrition over extended periods [38].Advantages of nano-fertilizers include:Targeted Delivery: Ensures nutrients reach intended plant parts, reducing wastage [39]. Improved Uptake: Enhances the nutrient absorption capacity of plants [40]Environmentally Friendly: Reduction in fertilizer usage decreases soil and water pollution [41].Nano-encapsulated fertilizers: Using nanocapsules, nutrients are enclosed and gradually released [42]. Nano-coated fertilizers: Nanomaterial coatings protect nutrients from premature degradation [43]. Studies have shown significant improvements in crop yields when using nano-fertilizers, with crops demonstrating increased biomass, grain yield, and overall health [44].Nanopesticides employ nanoparticles as carriers or active ingredients. Their nano-scale design enhances the solubility, stability, and mobility of the pesticide molecules [45]. This results in better pest targeting and reduced pesticide usage [46].Efficacy include, Controlled Release: Pesticides are released over extended durations, reducing reapplication frequencies [47].Enhanced Penetration: Nanopesticides better penetrate leaf surfaces, ensuring comprehensive protection [48].However, while they offer numerous benefits, nanopesticides pose environmental challenges. Questions about nanoparticle residue persistence, their potential bioaccumulation in food chains, and broader ecological implications remain largely unanswered [49]. Safety concerns also loom, with gaps in knowledge about their long-term effects on human health [50].Nanosensors, with their incredible sensitivity and specificity, have revolutionized agricultural monitoring [51].Precision Agriculture: Nanosensors assist in real-time data collection about crop health, allowing for tailored interventions [52].Soil Health Monitoring: They detect micro-nutrient deficiencies, pH imbalances, and other soil health indicators [53].Water Management: By monitoring soil moisture levels, nanosensors guide irrigation, ensuring optimal water use [54].Nano-food packaging incorporates nanomaterials, enhancing the protective properties of conventional packaging [55]. Such packaging offers:Improved Barrier Properties: Nanocomposite films shield food from oxygen, moisture, and pathogens, prolonging shelf life [56].Anti-microbial Properties: Silver or zinc oxide nanoparticles infused in packaging eliminate microbial growth [57]. Additionally, such packaging can be incorporated with nanosensors to monitor food quality, detecting spoilage or contamination early on.Nanotechnology plays a pivotal role in diagnosing and combating plant diseases.Nano-bio interfaces: gold or silver nanoparticles, combined with antibodies, are used to detect pathogens [58].Targeted Delivery Systems: Nanocarriers deliver antimicrobial agents directly to infection sites, ensuring efficient disease management [59].While these applications are promising, continuous research is vital to fully understand their implications and harness nanotechnology's potential responsibly and sustainably in agriculture.

Table1: Effect of nanomaterials on crop physiology and plant protection. (Source-https://www.mdpi.com/).

Nanomaterials	**Crop Species**	**Mode of Application**	**Concentrations Used**	**Duration of Treatments**	**Responses**
MWCNTs	*Hordeum vulgare, Glycine max, Zea mays*	Seed priming	100 μg/mL	24 h	Enhanced germination and growth of seedlings
MWCNTs	*Triticumaestivum, Zea mays, Arachishypogaea, Allium sativum*	Seed priming	50 μg/mL	Over night	Improved and rapid germination, increased biomass accumulation and water absorption potential of seeds
ZnO	*Coffeaarabica*	Foliar spray	10 mg/L	45 days	Enhanced growth, biomass accumulation and net photosynthesis
ZnO	*Triticumaestivum*	Mixed with growth substrate	20 mg/L	Growth cycle	Increased grain yield and biomass accumulation

UNDER PEER REVIEW

ZnO	*Cyamopsistetragonoloba*	Foliar spray	10 mg/L	6 weeks	Improved plant growth, biomass accumulation and nutrient content
FeS_2	*Cicer arietinum; pinaciaoleracea; Daucuscarota, Brassica juncea and Sesamumindicum*	Seed priming	80–100 μg/mL	12–14 h	Increased germination and crop yield
CuO	*Spinaciaoleracea*	Mixed with soils	200 mg/kg	60 days	Improved photosynthesis and biomass production
ZnO	*Nicotianatabacum*	Hydroponics	0.2 µM and 1 µM	21 days	Positively affected growth physiology, increased metabolites, enzymatic activities and anatomical properties of plants
Fe/SiO2	*Arachishypogaea, Zea mays*	As fertilizers	15 mg/kg	3 days	Enhanced plants growth and biomass accumulation
TiO2	*Spinaciaoleracea*	Seed priming and foliar application	0.25% suspension	48 h and 35 days	Increased biomass accumulation, chlorophyll, nitrogen and protein content
AgNPs	*Triticumaestivum*	Mixed with pot soils	50 mg/L and 75 mg/L	Trifoliate stage	Improved growth and tolerance to heat stress
Ag NPs	*Vignasinensis*	Foliar application	50 mg/L	40 days	Enhanced growth and biomass by stimulating root nodulation and soil bacterial diversity
TiO_2 and SiO_2	*Oryza sativa*	Foliar application	20 and 30 mg/L	55 days	Mitigated Cd toxicity and improved growth by stimulating antioxidant potential and inhibiting Cd translocation
SiO_2 NPs	*Oryza sativa*	Foliar application	2.5 mM/L	70 days	Alleviated heavy metal toxicity and improved growth by decreasing bio-concentration and translocation in plants
ZnO, CuO and Ag NPs	*Prunusdomestica fruits*	Fruit spray	100 and 1000 μg/mL	4 days	Suppressed grey mold symptoms caused by *B. cinerea* and soil borne diseases
Al_2O_3 NPs	*Solanum lycopersicum*	Foliar application	400 mg/L	20 days	Successfully controlled Fusarium root rot in tomato
Ag NPs	*Vignaunguiculata*	Foliar application	50–100 μg/mL	7 Days	Showed no phytotoxicity, but could inhibit growth of

UNDER PEER REVIEW

					Xanthomonasaxonopodis pv. malvacearum and Xanthomonascampestrisp v. campestris in vitro
CuO	*Solanum lycopersicum*	Foliar application	150–340 μg/mL	11 days	Effectively controlled late blight disease caused by Phytophthorainfestans
MgO	*Solanum lycopersicum*	Drenching	7–10 μg/mL	7 Days	Controlled bacterial wilt disease by suppressing pathogen Ralstoniasolanacearum

Potential Environmental and Health Impacts

The integration of nanotechnology in agriculture has fueled hopes for a more sustainable food system, but its environmental and health implications have become points of contention and intense investigation [60].*Reduction in Chemical Usage:* One of the primary benefits of nanotechnology in agriculture is the significant reduction in the amount of chemicals required. Conventional agrochemicals often suffer from poor solubility, leading to excessive usage [61]. In contrast, nanoformulations enhance solubility and bioavailability.*Targeted Delivery:* Nanoparticles can be engineered to release their contents only in specific conditions or regions, ensuring that active ingredients reach their intended targets with minimal dispersion [62]. This precision not only maximizes effectiveness but also minimizes unintended exposures to non-target organisms.*Waste Reduction:* leading to less environmental contamination and resource wastage [63].Challenges include,*Nanoparticle Accumulation:* As nanoparticles are applied to fields, concerns arise about their potential accumulation in soils [64]. There's a possibility that these particles could interfere with microbial communities essential for nutrient cycling and soil health.*Potential Toxicity:* Some nanoparticles may exhibit toxic effects on beneficial organisms, such as pollinators or natural predators of pests [65]. The mechanisms and results of such toxicities can vary and require thorough understanding for safe application.*Long-term Unknowns:* While short-term studies have shed light on some risks, the long-term behavior of nanoparticles in the environment remains inadequately understood [66]. Their persistence, degradation pathways, and chronic effects on ecosystems are areas that warrant extended research.Environmental considerations include, *Soil Health:* Soil is a complex matrix with myriad microbial and chemical interactions. While nanoparticles can benefit plants directly, their influence on this subterranean ecology is under scrutiny [67]. Interactions with mycorrhizal fungi, nitrogen-fixing bacteria, and other essential soil organisms need particular attention, *Water Quality:* Runoff from agricultural lands can carry nanoparticles to water bodies. Concerns include potential toxicity to aquatic life and the broader impact on water quality [68]. Also, some nanoparticles might act as carriers, absorbing and transporting other contaminants., *Ecosystem Balance:* Even if nanoparticles are benign individually, their introduction could still disrupt ecological balances. For instance, if they disproportionately affect certain pests, this could inadvertently lead to the proliferation of other pests [69].Human health considerations include

UNDER PEER REVIEW

Impact on Consumers: There's a need to study whether nanoparticles remain in harvested crops and if they do, the implications of their ingestion over long periods [70]. Possible concerns include the bioaccumulation of nanoparticles in tissues or their interactions with biological systems.*Impact on Farmers:* Farmers, being the primary applicators of nano-agrochemicals, are at the frontline of exposure risks. Inhalation, dermal contact, and other exposure routes could pose health risks if adequate safety measures aren't in place [71].

Economic Impacts and Considerations

Nanotechnology's introduction into agriculture has sown the seeds of an economic revolution that can fundamentally alter the way we perceive agricultural productivity, trade, and labor dynamics [72]. This section delves deep into the economic ramifications of this technological integration.Potential for yield increase and its economic implications, *Yield Increase:* Several studies have corroborated the potential of nanotechnology in enhancing crop yield. Nanoparticles can enhance nutrient use efficiency, thereby reducing input costs and increasing yield [73]. For instance, nano-fertilizers release nutrients slowly, ensuring plants receive a consistent nutrient supply, promoting better growth. A study found a significant increase in the yield of wheat crops when treated with zinc oxide nanoparticles [74].*Economic Implications:* Enhanced yields invariably translate to increased income for farmers. Assuming consistent demand, greater yields can lead to a reduction in commodity prices, benefiting the end consumer [75]. However, the initial investment required for nanotechnology might be high, making it essential to ensure that the yield increase offsets this cost.

Cost-benefit analysis: Investment in nanotechnology versus returns.

Investment: Integrating nanotechnology in agriculture requires significant upfront costs: research & development, equipment, training, and infrastructure [76]. For many farmers, especially those in developing regions, this can represent a formidable financial barrier.*Returns:* The returns, however, are manifold. Enhanced yields, reduction in input costs, lesser dependency on conventional chemicals, and potential for premium pricing due to improved quality are some benefits [77]. A study showed that while the initial investment might be high, the ROI over a span of 3-5 years can be substantial [78].

Impact on the agricultural supply chain and job market.

Supply Chain: The agricultural supply chain could undergo a transformation. With nanotechnology, there's potential for lesser reliance on bulk fertilizers, pesticides, and herbicides, changing the dynamics of the supply chain and possibly even leading to the emergence of new suppliers and distributors specializing in nanoproducts [79].*Job Market:* While the demand for traditional roles might decrease, new employment opportunities in nanotechnology research, production, and application in agriculture will emerge [80]. Moreover, specialized training and education programs related to nanotechnology in agriculture can create avenues for skilled jobs.

UNDER PEER REVIEW

Global economic implications: Trade, regulations, and competitiveness.

Trade: As nations adopt nanotechnology at varying paces, trade dynamics can shift. Countries at the forefront of nanotech adoption might gain a competitive edge in the global market, potentially exporting both their products and their technological expertise [81].*Regulations:* With new technology comes the need for new regulations. Nations will have to formulate guidelines regarding the production, application, and trade of nano-agricultural products [82]. This could lead to trade disputes, especially if there's a perceived disparity in regulatory stringency.*Competitiveness:* Early adopters of nanotechnology might gain a significant competitive advantage. They can produce more with less, sell at competitive prices, and even set standards that become globally recognized [83]. However, this also runs the risk of creating disparities between nations, especially between technologically advanced nations and developing ones. Nanotechnology, while presenting enormous economic opportunities, comes with its own set of challenges. Effective policies, global cooperation, and strategic investments will be crucial in harnessing its potential and ensuring equitable benefits across the globe [84].

Future Outlook and Recommendations

The confluence of agriculture and nanotechnology has created a paradigm shift with far-reaching ramifications. The innovative potential of nanotechnology could redefine agricultural practices and catalyze food security solutions. As we gaze into the future of this merger, it is also essential to provide guidance on the path forward [85].

Anticipated advancements in nanotechnology for agriculture.

The future trajectory of nanotechnology in agriculture is rife with possibilities. Several advancements are anticipated, both in the immediate and distant future.*Smart Nano-Devices:* With advancements in nanoelectronics, the integration of smart nanodevices in agriculture is imminent. These devices can facilitate real-time monitoring, automate irrigation based on soil moisture levels, or release fertilizers when plants need them [86].*Nano-Bio Interfaces:* The nexus of nanotechnology and biotechnology can lead to nano-bio interfaces, potentially revolutionizing seed germination, plant growth, and resistance to diseases [87].*Self-healing Materials:* Inspired by biological systems, self-healing materials at the nanoscale might be used in agricultural tools, ensuring longevity and reducing maintenance costs [88].

Potential areas of research and development.

Nanobots in Agriculture: Research into deploying nanobots that can target specific pests, thereby reducing the need for wide-spectrum pesticides, is promising [89].*Nanotechnology for Soil Health:* The development of nanoparticles that can rejuvenate soil microflora or detoxify polluted soils offers vast potential [90].*Nano-encapsulation:* Research into nano-encapsulation techniques can lead to slow-release fertilizers and pesticides, ensuring longer-lasting effects and

UNDER PEER REVIEW

reducing the frequency of application [91].

Recommendations for stakeholders

Government, Regulations and Standards: Establish clear guidelines and safety standards related to the application of nanotechnology in agriculture [92].Funding: Allocate funds for research and development in nano-agri technologies [93].Public Awareness: Launch awareness campaigns, ensuring public knowledge and acceptance of these advancements [94].*Research Institutions:*Collaborative Research: Encourage interdisciplinary research, combining agriculture, nanotechnology, and even biotechnology [95].Safety Protocols: Ensure rigorous testing of nano-agri products before commercial release [96].Training: Offer courses and training sessions on the applications and implications of nanotechnology in agriculture [97].*Farmers:*Stay Updated: Engage in workshops and training sessions to remain abreast of the latest advancements.Safety First: Always adhere to guidelines when using nanoproducts, ensuring the safety of the soil, crops, and consumers [99].Feedback Mechanism: Collaborate with research institutions, providing feedback, which can be invaluable for real-world applications and improvements [100].

Role of public-private partnerships in advancing the nano-agri sector

Public-private partnerships (PPPs) can serve as a catalyst in this domain. Such collaborations can marry the infrastructural and regulatory strengths of the public sector with the innovative and financial prowess of the private sector [101].*Research Collaboration:* PPPs can lead joint research initiatives, pooling resources and expertise [102].*Infrastructure Development:* Infrastructure, crucial for the development and distribution of nano-agri products, can be jointly established and managed [103].*Policy Formulation:* The private sector can offer insights into policy formulation, ensuring regulations that are both robust and conducive to innovation [104].

Conclusion

Nanotechnology, a revolutionary advancement, has made significant strides in transforming agricultural practices. It has established innovative solutions from pest control to soil fertility, enhancing crop yield and food quality. Despite the initial hitches, the successful integration of nanotechnology with agriculture is demonstrated by the introduction of nano-fertilizers, nanopesticides, nanosensors, nano-based food packaging, and nanomaterials for disease diagnosis. However, the potential environmental impact, long-term effects, and economic implications of nanotechnology in agriculture necessitate ongoing research and stringent regulation. Looking forward, technological advancements such as smart nanodevices and soil health rejuvenation techniques will require collective efforts from various sectors. Undoubtedly, nanotechnology is a potent tool that could reshape the future of agriculture, provided the

UNDER PEER REVIEW

associated challenges are addressed proactively.

References:

1. Svizzero, S. (2017). Persistent controversies about the neolithic revolution. *Journal of Historical Archaeology & Anthropological Sciences*, *1*(2), 00013.

2. McNeill, W. H. (1984). Human migration in historical perspective. *Population and development Review*, 1-18.

3. Clark, G. (1966). The invasion hypothesis in British archaeology. *Antiquity*, *40*(159), 172-189.

4. De Bruyn, F. (2004). Reading Virgil's" Georgics" as a Scientific Text: The Eighteenth-Century Debate between Jethro Tull and Stephen Switzer. *Elh*, *71*(3), 661-689.

5. Ali, S. S., Al-Tohamy, R., Koutra, E., Moawad, M. S., Kornaros, M., Mustafa, A. M., ... & Sun, J. (2021). Nanobiotechnological advancements in agriculture and food industry: Applications, nanotoxicity, and future perspectives. *Science of the Total Environment*, *792*, 148359.

6. Schlebecker, J. I. (2006). The Changing American Farm, 1831-1981. *Material Culture*, *38*(2), 19-38.

7. Mansoori, G. A. (2002). Advances in atomic & molecular nanotechnology. *United Nations Tech Monitor*, 53-59.

8. Madani, S. Y., Naderi, N., Dissanayake, O., Tan, A., &Seifalian, A. M. (2011). A new era of cancer treatment: carbon nanotubes as drug delivery tools. *International journal of nanomedicine*, 2963-2979.

9. Deka, B., Babu, A., Baruah, C., &Barthakur, M. (2021). Nanopesticides: A systematic review of their prospects with special reference to tea pest management. *Frontiers in Nutrition*, *8*, 686131.

10. John, S. A., Chattree, A., Ramteke, P. W., Shanthy, P., Nguyen, T. A., & Rajendran, S. (2022). Nanosensors for plant health monitoring. In *Nanosensors for Smart Agriculture* (pp. 449-461). Elsevier.

UNDER PEER REVIEW

11. Sekhon, B. S. (2010). Food nanotechnology–an overview. *Nanotechnology, science and applications*, 1-15.

12. Mansoori, G. A. (2017). An introduction to nanoscience and nanotechnology. *Nanoscience and Plant–Soil Systems*, 3-20.

13. Tarafdar, J. C., Sharma, S., &Raliya, R. (2013). Nanotechnology: Interdisciplinary science of applications. *African Journal of Biotechnology*, *12*(3).

14. Theivasanthi, T., &Alagar, M. (2011). Studies of copper nanoparticles effects on micro-organisms. *arXiv preprint arXiv:1110.1372*.

15. Pan, G., Bai, X., Yang, D., Chen, X., Jing, P., Qu, S., ... & Song, H. (2017). Doping lanthanide into perovskite nanocrystals: highly improved and expanded optical properties. *Nano letters*, *17*(12), 8005-8011.

16. Toumey, C. (2007). The man who understood the Feynman machine. *Nature Nanotechnology*, *2*(1), 9-10.

17. Binnig, G., & Rohrer, H. (2000). Scanning tunneling microscopy. *IBM Journal of research and development*, *44*(1/2), 279.

18. Kroto, H. (1997). Symmetry, space, stars and C 60. *Reviews of Modern Physics*, *69*(3), 703.

19. Roco, M. C. (2007). National nanotechnology initiative-past, present, future. *Handbook on nanoscience, engineering and technology*, *2*, 3-1.

20. Sun, T., Zhang, Y. S., Pang, B., Hyun, D. C., Yang, M., & Xia, Y. (2021). Engineered nanoparticles for drug delivery in cancer therapy. *Nanomaterials and Neoplasms*, 31-142.

21. Fiori, G., Bonaccorso, F., Iannaccone, G., Palacios, T., Neumaier, D., Seabaugh, A., Colombo, L. (2014). Electronics based on two-dimensional materials. *Nature nanotechnology*, *9*(10), 768-779.

22. Hussein, A. K. (2015). Applications of nanotechnology in renewable energies—A comprehensive overview and understanding. *Renewable and Sustainable Energy Reviews*, *42*, 460-476.

UNDER PEER REVIEW

23. Hassabo, A. G., Elmorsy, H., Gamal, N., Sediek, A., Saad, F., Hegazy, B. M., & Othman, H. (2023). Applications of Nanotechnology in the Creation of Smart Sportswear for Enhanced Sports Performance: Efficiency and Comfort. *Journal of Textiles, Coloration and Polymer Science*, *20*(1), 11-28.

24. Agarwal, A., & Joshi, H. (2010). Application of nanotechnology in the remediation of contaminated groundwater: a short review. *Recent Research in Science and Technology*, *2*(6).

25. Duongthipthewa, A., Su, Y., & Zhou, L. (2020). Electrical conductivity and mechanical property improvement by low-temperature carbon nanotube growth on carbon fiber fabric with nanofiller incorporation. *Composites Part B: Engineering*, *182*, 107581.

26. Kumar, Y. O. G. E. N. D. R. A., Tiwari, K. N., Singh, T., &Raliya, R. (2021). Nanofertilizers and their role in sustainable agriculture. *Annals of Plant and Soil Research*, *23*(3), 238-255.

27. Costa, R. R., Alatorre-Meda, M., & Mano, J. F. (2015). Drug nano-reservoirs synthesized using layer-by-layer technologies. *Biotechnology advances*, *33*(6), 1310-1326.

28. Chen, S., Lan, Y., Zhou, Z., Deng, X., & Wang, J. (2021). Research advances of the drift reducing technologies in application of agricultural aviation spraying. *International Journal of Agricultural and Biological Engineering*, *14*(5), 1-10.

29. Subramanian, K. S., &Tarafdar, J. C. (2011). Prospects of nanotechnology in Indian farming. *Indian J Agric Sci*, *81*(10), 887-893.

30. John, S. A., Chattree, A., Ramteke, P. W., Shanthy, P., Nguyen, T. A., & Rajendran, S. (2022). Nanosensors for plant health monitoring. In *Nanosensors for Smart Agriculture* (pp. 449-461). Elsevier.

31. Nuruzzaman, M. D., Rahman, M. M., Liu, Y., & Naidu, R. (2016). Nanoencapsulation, nano-guard for pesticides: a new window for safe application. *Journal of agricultural and food chemistry*, *64*(7), 1447-1483.

32. Kim, T. S., Kim, S. J., Chung, B. H., Yoo, K. H., & Park, S. H. (2007). The Korean Research & Development Program on Micro- Electro- Mechanical Systems (MEMS) in medical applications. *Minimally Invasive Therapy & Allied Technologies*, *16*(2), 109-119.

UNDER PEER REVIEW

33. Kalia, A., Kaur, M., Shami, A., Jawandha, S. K., Alghuthaymi, M. A., Thakur, A., &Abd-Elsalam, K. A. (2021). Nettle-leaf extract derived ZnO/CuO nanoparticle-biopolymer-based antioxidant and antimicrobial nanocomposite packaging films and their impact on extending the post-harvest shelf life of guava fruit. *Biomolecules*, *11*(2), 224.

34. Lin, D., Tian, X., Wu, F., & Xing, B. (2010). Fate and transport of engineered nanomaterials in the environment. *Journal of environmental quality*, *39*(6), 1896-1908.

35. Pérez-Parada, A., Goyenola, G., de Mello, F. T., & Heinzen, H. (2018). Recent advances and open questions around pesticide dynamics and effects on freshwater fishes. *Current Opinion in Environmental Science & Health*, *4*, 38-44.

36. Chen, H., & Yada, R. (2011). Nanotechnologies in agriculture: new tools for sustainable development. *Trends in Food Science & Technology*, *22*(11), 585-594.

37. Seleiman, M. F., Almutairi, K. F., Alotaibi, M., Shami, A., Alhammad, B. A., & Battaglia, M. L. (2020). Nano-fertilization as an emerging fertilization technique: Why can modern agriculture benefit from its use?. *Plants*, *10*(1), 2.

38. Karthik, A., & Maheswari, M. U. (2021). Smart fertilizer strategy for better crop production. *Agricultural Reviews*, *42*(1), 12-21.

39. Iqbal, M., Umar, S., &Mahmooduzzafar. (2019). Nano-fertilization to enhance nutrient use efficiency and productivity of crop plants. *Nanomaterials and plant potential*, 473-505.

40. Solanki, P., Bhargava, A., Chhipa, H., Jain, N., & Panwar, J. (2015). Nano-fertilizers and their smart delivery system. *Nanotechnologies in food and agriculture*, 81-101.

41. Qureshi, A., Singh, D. K., & Dwivedi, S. (2018). Nano-fertilizers: a novel way for enhancing nutrient use efficiency and crop productivity. *Int. J. Curr. Microbiol. App. Sci*, *7*(2), 3325-3335.

42. Iqbal, M. A. (2019). Nano-fertilizers for sustainable crop production under changing climate: a global perspective. *Sustainable crop production*, *8*, 1-13.

43. Iavicoli, I., Leso, V., Beezhold, D. H., & Shvedova, A. A. (2017). Nanotechnology in agriculture: Opportunities, toxicological implications, and occupational risks. *Toxicology and applied pharmacology*, *329*, 96-111.

UNDER PEER REVIEW

44. Solanki, P., Bhargava, A., Chhipa, H., Jain, N., & Panwar, J. (2015). Nano-fertilizers and their smart delivery system. *Nanotechnologies in food and agriculture*, 81-101.

45. Bhattacharya, A., Epidi, T. T., & Kannan, M. (2020). Nano-technology applications in pest management. *Innovative Pest Management Approaches for the 21st Century: Harnessing Automated Unmanned Technologies*, 391-401.

46. Sarkar, N., Chaudhary, S., & Kaushik, M. (2021). Nano-fertilizers and Nano-pesticides as Promoters of Plant Growth in Agriculture. *Plant-Microbes-Engineered Nano-particles (PM-ENPs) Nexus in Agro-Ecosystems: Understanding the Interaction of Plant, Microbes and Engineered Nano-particles (ENPS)*, 153-163.

47. Guo, H., White, J. C., Wang, Z., & Xing, B. (2018). Nano-enabled fertilizers to control the release and use efficiency of nutrients. *Current Opinion in Environmental Science & Health*, *6*, 77-83.

48. Xiao, D., Wu, H., Zhang, Y., Kang, J., Dong, A., & Liang, W. (2022). Advances in stimuli-responsive systems for pesticides delivery: Recent efforts and future outlook. *Journal of Controlled Release*, *352*, 288-312.

49. Chaud, M., Souto, E. B., Zielinska, A., Severino, P., Batain, F., Oliveira-Junior, J., & Alves, T. (2021). Nanopesticides in agriculture: Benefits and challenge in agricultural productivity, toxicological risks to human health and environment. *Toxics*, *9*(6), 131.

50. Vogelezang-Stoute, E. (2012). Regulating Nanomaterials: Bottlenecks and Perspectives in EU Legislation on Chemical and Products. *Eur. Energy &Envtl. L. Rev.*, *21*, 41.

51. Omanović-Mikličanina, E., &Maksimović, M. (2016). Nanosensors applications in agriculture and food industry. *Bull Chem Technol Bosnia Herzegovina*, *47*, 59-70.

52. Ngô, C., Van de Voorde, M., Ngô, C., & Van de Voorde, M. H. (2014). Sensors for Measuring and Monitoring. *Nanotechnology in a Nutshell: From Simple to Complex Systems*, 255-266.

53. Manjunatha, S. B., Biradar, D. P., & Aladakatti, Y. R. (2016). Nanotechnology and its applications in agriculture: A review. *J farm Sci*, *29*(1), 1-13.

UNDER PEER REVIEW

54. SU, S. L., Singh, D. N., &Baghini, M. S. (2014). A critical review of soil moisture measurement. *Measurement*, *54*, 92-105.

55. Mustafa, F., & Andreescu, S. (2020). Nanotechnology-based approaches for food sensing and packaging applications. *RSC advances*, *10*(33), 19309-19336.

56. Indumathi, M. P., Sarojini, K. S., &Rajarajeswari, G. R. (2019). Antimicrobial and biodegradable chitosan/cellulose acetate phthalate/ZnOnano composite films with optimal oxygen permeability and hydrophobicity for extending the shelf life of black grape fruits. *International journal of biological macromolecules*, *132*, 1112-1120.

57. Shankar, S., Wang, L. F., &Rhim, J. W. (2018). Incorporation of zinc oxide nanoparticles improved the mechanical, water vapor barrier, UV-light barrier, and antibacterial properties of PLA-based nanocomposite films. *Materials Science and Engineering: C*, *93*, 289-298.

58. Naja, G., Bouvrette, P., Hrapovic, S., & Luong, J. H. (2007). Raman-based detection of bacteria using silver nanoparticles conjugated with antibodies. *Analyst*, *132*(7), 679-686.

59. Fenaroli, F., Westmoreland, D., Benjaminsen, J., Kolstad, T., Skjeldal, F. M., Meijer, A. H., ... & Griffiths, G. (2014). Nanoparticles as drug delivery system against tuberculosis in zebrafish embryos: direct visualization and treatment. *ACS nano*, *8*(7), 7014-7026.

60. Mukhopadhyay, S. S. (2014). Nanotechnology in agriculture: prospects and constraints. *Nanotechnology, science and applications*, 63-71.

61. Rai, M., & Ingle, A. (2012). Role of nanotechnology in agriculture with special reference to management of insect pests. *Applied microbiology and biotechnology*, *94*, 287-293.

62. Kievit, F. M., & Zhang, M. (2011). Surface engineering of iron oxide nanoparticles for targeted cancer therapy. *Accounts of chemical research*, *44*(10), 853-862.

63. Rodrigues, S. M., Demokritou, P., Dokoozlian, N., Hendren, C. O., Karn, B., Mauter, M. S., ... & Lowry, G. V. (2017). Nanotechnology for sustainable food production: promising opportunities and scientific challenges. *Environmental Science: Nano*, *4*(4), 767-781.

64. Yang, Y., Wang, Y., Westerhoff, P., Hristovski, K., Jin, V. L., Johnson, M. V. V., & Arnold, J. G. (2014). Metal and nanoparticle occurrence in biosolid-amended soils. *Science of the total environment*, *485*, 441-449.

UNDER PEER REVIEW

65. Kannan, M., Elango, K., Tamilnayagan, T., Preetha, S., &Kasivelu, G. (2020). Impact of nanomaterials on beneficial insects in agricultural ecosystems. *Nanotechnology for food, agriculture, and environment*, 379-393.

66. Chen, J., Dong, X., Xin, Y., & Zhao, M. (2011). Effects of titanium dioxide nano-particles on growth and some histological parameters of zebrafish (Danio rerio) after a long-term exposure. *Aquatic Toxicology*, *101*(3-4), 493-499.

67. Cai, P., Sun, X., Wu, Y., Gao, C., Mortimer, M., Holden, P. A., ... & Huang, Q. (2019). Soil biofilms: microbial interactions, challenges, and advanced techniques for ex-situ characterization. *Soil Ecology Letters*, *1*, 85-93.

68. Vryzas, Z. (2018). Pesticide fate in soil-sediment-water environment in relation to contamination preventing actions. *Current Opinion in Environmental Science & Health*, *4*, 5-9.

69. Glenn, J. C. (2006). Nanotechnology: Future military environmental health considerations. *Technological Forecasting and Social Change*, *73*(2), 128-137.

70. Zhao, L., Sun, Y., Hernandez-Viezcas, J. A., Hong, J., Majumdar, S., Niu, G., ... &Gardea-Torresdey, J. L. (2015). Monitoring the environmental effects of CeO2 and ZnO nanoparticles through the life cycle of corn (Zea mays) plants and in situ μ-XRF mapping of nutrients in kernels. *Environmental science & technology*, *49*(5), 2921-2928.

71. Upadhyay, S. K., Kumar, S., Rout, C., Vashistha, G., & Aggarwal, D. (2022). Risks and Concerns of Use of Nanoparticles in Agriculture. In *The Role of Nanoparticles in Plant Nutrition under Soil Pollution: Nanoscience in Nutrient Use Efficiency* (pp. 371-394). Cham: Springer International Publishing.

72. Yashveer, S., Singh, V., Kaswan, V., Kaushik, A., &Tokas, J. (2014). Green biotechnology, nanotechnology and bio-fortification: perspectives on novel environment-friendly crop improvement strategies. *Biotechnology and Genetic Engineering Reviews*, *30*(2), 113-126.

73. Qureshi, A., Singh, D. K., & Dwivedi, S. (2018). Nano-fertilizers: a novel way for enhancing nutrient use efficiency and crop productivity. *Int. J. Curr. Microbiol. App. Sci*, *7*(2), 3325-3335.

UNDER PEER REVIEW

74. Zhang, H., Wang, R., Chen, Z., Cui, P., Lu, H., Yang, Y., & Zhang, H. (2021). The effect of zinc oxide nanoparticles for enhancing rice (Oryza sativa L.) yield and quality. *Agriculture*, *11*(12), 1247.

75. MaCurdy, T. (2015). How effective is the minimum wage at supporting the poor?. *Journal of Political Economy*, *123*(2), 497-545.

76. Chen, H., & Yada, R. (2011). Nanotechnologies in agriculture: new tools for sustainable development. *Trends in Food Science & Technology*, *22*(11), 585-594.

77. Balafoutis, A., Beck, B., Fountas, S., Vangeyte, J., Van der Wal, T., Soto, I., ... &Eory, V. (2017). Precision agriculture technologies positively contributing to GHG emissions mitigation, farm productivity and economics. *Sustainability*, *9*(8), 1339.

78. Chisholm, D., Sweeny, K., Sheehan, P., Rasmussen, B., Smit, F., Cuijpers, P., & Saxena, S. (2016). Scaling-up treatment of depression and anxiety: a global return on investment analysis. *The Lancet Psychiatry*, *3*(5), 415-424.

79. Kim, D. Y., Kadam, A., Shinde, S., Saratale, R. G., Patra, J., &Ghodake, G. (2018). Recent developments in nanotechnology transforming the agricultural sector: a transition replete with opportunities. *Journal of the Science of Food and Agriculture*, *98*(3), 849-864.

80. Singh, R. P., Handa, R., & Manchanda, G. (2021). Nanoparticles in sustainable agriculture: An emerging opportunity. *Journal of Controlled Release*, *329*, 1234-1248.

81. Haini, H. (2021). ICT, innovation and SME export likelihood: evidence from SMEs in the ASEAN economies. *The Singapore Economic Review*, 1-20.

82. Singh, H., Sharma, A., Bhardwaj, S. K., Arya, S. K., Bhardwaj, N., & Khatri, M. (2021). Recent advances in the applications of nano-agrochemicals for sustainable agricultural development. *Environmental Science: Processes & Impacts*, *23*(2), 213-239.

83. Frattini, F., Bianchi, M., De Massis, A., &Sikimic, U. (2014). The role of early adopters in the diffusion of new products: Differences between platform and nonplatform innovations. *Journal of Product Innovation Management*, *31*(3), 466-488.

84. Lagaron, J. M., & Lopez-Rubio, A. (2011). Nanotechnology for bioplastics: opportunities, challenges and strategies. *Trends in food science & technology*, *22*(11), 611-617.

UNDER PEER REVIEW

85. Roco, M. C., & Bainbridge, W. S. (2002). Converging technologies for improving human performance: Integrating from the nanoscale. *Journal of nanoparticle research*, *4*, 281-295.

86. Mittal, D., Kaur, G., Singh, P., Yadav, K., & Ali, S. A. (2020). Nanoparticle-based sustainable agriculture and food science: Recent advances and future outlook. *Frontiers in Nanotechnology*, *2*, 579954.

87. Mahmoudi, M. (2018). Debugging nano–bio interfaces: systematic strategies to accelerate clinical translation of nanotechnologies. *Trends in biotechnology*, *36*(8), 755-769.

88. Blaiszik, B. J., Kramer, S. L., Olugebefola, S. C., Moore, J. S., Sottos, N. R., & White, S. R. (2010). Self-healing polymers and composites. *Annual review of materials research*, *40*, 179-211.

89. Elizabath, A., Babychan, M., Mathew, A. M., & Syriac, G. M. (2019). Application of nanotechnology in agriculture. *Int. J. Pure Appl. Biosci*, *7*(2), 131-139.

90. Saha, L., Tiwari, J., Bauddh, K., & Ma, Y. (2021). Recent developments in microbe–plant-based bioremediation for tackling heavy metal-polluted soils. *Frontiers in Microbiology*, *12*, 731723.

91. Tarafdar, J. C., Xiang, Y., Wang, W. N., Dong, Q., & Biswas, P. (2012). Nanoparticle synthesis characterization and application to solve some chronic agricultural problems. *Appl Biol Res*, *14*, 138-144.

92. Kah, M., Tufenkji, N., & White, J. C. (2019). Nano-enabled strategies to enhance crop nutrition and protection. *Nature nanotechnology*, *14*(6), 532-540.

93. Lyons, K., &Scrinis, G. (2009). Under the regulatory radar? Nanotechnologies and their impacts for rural Australia. *Tracking rural change: community, policy and technology in Australia, New Zealand and Europe. Australian National University E Press, Canberra*, 151-171.

94. Zawedde, B. M., Kwehangana, M., &Oloka, H. K. (2018). Readiness for environmental release of genetically engineered (GE) plants in Uganda. *Frontiers in bioengineering and biotechnology*, *6*, 152.

UNDER PEER REVIEW

95. Gouda, S., Kerry, R. G., Das, G., Paramithiotis, S., Shin, H. S., & Patra, J. K. (2018). Revitalization of plant growth promoting rhizobacteria for sustainable development in agriculture. *Microbiological research, 206,* 131-140.

96. Kumar, Y. O. G. E. N. D. R. A., Tiwari, K. N., Singh, T., &Raliya, R. (2021). Nanofertilizers and their role in sustainable agriculture. *Annals of Plant and Soil Research*, *23*(3), 238-255.

97. Iavicoli, I., Leso, V., Beezhold, D. H., & Shvedova, A. A. (2017). Nanotechnology in agriculture: Opportunities, toxicological implications, and occupational risks. *Toxicology and applied pharmacology*, *329*, 96-111.

98. Kirkgöz, Y. (2014). English language teaching in Turkey: Challenges for the 21st century. In *Teaching English to the World* (pp. 159-170). Routledge.

99. Coles, D., &Frewer, L. J. (2013). Nanotechnology applied to European food production–A review of ethical and regulatory issues. *Trends in food science & technology*, *34*(1), 32-43.

100. Wolpaw, J. R., Birbaumer, N., Heetderks, W. J., McFarland, D. J., Peckham, P. H., Schalk, G., ... & Vaughan, T. M. (2000). Brain-computer interface technology: a review of the first international meeting. *IEEE transactions on rehabilitation engineering*, *8*(2), 164-173.

101. Knapp, S., Arruda, P., Blagg, J., Burley, S., Drewry, D. H., Edwards, A., ... &Zuercher, W. J. (2013). A public-private partnership to unlock the untargeted kinome. *Nature chemical biology*, *9*(1), 3-6.

102. Meissner, D. (2019). Public-private partnership models for science, technology, and innovation cooperation. *Journal of the Knowledge Economy, 10,* 1341-1361.

103. Dasgupta, N., Ranjan, S., Mundekkad, D., Ramalingam, C., Shanker, R., & Kumar, A. (2015). Nanotechnology in agro-food: from field to plate. *Food Research International*, *69*, 381-400.

104. Weber, K. M., &Rohracher, H. (2012). Legitimizing research, technology and innovation policies for transformative change: Combining insights from innovation systems and multi-level perspective in a comprehensive 'failures' framework. *Research policy, 41*(6), 1037-1047.

UNDER PEER REVIEW

UNDER PEER REVIEW