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Research on Application of Nanomaterials in Agriculture

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Abstract. The agriculture sector is grappling with significant challenges, including declining crop yields due to soil degradation, increasing pest resistance to conventional pesticides, and the pressing need for sustainable farming practices to mitigate environmental degradation. Over the past three decades, nanotechnology has emerged as a promising field, offering innovative solutions to these issues. This article sorts out the previous work of nanotechnology applied in the field of pesticides, fertilizers, animal husbandry and food testing, and obtains that nanomaterials can improve the utilization rate of pesticides and reduce the loss rate, while also improving the effectiveness of fertilizers to achieve the effect of reducing fertilizer usage and increasing production. In animal husbandry, nanoparticles can improve the utilization of nutritional additives. Meanwhile, nanoparticles have certain antibacterial and antiviral activity, which can solve the problem of drug resistance of Staphylococcus aureus, Escherichia coli, Salmonella etc. towards antimicrobial drugs. Nanoparticles as immune adjuvants can also improve the immune effect of vaccines on animals. In the field of food testing, bio-nanosensors can detect bacteria and viruses quickly and accurately to improve food safety, while Raman optical sensors prepared by metal nanoparticles have a broad prospect in the field of drug residue detection. However, the toxicity of nanomaterials and their potential safety hazards for human beings need to be emphasized. Based on the safety assessment of nanomaterials, it is our aim to make good use of nanotechnology and achieve further innovative results in the agricultural field.

1 Introduction

Clearly defining the scope of this review, we focus on recent advancements in the application of nanotechnology in agriculture. Our aim is to provide an updated and comprehensive overview of how nanotechnology has been utilized to address contemporary challenges in crop production, animal husbandry, and food safety. This article specifically highlights key breakthroughs and innovative approaches that have the potential to transform agricultural practices, emphasizing the importance of sustainable and efficient solutions in the face of growing global demands for food security.

Currently, the agriculture sector is facing challenges such as shortages of arable land, reductions in the labour force due to the trend of an increase in the aging population and an exodus of young people in rural areas, extreme weathers with high temperatures which result in droughts, environmental pollution problems, and in particular, the recent Russian-Ukrainian conflict that erupted in February 2022, which had triggered a protracted global food crisis. The United Nations World Food Program has estimated that, in 2023, more than 345 million people around the globe will be facing or suffering from a serious risk of food insecurity, which is more than twice the population compared with that in 2019 [1-2]. To address the challenges the agriculture sector is currently facing, increasing yield, improving efficiency and ensuring health and safety are the main directions of current research.

Due to certain unique properties of nanomaterials such as its small size, high reactivity, surface effect and quantum size effect, nanomaterials can potentially play a great role in promoting crop growth. In addition, they can be used to solve some environmental pollution problems caused by pesticide overuse, and the problem of low crop yields due to the loss of fertilizer, etc. Nanotechnology can also be used to modify nutrient supplement, antimicrobials, and vaccines to improve their effectiveness in animals, as well as to improve efficiency and accuracy in food examination and analysis [3]. This paper will focus on summarizing the applications of nanotechnology in the fields of crop production, animal husbandry and food examination and analysis, as well as some potential risks of applying such technology.

2 Crop production area

2.1 Agrochemical

To ensure the healthy growth of agricultural products, pesticides are one of the indispensable materials for crop cultivation because they can effectively control or eliminate pests. But there are many disadvantages of using traditional pesticides, such as being biohazardous, expensive to use, and the gradual development of

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pesticide resistance in pests [4]. Traditional pesticides are biohazardous because the drug carriers in it are huge in size, poorly dispersed, stored in the plant for a long time and requires a lengthy period before being completely degraded. When herbivores consume them, part of the pesticides will be transferred into the animal's body, which may further accumulate in the human body by consumption of meat. Conventional pesticides also add solvents which are highly toxic such as certain alcohols and ketones to microemulsions, therefore causing serious contamination to nearby water and soil [5]. In addition, soil infiltration, rain erosion, surface runoff and leaching can lead to a loss of 50-70 % of traditional pesticides, therefore making the use of traditional pesticides costly and inefficient and forcing farmers to increase the amount of pesticides used, which forms a vicious circle and causes more serious biological and environmental pollution as a result [6].

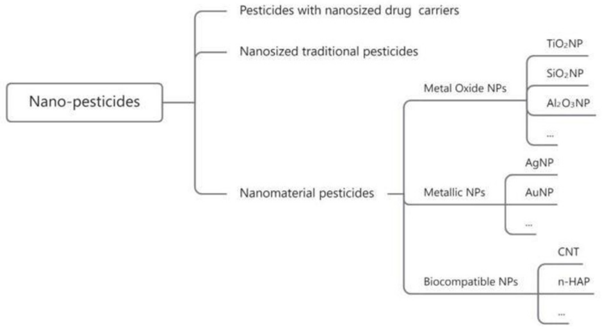

Fig. 1. Types of nanopesticides.

Drug carrier nanoparticles increases bioavailability by improving the water-based dispersion of insoluble pesticides, as well as increasing the adhesion area of pesticides, retention and coverage properties due to the large specific surface area of nanomaterials, thus improving pesticide utilization and reducing the rate of loss [4,7]. At present, nano-pesticides are mainly categorized into nanomaterial pesticides, nanosized traditional pesticides and pesticides with nanosized drug carriers, with nanomaterial pesticides being further categorized into organic NPs and inorganic NPs. Several common inorganic NPs used in agriculture are some metal NPs (e.g., AgNPs [8], AuNPs [9]), bioactive NPs (e.g., nano hydroxyapatite [10], carbon nanotubes [11]), biodegradable NPs, and some common organic materials are made from natural plants and natural polymers (Fig. 1).

2.1.1 Nanomaterial pesticides - AgNP

Mishra prepared AgNP solutions with particle size between intervals of 10-20 nm and found that AgNP solutions at concentrations of 2, 4, and 10 μg/mL, respectively, almost completely inhibited the germination of spores that induce Bipolaris sorokiniana in wheat [12]. Lamsal conducted aerial spraying experiments on cucumber and pumpkin with AgNP solutions prepared at concentrations of 10, 30, 50, and 100 μg/mL, and found that the use of AgNP solutions as a preventive measure prior to infection can reduce the prevalence rate of powdery mildew to 45, 40, 27, and 18 %, respectively, for cucumber, and 53.4, 34.4, 25 and 20 %, respectively, for pumpkin [8].

2.1.2 Nanomaterial pesticides - SiO2NP

Nano-silica penetrates the epidermal lipids of pests through physical adhesion, interacts with red blood cells and change interfacial water structures of the cell, thus killing the pests by distorting and breaking the membrane [13]. A variety of nanoparticle composites, including silica-silver nanoparticles have shown good results towards the control of several phytopathogenic fungi such as Botrytis cinerea, rice blast diseases and anthracnose [14].

2.1.3 Nanosized traditional pesticides – Nano-encapsulation

Nano-encapsulated particles are easily dispersed and suspended in water. In comparison with the traditional microencapsulation, it has special characteristics such as reduction in pesticides usage, increasing the time interval between reapplying pesticides and having lower toxicity, etc. Its sustained-release and targeted delivery properties, in particular, which improves the efficiency of pesticides utilization and reduces the possibility of pesticide resistance developing in pests [15-17].

2.2 Fertilizer

Element nitrogen, phosphorus and potassium play a key role in increasing the production yield of crops, with various nitrogen, phosphorus and potassium fertilizers being widely used all over the world. However, according to Kanjana's research, 40-70 % of nitrogen fertilizers, 50-70 % of potassium fertilizers, 80-90 % of phosphorus fertilizers, and 95 % of the micronutrients are lost during delivery, which is extremely wasteful and causes ineffective enhancement in crop yields, making farmers significantly increase the amount of fertilizers used, causing overuse of fertiliser and raising the cost of production [18]. The addition of nano-fertilizers such as nanocarbon or molybdenum-based nanoparticles can effectively solve these problems.

Several research have shown that traditional fertilizers can be used in combination with carbon nanomaterials to improve the effectiveness of fertilizers. Fei Wang found that adding nanocarbon to nitrogen fertilizer used for corn, the utilization rate of the nitrogen fertiliser increased up to 20.3 % more and corn yield raised up to 28.8 % [19]. Wang Xiaoyan found that nanocarbon-enhanced urea was more effective than ordinary urea in terms of the tiller number and dry matter accumulation in rice, and the seed yield could be increased by up to 10.2 % [20], Wu Meiyan also used nanocarbon sustained-release fertilizers and found that the relative chlorophyll content (SPAD value) of rice at the spike was improved, the number of effective spikes and grains increased, and the yield and nitrogen fertilizer utilization of rice increased [21]; Shumin Li found that the addition of nanocarbon to fertilizers promoted the growth of soybeans, increased the relative growth rate of the seedlings, and increased the yield by up to 24.6 % [22]; Xue Zhaowen found that the addition of a ratio of 0.3 % nanocarbon to conventional fertilizers significantly improved the stress resistance and production yield of potatoes [23]. Liu Jian found that applying nano-carbon enhanced fertilizers to white radish, eggplant, pepper and celery can promote early development, improve crop quality, significantly increase crop yield, and at the same time save up to 30-50 % of fertilizer [24]; The addition of nanocarbon to nitrate-sulfur based fertilizers by Won-Jin Liang improves dry mass and SPAD value of Brassica chinensis [25], while Yujie Wang discovered that nanocarbon can also effectively improve saline soils and enhance the ability of plants to resist drought, high temperature and other climate stresses [26].

Rong prepared a molybdenum-based nanoparticle solution by reacting ammonium molybdate as a precursor with earthworm vermicast, and performed a foliar spray on Brassica chinensis. Compared with conventional molybdenum fertilizers, the aboveground fresh weight of Brassica chinensis increased by 59.5 %, the net photosynthetic rate and the relative chlorophyll content increased by 27.9 % and 6.8 %, and the content of nitrogen, phosphorus, and potassium minerals increased by 62.7 %, 52.5 %, and 82.6 %, respectively, with the use of 60 mg/L MoO3NP [27].

3 Livestock area

3.1 Nutritional Additives

The particle size of nutrients affects absorption in the gastrointestinal tract of animals [28-29]. Jani performs experiment by giving mice three types of polystyrene nanoparticles orally with diameter sizes of 50, 500 and 1000 nm to mice, and then measured the absorption and distribution rate of the particles in the lymph nodes, mesentery, liver and spleen of the mice. The results showed that polystyrene with a size of 50 nm appeared in the lymph nodes 6 hours after oral administration of the drug, whereas particles with a size of 500 and 1,000 nm appeared more slowly, and were poorly distributed in the tissues [30].

Piglet stress due to lack of weaning can lead to growth restriction or high rates of diarrhea, which can be alleviated with zinc supplementation [31-32], Su fed the weaned piglets with normal animal fodder only in one group and animal fodder with 200, 400, 600 mg/kg of embedded zinc oxide nanoparticles in three other groups, and found that the 400 mg/kg zinc oxide nanoparticles group had the highest zinc utilization, and the zinc utilization of the zinc oxide nanoparticles group was increased by 25.6, 26.3, and 21.7 %, respectively, when compared with the group that was fed with only normal animal fodder [33]. In livestock, nanotechnology is applied to enhance the efficacy of nutritional additives and vaccines. Nanoparticles like zinc oxide (ZnO NPs) and selenium nanoparticles (SeNPs) have been used to improve the bioavailability of these trace elements, leading to better animal health and growth performance. The specific mechanism includes the increased solubility and absorption rate of these nanoparticles in the gastrointestinal tract, which contributes to improved overall nutrient utilization.

3.1.1 ZnNP

According to Partha's experiment of comparing ZnNP and inorganic Zn particles as goat fodder, serum Zn levels in goat increased significantly when ZnNP is used compared to inorganic Zn particles. The results clearly demonstrated that ZnNP at different concentrations exhibit similar effects in terms of immunity and thyroid hormone profiles. In addition, the research also show that ZnNP at 25 mg/kg have the same effect on goat as that of inorganic Zn particles at 50 mg/kg when it is used as animal fodder. Hence, ZnNP can be supplemented at half the dose of inorganic Zn sources to lower the amount of Zn used [34]. This might be correlated to better bioavailability of ZnNP than inorganic Zn particles, resulting in better absorption, distribution and uptake of Zn [35].

3.1.2 SeNP

The delivery of SeNP compared to inorganic Se particles is much more efficient as it does not need to be metabolized before being incorporated into selenoproteins and it can be absorbed by the body at a much faster rate than inorganic Se particles [36-37]. Gangadoo and others experimented different concentrations of SeNP and inorganic Se particles as supplements to boiler chickens and the result shows that 0.9 ppm SeNP treatment produces the best result, with higher concentrations in the spleen, duodenum and ileum of the spoiler chicken. Additionally, 0.9 ppm SeNP showed improved absorption in the duodenum, and lower retention in the brain tissue [38].

3.1.3 Nano encapsulation

Nouri's experiment towards the application of chitosan nano encapsulation of essential oils of broiler chicken mainly focuses on mint, thyme and cinnamon. The result of the research shows that the nano encapsulation of oil caused an increase in the percentage of the main compounds, in particular L-menthol and L-menthone in mint, (E)-cinnamaldehyde, eugenol and (E) cinnamyl acetate in cinnamon, and carvacrol and thymol in thyme. It also indicates that the broilers chicken that were fed with diets containing nano-encapsuled thyme or nano-encapsuled mint had the best daily body weight gain. Applying nano-encapsuled thyme had the most significant effect on the feed conversion ratio of the broiler chickens. Nano-encapsulation also increased concentrations of IgY and IgM which is essential to the immune system, where nano-encapsulated thyme and cinnamon had the most significant effect on increasing IgY concentrations [39].

3.2 Antibacterial Agent

The irrational use or abuse of antimicrobials and anticoccidials in veterinary clinics and animal husbandry has led to the emergence of resistance to antimicrobials such as Staphylococcus aureus, Escherichia coli, Salmonella and even the emergence of multi-drug resistance. However, this situation can be improved by nanotechnology [40].

3.2.1 Metal Nanoparticles

Copper nanoparticles achieve effective antimicrobial and antiviral activities through the interaction of their antibacterial surfaces with the microorganisms [41]. Silver nanoparticles prevent viruses from entering cells and block cellular pathways by interacting with the viral envelope and viral membrane proteins, and inactivate viruses by interfering with viral genomes and the viral replication process [42]. AgNPs and Ag ions released from AgNPs have an affinity for sulfuate and phosphate groups, which can disrupt cell membranes by acting on phospholipid tails and proteins containing cysteine or methionine [43].

3.2.2 Metal Oxide Nanoparticles

Titanium dioxide nanoparticles prepared by Sara via sonochemical methods demonstrate antibacterial and antiviral activity [44]. Antibacterial and antiviral coatings based on silica nanoparticles were prepared by Botequim by adding a quaternary ammonium surfactant, didodecyldimethylammonium bromide, to the surface of the nanoparticles [45]. In piglets and broilers, it was found that copper-containing silicate nanoparticles had a strong killing effect on Escherichia coli, Salmonella typhimurium and Staphylococcus aureus, which was mainly attributed to the adsorption properties of nanosilicates and the bactericidal activities of Cu2+ [46-47].

3.3 Vaccines

The mechanisms of the vaccine is that antigen-presenting cells deliver antigenic substances to lymphoid cells, which transport B-lymphoblasts through the mesenteric lymph nodes to different mucosal sites, thus producing secretory IgA antibodies that are distributed in visceral and glandular tissues, the genitourinary tract, the respiratory tract and other parts of the body, which can enhance the body's immune response through nano-treated particles [48]. Stieneker found that nanoscale polymethylmethacrylate (PMMA) increased antibody concentration of the HIV vaccine in rats by 10-100 times, causing strong antibody response and resistance to infection, and is likely to be a safe and effective immune adjuvant [49]. Kossovsky found that surface-modified nanoparticles fully exposed the surface of protein antigens and made the antigen structure more stable, thus eliciting a strong, specific immune response in rabbits [50]. Consequently, nanoparticles as immune adjuvants can improve the immunization effect of vaccines on animals and will be widely used in the production of livestock and poultry vaccines in the future.

4 Food testing area

In the field of food detection, traditional detection methods are time-consuming and have low accuracy, while sensors made of nanomaterials have fast response, high accuracy and high sensitivity [51]. Currently, common nanomaterials are mainly used for biosensing, optical sensing and electrochemical sensing, in which bio-nanosensors can quickly and accurately detect bacteria and viruses to improve food safety, and it also have a wide range of applications for contaminants in agricultural products, pesticides, or organophosphorus in banned additives for fertilizers [52-54]. Different raman optical sensors prepared by metal nanoparticles have shown improvements in precision, speed and reliability of drug residue detection, and have great prospects in the field of drug residue detection [55]. Hengye used a nanohybrid system consisting of AuNPs and tetrakis (N-methyl-4-pyridyl) porphyrin as an optical probe to achieve quantitative detection of five pesticides, including paraquat, trichlorfon, metribuzin, chlorpyrifos and fenitrothion [56]. In the realm of food testing, nanotechnology plays a critical role in enhancing detection sensitivity and accuracy. Bio-nanosensors, which utilize engineered nanoparticles, have been developed for rapid and precise detection of foodborne pathogens. For example, gold nanoparticles functionalized with specific antibodies can detect Salmonella with high specificity, offering a significant advancement over traditional culture-based methods.

5 Potential risks of using nanotechnology

Though applications of nanotechnology have numerous advantages in agriculture, some of its potential risks and danger should be addressed as well. Currently, there is a lack of in-depth analysis into such area where there is only a limited range of nanoparticles being studied, causing safety concerns of possible health risks or harmful side-effects. According to several research, many nanoparticles exhibited both positive and negative effects towards plant growth, also posing health risks towards human [57]. For example, metal nanoparticles such as AgNPs decrease shoots weight in Triticum aestivum [57] and inhibit the root length when used at high concentrations in Vigna radiata and Sorghum bicolor [58-59]. Ray’s study reported that AuNPs are generally not toxic due to its extraordinary properties, but gold nanorods surprisingly turned out to be highly toxic towards human skin HaCaT keratinocyte cells. Further investigation shows that the toxicity is due to Hexadecyl-cetyltrimethylammonium bromide (CTAB), which is a surfactant used during the synthesis of numerous nanorods. Though the team performs three centrifugations and removed most of the excess CTAB in solution, the CTAB in the nanorod-bound CTAB layer cannot be removed due to nanorods become unstable when CTAB in the layer is removed, resulting in 40 % cell death [60]. Some metal oxide nanoparticles also show side-effects. Al2O3NPs show negative impacts in Nicotiana tabacum which decrease root length and seedling growth when used in high concentrations [61], while also inhibiting root elongation in corn, cucumber, soybean, cabbage, and carrot [62]. Fe3O4NPs reduce the shoot and root length in plants at high concentrations, especially when used on Arabidopsis thaliana [57]. Carbon nanotubes, on the other hand, can induce inflammatory and apoptosis responses in human T-cells [63-64]. Ultrafine carbon show greater lung penetration than larger particles and are able to cross the blood-brain barrier and impact the central nervous system [65]. Lam conducted experiments on the lungs of mice and reported that single-walled CNTs (SWCNTs) produce pulmonary inflammation [66].

6 Conclusions

In the past 30 years, nanotechnology has occupied an important position in the field of agriculture, and this paper, by combing the previous work of nanotechnology applied in the field of pesticides, fertilizers, animal husbandry and food testing, obtains the following conclusions:

(1) Nanomaterials can improve the utilization rate of pesticides and reduce the loss rate, and can also improve the effectiveness of fertilizers to achieve the effect of reducing fertilizer usage and increasing production;

(2) In animal husbandry, nanoparticles can improve the utilization of nutritional additives, such as efficiently solving the problem of piglet diarrhea; Nanoparticles have certain antibacterial and antiviral activity, which can solve the drug resistance of Staphylococcus aureus, Escherichia coli, Salmonella etc. towards antimicrobial drugs; Nanoparticles as immune adjuvants can improve the immune effect of vaccines on animals;

(3) Bio-nanosensors can detect bacteria and viruses quickly and accurately to improve food safety; Raman optical sensors prepared by metal nanoparticles have a broad prospect in the field of drug residue detection.

Though applications of nanotechnology have numerous advantages in agriculture, some of its potential risks and danger should be addressed as well. The toxicity of nanomaterials and their potential safety hazards for human beings need to be emphasized. Based on the safety assessment of nanomaterials, it is the aim of human beings to make good use of nanotechnology and achieve further innovative results in the agricultural field.

References

1. FSIN, WFP. 2019 Global Report on Food Crises. GRFC 2019.
2. FSIN, WFP. FSIN and Global Network Against Food Crises. 2023. GRFC 2023 Rome.
3. P. Goswami, S. Yadav, J. Mathur. Positive and negative effects of nanoparticles on plants and their applications in agriculture. Plant Sci Today. 2019, 6, pp. 232-42.
4. Qi-gui LI. Application of nanomaterials and nanotechnology in agriculture. Hubei Nongjihua. 2020, 15, pp. 46-7. (in Chinese)
5. Xin CHEN, Hai-ming LIN. Aubergine new material will play an important role in modern eco-agriculture. Gansu Agriculture. 2019, 8, pp. 95-98. (in Chinese)
6. M. Usman, M. Farooq, A. Wakeel, A. Nawaz, S. A. Cheema, H. U. Rehman, I. Ashraf, M. Sanaullah. Nanotechnology in agriculture: Current status, challenges and future opportunities. Sci Total Environ. 2020, 721, p. 137778.
7. Chang-jiao SUN, Hai-xin CUI, Yan WANG, Zhang-hua ZENG, Xiang ZHAO, Bo CUI. Studies on applications of nanomaterial and nanotechnology in agriculture. Journal of Agricultural Science and Technology, 2016, 18(1), pp. 18-25. (in Chinese)
8. K. Lamsal, S. W. Kim, J. H. Jung, Y. S. Kim, K. S. Kim, Y. S. Lee. Inhibition effects of silver nanoparticles against powdery mildews on cucumber and pumpkin. Mycobiology. 2011 Mar, 39(1), pp. 26-32.
9. S. Arora, P. Sharma, S. Kumar, R. Nayan, P. K. Khanna, M. G. H. Zaidi. Gold-nanoparticles induced enhancement in growth and seed yield of Brassica juncea. Plant Growth Regul. 2012, 66(3), pp. 303-10.
10. Pei-zhu WU. Study on n-Hap as a model of targeted drug delivery system. Jinan University. 2004. (in Chinese)
11. S. Mathew, C. P. Victório. Carbon nanotubes applications in agriculture. 2022. (in: J. Abraham, S. Thomas, N. Kalarikkal. Handbook of carbon nanotubes. Springer Cham.)
12. S. Mishra, B. R. Singh, A. Singh, C. Keswani, A. H. Naqvi, H. B. Singh. Biofabricated silver nanoparticles act as a strong fungicide against Bipolaris sorokiniana causing spot blotch disease in wheat. PLoS ONE. 2014 May 19, 9(5), e97881.
13. T. K. Barik, B. Sahu, V. Swain. Nanosilica-from medicine to pest control. Parasitol Res. 2008 Jul, 103(2), pp. 253-8.
14. H. J. Park, S. H. Kim, H. J. Kim, C. Seong. A new composition of nanosized silica-silver for control of various plant diseases. Plant Pathol J. 2006, 22(3), pp. 295–302.
15. An-qi WANG, Yan WANG, Chun-xin WANG, Bo CUI, Chang-jiao SUN, Xiang ZHAO, Zhang-hua ZENG, Jun-wei YAO, Guo-qiang LIU, Hai-xin CUI. Research progress on nanocapsules formulations of pesticides. Journal of Agricultural Science and Technology. 2018, 20(2), pp. 10-8. (in Chinese)

16. Dong-qing Cai, Long-hai Wang, Gui-long Zhang, Xin Zhang, Zheng-yan Wu. Controlling pesticide loss by natural porous micro/nano composites: Straw ash-based biochar and biosilica. ACS Appl Mater Interfaces. 2013 Sep 25, 5(18), pp. 9212-6.
17. Jin Xu, Wen-xiu Zhao, Ya-wei Ning, M. Bashari, Feng-feng Wu, Hai-ying Chen, Na Yang, Zheng-yu Jin, Bao-cai Xu, Li-xia Zhang, Xue-ming Xu. Improved stability and controlled release of ω3/ω6 polyunsaturated fatty acids by spring dextrin encapsulation. Carbohydr Polym. 2013 Feb 15, 92(2), pp. 1633-40.
18. D. Kanjana. Advancement of nanotechnology applications on plant nutrients management and soil improvement. 2017. (in: R. Prasad, V. Kumar, M. Kumar. Nanotechnology. Springer Singapore.)
19. Fei Wang. Effects of nanocarbon on nitrogen uptake, accumulation and yield of maize under different nitrogen levels. Northeast Agricultural University. 2016. (in Chinese)
20. Xiao-yan WANG, Guo-hui MA, Hao DI, Xiao-hai TIAN, Yi WANG. Effects of NMUrea on rice yield and agronomic nitrogen efficiency. Plant Nutrition and Fertilizing Science. 2010, 16(6), pp. 1479-85. (in Chinese)
21. Mei-yan WU, Ruo-chao HAO, Xiao-hai TIAN, Xiao-ling WANG, Guo-hui MA, Hai-tao TANG. Effects of adding nano-carbon in slow-released fertilizer on grain yield and nitrogen use efficiency of super hybrid rice. Hybrid Rice. 2010, 25(4), pp. 86-90. (in Chinese)
22. Shu-min LI, Xiao-guang HAN, Ai-yuan ZHANG, Fei WANG, De-jiang WANG, Cheng-yu ZHENG, Tong-tong LIU. Effect of different urea added nano-carbon synergist on dry matter accumulation and yield of soybean. Journal of Northeast Agricultural University. 2015, 46(4), pp. 10-6. (in Chinese)
23. Zhao-wen Xue. Experimental application of nanocarbon fertilizer synergist on autumn potatoes. Agricultural Science and Technology Newsletter. 2015, 9, pp.104-6. (in Chinese)
24. Jian LIU, Yang-de ZHANG, Zhi-ming ZHANG. The application research of nano-biotechnology to promote increasing of vegetable production. Hubei Agricultural Sciences. 2009, 48(1), pp. 123-7. (in Chinese)
25. Yuan-zhen LIANG, Zhong-kun ZHU, Zhi-lei FAN, Jing-li GUO, Li-xin WANG, Meng-jun ZHANG. Effects of nano carbon added to nitrate sulfur based compound fertilizer on growth and nitrogen, phosphorus and potassium content of Brassica chinensis L.. Fertilizer & Health. 2022, 49(1), pp. 38-42. (in Chinese)
26. Yu-jie WANG, Ri-yuan CHEN, Hou-cheng LIU, Shi-wei SONG, Guang-wen SUN. Applications of nanomaterials in agriculture and its effects on the growth and development of plants. Plant Physiology Journal. 2017, 53(6), pp. 933–42. (in Chinese)
27. Ling-jie Rong. Green synthesis of nano-sized molybdenum oxide particles and its effect on yield and quality of pakchoi. Huazhong Agricultural University. 2022 Aug. (in Chinese)
28. A. T. Florence, A. M. Hillery, N. Hussain, P. U. Jani. Factors affecting the oral uptake and translocation of polystyrene nanoparticles: Histological and analytical evidence. J Drug Target. 1995, 3(1), 65-70.
29. F. Delie. Evaluation of nano- and microparticle uptake by the gastrointestinal tract. Adv Drug Deliv Rev. 1998 Dec 1, 34(2-3), pp. 221-33.
30. P. U. Jani, D. E. McCarthy, A. T. Florence. Nanospheres and microsphere uptake via Peyer’s patches: Observation of the rate of uptake in the rat after a single oral dose. Int J Pharm. 1992, 86(2-3), pp. 239-46.
31. Shao-li Ji, R. Calonge, A. Castillo. Comparison of the effectiveness of two zinc sources in the prevention of piglet diarrhea. Animal Science Abroad – Pigs and Poultry. 2013, 33(8), pp. 6-8. (in Chinese)
32. Jian-bo Ren, Zhong-hong Hu, Hong-bo Zhao, Guang-fei Ying. Effect of different form zinc oxide on the growth performance and diarrhea in the early-weaned piglets. China Animal Husbandry & Veterinary Medicine. 2013, 40(6), pp. 125-8. (in Chinese)
33. Zhi-min SU. Effects of zinc oxide and nano zinc oxide on growth performance and zinc utilization of weaned piglets. China Feed. 2023, 4, pp. 41-4. (in Chinese)
34. P. S. Swain, S. B. N. Rao, D. Rajendran, P. Krishnamoorthy, S. Mondal, D. Pal, S. Selvaraju. Nano zinc supplementation in goat (Capra hircus) ration improves immunity, serum zinc profile and IGF-1 hormones without affecting thyroid hormones. J Anim Physiol Anim Nutr. 2021 Jul, 105(4), pp. 621-9.
35. N. Kumar, R. P. Verma, L. P. Singh, V. P. Varshney, R. S. Dass. Effect of different levels and sources of zinc supplementation on quantitative and qualitative semen attributes and serum testosterone level in crossbred cattle (Bos indicus × Bos taurus) bulls. Reprod Nutr Dev. 2006, 46(6), pp. 663-75.
36. S. Gangadoo, D. Stanley, R. J. Hughes, R. J. Moore, J. Chapman. Nanoparticles in feed: Progress and prospects in poultry research. Trends Food Sci Technol. 2016, 58, pp. 115-26.
37. K. T. Suzuki, Y. Ogra. Metabolic pathway for selenium in the body: Speciation by HPLC-ICP MS with enriched Se. Food Addit Contam. 2002 Oct, 19(10), pp. 974-83.
38. S. Gangadoo, I. Dinev, N. L. Willson, R. J. Moore, J. Chapman, D. Stanley. Nanoparticles of selenium as high bioavailable and non-toxic supplement alternatives for broiler chickens. Environ Sci Pollut Res Int. 2020 May, 27(14), pp. 16159-166.

39. A. Nouri. Chitosan nano-encapsulation improves the effects of mint, thyme, and cinnamon essential oils in broiler chickens. Br Poult Sci. 2019 Oct, 60(5), pp. 530-8.
40. Ying-hua SHI, Cheng-zhang WANG, Zi-rong XU. The application and prospect of nanotechnology in animal husbandry. Jour. of Northwest Sci-Tech Univ. of Agri. and For. (Nat. Sci. Ed.). 2006 Aug, 34(8), pp. 49-52. (in Chinese)
41. A. P. Ingle, N. Duran, M. Rai. Bioactivity, mechanism of action, and cytotoxicity of copper-based nanoparticles: A review. Appl Microbiol Biotechnol. 2014 Feb, 98(3), pp. 1001-9.
42. M. Rai, S. D. Deshmukh, A. P. Ingle, I. R. Gupta, M. Galdiero, S. Galdiero. Metal nanoparticles: The protective nanoshield against virus infection. Crit Rev Microbiol. 2016, 42(1), pp. 46-56.
43. S. Park, H. H. Park, S. Y. Kim, S. J. Kim, K. Woo, G. Ko. Antiviral properties of silver nanoparticles on a magnetic hybrid colloid. Appl Environ Microbiol. 2014 Apr, 80(8), pp. 2343-50.
44. S. Akhtar, K. Shahzad, S. Mushtaq, I. Ali, M. H. Rafe, S. M. Fazal-ul-karim. Antibacterial and antiviral potential of colloidal titanium dioxide (TiO2) nanoparticles suitable for biological applications. Materials Research Express. 2019, 6(10), p. 105409.
45. D. Botequim, J. Maia, M. M. F. Lino, L. M. F. Lopes, P. N. Simões, L. M. Ilharco, L. Ferreira. Nanoparticles and surfaces presenting antifungal, antibacterial and antiviral properties. Langmuir. 2012 May 22, 28(20), pp. 7646-56.
46. Tong Guo. Adsorption and bactericidal mechanism of copper-loaded silicate nanoparticles on intestinal pathogenic bacteria in weaned piglets. Zhejiang University. 2004. (in Chinese)
47. Yu-long Ma. Characterization of copper-loaded silicate nanoparticles and the mechanism of their application effect on broiler chickens. Zhejiang University. 2004. (in Chinese)
48. M. R. Mcdermott, J. Bienenstock. Evidence for a common mucosal immunologic system. I. Migration of B immunoblasts into intestinal, respiratory, and genital tissues. J Immunol. 1979 May, 122(5), pp. 1892-8.
49. F. Stieneker, J. Kreuter, J. Löwer. High antibody titres in mice with polymethylmethacrylate nanoparticles as adjuvant for HIV vaccines. AIDS. 1991 Apr, 5(4), pp. 431-5.
50. N. Kossovsky, A. Gelman, H. J. Hnatyszyn, E. Sponsler, G. M. Chow. Conformationally stabilizing self-assembling nanostructured delivery vehicles for biochemically reactive pairs. Nanostructured Mater. 1995, 5(2), pp. 233-47.
51. Jian-ying CHEN. Essentials of plant protection technology for green agriculture. Hubei Nongjihua. 2020, 15, pp. 47-8.
52. S. Otles, B. Yalçın. Nano-biosensors as new tool for detection of food quality and safety. LogForum. 2010, 6(4), pp. 67-70.
53. R. Prasad, A. Bhattacharyya, Q. D. Nguyen. Nanotechnology in sustainable agriculture: Recent developments, challenges, and perspectives. Front Microbiol. 2017 Jun, 20(8), p. 1014.
54. R. P. Singh. Application of nanomaterials toward development of nanobiosensors and their utility in agriculture. 2017. (in: R. Prasad, M. Kumar, V. Kumar. Nanotechnology. Springer Singapore.)
55. De-hong YANG, Lei-lei ZHANG, Cheng ZHU. Application of SERS technology in the detection of harmful chemical residues in agricultural products. Spectroscopy and Spectral Analysis. 2020 Oct, 40(10), pp. 3048-55. (in Chinese)
56. Heng-ye CHEN, Qiong SHI, Hai-yan FU, Ou HU, Yao FAN, Lu XU, Lei ZHANG, Wei LAN, Dong-lei SUN, Tian-ming YANG, Yuan-bin SHE. Rapid detection of five pesticide residues using complexes of gold nanoparticle and porphyrin combined with ultraviolet visible spectrum. J Sci Food Agric. 2020 Sep, 100(12), pp. 4464-73.
57. P. Goswami, S. Yadav, J. Mathur. Positive and negative effects of nanoparticles on plants and their applications in agriculture. Plant Science Today. 2019, 6(2), pp. 232-242.
58. C. Krishnaraj, R. Ramachandran, K. Mohan, P. T. Kalaichelvan. Optimization for rapid synthesis of silver nanoparticles and its effect on phytopathogenic fungi. Spectrochim. Acta A. Mol. Biomol. Spectrosc. 2012 Jul, 93, pp. 95-9.
59. N. K. Fageria, V. C. Baligar, R. J. Wright. Iron nutrition of plants: An overview on the chemistry and physiology of its deficiency and toxicity. Pesq. Agropec. Bras. 1990, 25(4), pp. 553-70.
60. P. C. Ray, Hong-tao YU, P. P. Fu. Toxicity and environmental risks of nanomaterials: Challenges and future needs. J Environ Sci Health C Environ Carcinog Ecotoxicol Rev. 2009 Jan, 27(1), pp. 1-35.
61. C. D. Foy, A. L. Fleming. Aluminum tolerances of two wheat genotypes related to nitrate reductase activities. J. Plant Nutr. 1982, 5(11), pp. 1313-33.
62. Ling YANG, D. J. Watts. Particle surface characteristics may play an important role in phytotoxicity of alumina nanoparticles. Toxicol Lett. 2005 Aug 14, 158(2), pp. 122-32.
63. Liang-hao DING, J. Stilwell, Ting-ting ZHANG, O. Elboudwarej, Hui-jian JIANG, J. P. Selegue, P. A. Cooke, J. W. Gray, Fan-qing F. Chen. Molecular characterization of the cytotoxic mechanism of multiwall carbon nanotubes and nano-onions on human skin fibroblast. Nano Lett. 2005 Dec, 5(12), pp. 2448-64.
64. M. Bottini, S. Bruckner, K. Nika, N. Bottini, S. Bellucci, A. Magrini, A. Bergamaschi, T. Mustelin. Multi-walled carbon nanotubes induce T

lymphocyte apoptosis. Toxicol Lett. 2006 Jan 5, 160(2), pp. 121-6.

65. V. M. Silva, N. Corson, A. Elder, G. Oberdörster. The rat ear vein model for investigating in vivo thrombogenicity of ultrafine particles (UFP). Toxicol Sci. 2005 Jun, 85(2), pp. 983-989.
66. C. W. Lam, J. T. James, R. McCluskey, R. L. Hunter. Pulmonary toxicity of single-wall carbon nanotubes in mice 7 and 90 days after intratracheal instillation. Toxicol Sci. 2004 Jan, 77(1), pp. 126-34.