Proceedings of CONF-MCEE 2026 Symposium: Geomaterials and Environmental Engineering
DOI: 10.54254/2755-2721/2026.MH29332

The Application of Nanotechnology

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Abstract. Nanotechnology, as a cutting-edge technology, has demonstrated irreplaceable application value and broad prospects in ensuring food security, promoting the green and sustainable development of agriculture, enhancing the precision of cancer treatment and reducing medical side effects, as well as breaking through the bottlenecks of flexible electronic materials and adapting to new scenarios such as wearable devices. This article takes the core research and development plans and key technological breakthrough activities of nanotechnology in three major fields as the analysis objects, systematically sorts out its research and development priorities and commercial application trends, and focuses on analyzing the practical experience in the risk assessment of nanotechnology in each field . This article systematically reviews the application mechanisms, typical cases and existing challenges of nanotechnology in three major fields. In the agricultural food sector, it focuses on controlled-release nano-pesticides, nano-materials for antibacterial and barrier effects, and nano-sensors for high-sensitivity detection and in the cancer treatment field, it revolves around nano-carriers for targeted delivery, combined treatment for synergy, and integrated diagnosis and treatment. In the flexible electronics field, it elaborates on nano-silver conductive networks, cellulose-based substrates for support, and composite device optimization.

Keywords: Nanotechnology, Food and Agricultural Applications, Cancer therapy, Flexible electronics, Drug delivery

1. Introduction

Nanotechnology changes the structure and properties of materials ranging from 1 to 100nanometres, relying on the quantum size effect and surface effect, which has become a key to solve the difficulties in different fields. For example, in agriculture, traditional pesticides tend to aggregate after dilution, resulting in low target attachment rates and environmental pollution [1]. Food preservation relies on chemical preservative which pose safety risks. The detection method such as High Performance Liquid Chromatography take more than 2 hours for detection, which can not meet the need of real time monitoring for supply chain [2]. Moreover in the medical field, the chemotherapy drugs are non-targeted, damaging the normal tissues, and hydrophobic drugs like paclitaxel have low solubility, which limit treatment efficiency [3]. Lastly in flexible electronics, the electron conductivity in rigid substrate and Indium Tin Oxide film decreases by 50% when it is bent,

DOI: 10.54254/2755-2721/2026.MH29332

resulting in difficulty in adapting to wearable devices [4,5]. These technological gaps severely restrict the sustainable development of related industries.

This article systematically reviews the application mechanisms, typical cases and existing challenges of nanotechnology in three major fields. In the agricultural food sector, it focuses on nano-pesticides with controlled release, nano-materials for antibacterial and barrier effects, and nano-sensors for high-sensitivity detection and in the cancer treatment field, it revolves around nano-carriers for targeted delivery, combined treatment for synergy, and integrated diagnosis and treatment. In the flexible electronics field, it elaborates on nano-silver conductive networks, cellulose-based substrates for support, and optimization of composite devices.

2. Application and challenge of nanotechnology in different industries

2.1. The application of nanotechnology in the field of agricultural food production

2.1.1. Core techniques and typical examples

Nanotechnology addresses the three core demands of agriculture and food - "efficiency, preservation, and detection" - through material function design, forming a multi-dimensional technology system.

In the field of nano pesticides, controlled release and targeted characteristics significantly enhance the efficacy and reduce environmental risks. Nano emulsions, as the mainstream formulation, can be prepared through high-energy or low-energy methods: the chlorfenapyr O/W nano emulsion prepared by ultrasonic emulsification has an average particle size of 12.4±1.13 nm and a polydispersity index (PDI) of only 0.2, with an LC_{50} value for Anopheles mosquitoes at 3.4 mg/L, showing a 15-fold increase in insecticidal activity compared to traditional emulsions, and the contact angle on rice leaf surfaces decreases from 75° to 42°, with a significant increase in adhesion rate [2]; the avicides nano emulsion prepared by the phase transition temperature method, when the mass fraction of the surfactant castor oil polyoxyethylene ether (EL-40) is 5%, the particle size is the smallest (92 nm), with an LC_{50} value for 3rd instar larvae of Helicoverpa armigera at 0.0686 mg/L, superior to the emulsion type (0.12 mg/L) [2]. The mesoporous carrier achieves pesticide slow-release through high specific surface area and controllable pore size. After loading the organochlorine insecticide chlorpyrifos onto amino-modified mesoporous SiO_2, the release half-life is extended from 2.5 days to 18 days, and the residual amount in the rice field after 30 days of application is reduced by 72% compared to the traditional formulation, and it has no significant impact on soil urease and sucrase activity [1].

In terms of food preservation, nano materials have both physical barrier and antibacterial functions. The packaging film prepared by compounding bacterial cellulose (BC) and MXene has an oxygen transmission rate (OTR) as low as 0.8 $cm^3/(m^2 \cdot 24h \cdot atm)$, which is 84.6% lower than that of pure BC film (5.2 $cm^3/(m^2 \cdot 24h \cdot atm)$), when used for strawberry packaging, it can reduce the fruit respiration rate from 28 mg/(kg·h) to 15 mg/(kg·h), and the shelf life is extended from 3 days to 9 days, with a 30% reduction in hardness loss rate and a 25% reduction in vitamin C loss rate [2]. The nano metal oxides exert antibacterial effects by disrupting microbial cell membranes. The composite coating of 10–20 nm nano-silver and chitosan has an antibacterial zone diameter of 18 mm for Escherichia coli and 20 mm for Staphylococcus aureus, and after 10 days of storage, the colony count in the fresh-cut apple group is reduced by two orders of magnitude compared to the uncoated group, with a significant reduction in browning degree [2]; when 0.5% by mass of 30-50 nm nano

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ZnO is added to the polyethylene film, the inhibition rate of Penicillium is 90%, and the mold growth time of baker's yeast is delayed from 5 days to 12 days [2].

In the field of safety detection, nano sensors achieve rapid and highly sensitive identification of pollutants. Quantum dots (QD) sensors are based on the principle of fluorescence quenching, after modifying acetylcholinesterase with CdTe QDs, the detection limit for methyl parathion is as low as 0.005 ng/mL, with a detection time of only 10 minutes, and the recovery rate in the vegetable extract solution is 90% to 105% [2]; gold nanoparticles (AuNP) sensors utilize the surface plasmon resonance (SPR) effect, after labeling anti-cypermethrin antibodies with AuNPs, the detection limit for cypermethrin is 0.01 mg/kg, and the detection results of rice samples are consistent with those of high-performance liquid chromatography (HPLC) method at 98% [6]. In microbial detection, Fe_3O_4 magnetic nanobeads coupled with Salmonella antibodies, after magnetic separation enrichment and combination with enzyme-linked immunosorbent assay, the detection limit reaches 10 CFU/mL, and the detection time is shortened from 24 hours of traditional culture method to 2 hours [3].

2.1.2. Challenges

During industrialization, high production costs constitute a primary barrier. The production of nano pesticides requires high-end equipment such as high-pressure homogenizers and ultrasonic devices, with investment costs being 3 to 5 times higher than those of traditional production lines. The energy consumption for ultrasonic emulsification per liter of emulsion reaches 0.5 kW·h, resulting in a 40% to 60% higher market price for nano pesticides compared to traditional formulations, rendering them unaffordable for small- and medium-sized farmers [1,5]. During the roll-to-roll production of nano food packaging films, nano Ag is prone to agglomeration, causing fluctuations in the conductivity of the film surface of over 20%, which affects product consistency [2].

Inadequate biosafety data gives rise to concerns. Nano TiO_2 has a half-life of several years in the soil and long-term application may lead to a 10% to 15% decrease in soil enzyme activity, and it can be absorbed by plant roots and enter the food chain, accumulating to 0.05 mg/kg in wheat grains [3]. Nano Ag may release Ag^+ in acidic food simulants, and concentrations exceeding 0.1 mg/L may have potential toxicity to human liver cells [2]. Moreover, consumers' acceptance of "nano food" is low, with over 60% of respondents expressing safety concerns, which hinders market promotion [6].

2.2. Application of nanotechnology in the field of cancer treatment

2.2.1. Core techniques and typical examples

Nanotechnology significantly enhances cancer treatment efficacy and reduces toxic side effects through precise delivery, collaborative treatment, and integrated diagnosis and treatment, driving the transformation of treatment models toward precision.

In terms of targeted drug delivery, nanocarriers achieve drug enrichment at the tumor site through passive or active targeting. Liposomes, as the most mature carrier in clinical application, can prolong circulation time after modification with PEG. Doxil, a doxorubicin liposome formulation, has a particle size of approximately 100 nm and a blood drug half-life of 55 hours—36 times longer than that of free doxorubicin (1.5 hours). The drug concentration at the tumor site in ovarian cancer patients is 5 times that of free drug, and the incidence of cardiac toxicity is reduced from 20% to 5%. Albumin-bound paclitaxel nanoparticles (e.g., Abraxane) enter tumor cells through the mediation of gp60 receptors, and the objective response rate (ORR) of pancreatic cancer patients from traditional paclitaxel injection is increased from 12% to 23%, and the incidence of

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neurotoxicity is reduced by 40% [7]. A Active targeting carriers further enhance efficiency via surface-modified ligands. Folic acid-modified poly (lactic acid) (PLA) nanoparticles loaded with methotrexate, and the uptake of folic acid receptor-expressing breast cancer cells (MCF-7) is 3 times higher than the unmodified group, with an IC_{50} value from 0.5 μg/mL to 0.1 μg/mL [9]. Anti-HER2 antibody-modified liposomes load doxorubicin and have a tumor growth inhibition rate of 85% in HER2-positive breast cancer mouse models, which is significantly higher than that of unmodified liposomes (50%) and light thermal therapy (45%), and the incidence of cardiotoxicity is reduced [8]. pH-responsive poly β-amino ester (PBAE) nanoparticles and other stimuli-responsive carriers can rapidly degrade in acidic tumor environments (pH = 5.5), with a drug release rate of 90%, while the release rate in normal tissues (pH = 7.4) is only 20%. In lung cancer treatment, the tumor volume reduction rate reaches 70% [1].

Multimodal combined therapy enhances anti-tumor effects through synergistic effects. In chemotherapy - photothermal combined therapy, doxorubicin-loaded gold nanoshells (AuNSs), the local temperature in the tumor area rises to 42-45°C under 808 nm near-infrared light irradiation, destroying tumor blood vessels and enhancing cell membrane permeability, promoting drug entry into cells. The tumor suppression rate in a melanoma mouse model reaches 92%, which is significantly higher than that of single chemotherapy (50%) or photothermal therapy (45%). In a colorectal cancer model, the survival time of mice is prolonged by 2 times compared to the single treatment group, and the tumor recurrence rate is reduced by 60% [9]. In radiotherapy - nano-sensitization combined therapy, nano-materials with high atomic number (such as Gd, HfO_2) can enhance radiotherapy effects. Gd-based nanoparticles (AGuIX) have a particle size of approximately 5 nm and generate more free radicals through enhanced X-ray absorption, enhancing DNA damage. After intratumoral injection of HfO_2 nanoparticles, electrons are released under radiotherapy, enhancing DNA damage, and the pathological complete response rate (pCR) of patients with soft tissue sarcoma reaches 16%, which is 1 times higher than the simple radiotherapy group (8%) [1].

Integrated diagnosis and therapy enables “visualized tumor treatment” for tumors, balancing imaging and therapeutic functions. In the magnetic resonance imaging (MRI) - treatment integration, doxorubicin-loaded superparamagnetic iron oxide nanoparticles (SPIONs), the T_2 weighted MRI relaxation rate (r_2) reaches 150 $mM^{-1}s^{-1}$, which can clearly display the location and size of liver cancer, and simultaneously achieve a 80% tumor inhibition rate [9]; In the photoacoustic imaging (PAI) - photothermal therapy integration, black phosphorus quantum dots (BP QDs) have strong absorption in the near-infrared region, and the PAI imaging depth reaches 1 cm, which enables real-time monitoring of tumor morphological changes. Under 808 nm laser irradiation, the tumor suppression rate for breast cancer is 95%, and BP QDs can gradually degrade in the body without long-term accumulation [8]; In the fluorescence imaging - surgical navigation integration, indocyanine green (ICG) labeled mesoporous SiO_2 nanoparticles have a fluorescence quantum yield of 0.8. In gastric cancer surgery, they can precisely identify the tumor boundary, increasing the resection accuracy by 30% [9].

2.2.2. Challenges

Metabolic safety risks need to be addressed urgently. Nanocarriers such as carbon nanotubes may accumulate in organs like the liver and spleen. Although they can be modified with PEG to reduce immunogenicity, the long-term toxic effects of their metabolites remain unclarified [6]; quantum dots (such as CdTe) may release heavy metal ions, causing kidney damage, and their biodegradation mechanism requires further study [10].

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The difficulty in large-scale production hinders clinical translation. Liposome production requires high-precision filtration equipment to control the uniformity of particle size, and the drug encapsulation efficiency between batches can fluctuate by more than 10%; the synthesis of polymeric nanoparticles is complex, and the production cost is 60% to 80% higher than that of traditional drugs [5]. In addition, the research cycle of nanomedicines is long (average 8-10 years), and the biological compatibility of some nanomaterials (such as carbon nanotubes) has not been verified through long-term clinical trials, limiting their wide application [10].

2.3. The application of nanotechnology in the field of flexible electronics

2.3.1. Core techniques and typical example

Nanotechnology overcomes the limitations of poor flexibility and insufficient conductivity in traditional devices through the collaborative design of nanoconductive materials and flexible substrates, providing key support for the development of flexible electronics.

Silver nanomaterials, with their high conductivity and flexibility, have become the core components of flexible electrodes. Silver nanowires (diameter 20-50 nm, length 10-20 μm) are constructed into a three-dimensional conductive network through solution coating, with a conductivity of 10^5 S/m. Following hot-pressing treatment, the inter-wire contact resistance is reduced by 50%, and after 1000 bending cycles on a PET substrate, the conductivity attenuation is only 3% [11]. Silver nanoparticles (particle size 5-10 nm) are combined with polyvinylpyrrolidone (PVP), and the line width of printed flexible circuits can reach 50 μm, with a resistivity of 8×10^{-6} Ω·cm, close to ITO (5×10^{-6} Ω·cm), and the performance remains stable after 10,000 bends [5]. To enhance antioxidant properties, silver nanowires are coated with SiO_2 (coating layer thickness 5 nm), and after storage at 85°C and 85% humidity for 30 days, the conductivity attenuation is reduced from 25% to 5%; graphene and silver nanomaterials are combined, and the graphene layers block oxygen, ensuring the silver electrodes maintains good conductivity after being exposed to air for 6 months [5].

Cellulose-based materials, owing to their excellent flexibility and biocompatibility, are favored as flexible substrates. Bacterial cellulose (BC) has a crystallinity of over 95%, a tensile strength of 200 MPa, a elongation at break of 15%, and a better adhesion to the skin than PET substrates. Its water vapor transmission rate (WVTR) reaches 2000 g/(m²·24h), meeting the requirements of wearable devices . Cellulose nanofibers (CNF) after acetylation modification have significantly improved water resistance, with mechanical performance degradation reduced, and the transparency of the flexible electrode formed by combining with silver nanomaterials reaches 89% . Further functional modification expands application scenarios. CNF and MXene are combined to prepare a flexible membrane surface with a resistance of 10 Ω/sq, with a resistance change rate of less than 10% when stretched to 150%, which can be used in flexible strain sensors ; BC and polydopamine (PDA) are combined, enhancing surface adhesion, increasing the adhesion of silver nanowires by 40%, and the conductivity attenuation is less than 5% after 100,000 bends .

Composite devices fulfill diverse application requirements via structural optimization. In the field of flexible touch screens, the transparent light transmittance of the nano-silver wire/BC composite electrode is 89%, the haze is 15%, the touch response time is less than 10 ms, and flexibility enhanced by 3-fold compared to ITO/PET touchscreens [5]; In the field of wearable health monitoring, the thickness of the CNF/silver nanomaterial composite film is only 30 μm, and the signal noise when adhering to the skin is less than 1%, with a heart rate detection error of less than 2 beats per minute, and the performance remains stable for 72 hours [5]; In the field of flexible energy

DOI: 10.54254/2755-2721/2026.MH29332

storage, the nano-silver/CNF/polyaniline composite electrode has an area-specific capacitance of 2935 mF/cm² at a current density of 1 mA/cm², and the capacitance retention rate remains at 90% after 1000 bends .

2.3.2. Challenges

The cost issue hinders the industrialization promotion. The preparation of silver requires high-precision ultrasonic dispersion and purification equipment, with production costs 25%–30% higher than those of traditional ITO [5]; the industrial production of cellulose-based substrates needs to solve the problem of drying shrinkage, and the BC membrane roll-to-roll production has a shrinkage rate of 15%, which affects the size accuracy of the devices [11].

Environmental factors significantly affect performance stability. Cellulose substrates tend to absorb moisture in high humidity environments, causing fluctuations in the electrical performance of the devices; during long-term use, nano-silver may migrate, increasing the risk of device short circuit [11].

The insufficient process compatibility limits large-scale production. The composite of nano-silver and cellulose mostly relies on multi-step coating processes, with low production efficiency and difficulty in meeting the large-scale production requirements of flexible electronic devices. The development of a one-step molding process is required.

3. Conclusion

Through a review of relevant literature, this study reveals that nanotechnology has achieved breakthroughs over traditional technologies in three key fields: agriculture and food, medical cancer treatment, and flexible electronics: In the field of agriculture and food, nanocarriers solve the problems of low efficiency of pesticide use and food safety detection, promoting green and sustainable agricultural development; in the medical field, nanotargeted delivery and combined therapy significantly improve the accuracy of cancer treatment, reduce toxic side effects, and improve patient prognosis; in the field of flexible electronics, the nanosilver - cellulose composite system provides excellent conductivity and flexibility for devices, enabling adaptation to new scenarios (e.g., wearable devices and flexible displays). Together, these three fields demonstrate the core value of nanotechnology as a driving force for cross-domain technological innovation . This study is limited by the number of literature sources used, future research could incorporate more literature for in-depth discussion.

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DOI: 10.54254/2755-2721/2026.MH29332

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