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REVIEW ARTICLE

Electrospinning applications in sustainable agriculture: Enhancing soil health, seed coatings and post-harvest antimicrobial protection

R Adhithiya Rajah[1], K Raja[1*], I Johnson[2], S Marimuthu[1] & A Subramanian[3]

[1]Centre for Agricultural Nanotechnology, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India
[2]Department of Plant Pathology, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India
[3]Department of Cotton, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India

*Correspondence email - rajaksst@gmail.com

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Abstract

Nanotechnology holds significant potential in agriculture, contributing to various applications such as nanofertilizers, nanopesticides, nanoherbicides, nanosensors and more recently, electrospun nanofibers. Among such advancements, electrospinning has emerged as a versatile and cost-effective technique for fabricating nanofibers, offering significant potential to enhance sustainability in agricultural practices. Recent applications of electrospun fibers have primarily focused on drug delivery, wound dressings and seed coatings infused with growth hormones. These nanofibers exhibit notable properties such as a high surface-area-to-volume ratio, excellent porosity and the ability to facilitate controlled release of active compounds. Encapsulating microorganisms and agrochemicals within electrospun fibers offers an environmentally friendly approach to improve soil health. By forming a protective layer, the electrospun nanofibers help safeguard seeds against abiotic factors such as drought and temperature fluctuations, as well as biotic threats like pathogens and pests. Furthermore, embedding natural or synthetic antimicrobial agents into electrospun films offers an eco-friendly solution for post-harvest protection by effectively minimizing spoilage and the risk of pathogen invasion. This review emphasizes the diverse roles of electrospun nanofibers in sustainable agriculture, including soil enhancement, seed improvement and post-harvest protection, while also promoting eco-friendly practices using biodegradable polymers and bioactive agents.

Keywords: controlled release; electrospun nanofibers; seed coating; soil health improvement; sustainable agriculture

Introduction

The world population is projected to increase from 7.8 billion in 2020 to 9.1 billion in 2050, placing immense pressure on global food production and agricultural sustainability (1). Feeding this growing population while ensuring food security remains a significant challenge, necessitating advancements in agricultural technologies and resource-efficient practices. Conventional fertilizers, including nitrogen (N), phosphorus (P) and potassium (K), are widely used to enhance crop yields. However, these fertilizers suffer from low nutrient-use efficiency, leading to significant nutrient losses through runoff, leaching and volatilization. These inefficiencies not only diminish economic returns for farmers but also contribute to environmental degradation, including water pollution, eutrophication and greenhouse gas emissions (2).

To address these challenges, biodegradable fertilizer coatings have gained attention for their ability to enhance nutrient encapsulation and minimize losses (3). Among such advancements, electrospinning has emerged as a promising technique for fabricating polymeric nanofibers with high surface area and tunable properties. Compared to traditional coating methods, electrospinning offers improved encapsulation efficiency and controlled nutrient release, making it highly suitable for developing polymer-coated controlled-release fertilizers (PC-CRFs) (4).

First patented in 1900 by John Francis Cooley, electrospinning has since evolved into a versatile platform with applications across medicine, textiles and agriculture (5, 6). Innovations like coaxial electrospinning enable the encapsulation of bioactive compounds within nanofibers, supporting sustained and targeted delivery (7).

Fig. 1 illustrates the formulation strategy for producing desired nanofibers by combining natural and synthetic biopolymers. Natural biopolymers such as chitosan, cellulose, hyaluronic acid, collagen, kefiran and alginate are derived from various biological sources like plants, animals and microbes. These can be chemically modified to enhance properties or blended with synthetic biopolymers like polyvinyl alcohol (PVA), polyethylene oxide (PEO) and polylactic acid (PLA) to improve processability and performance. The combination of biopolymer types and solvent system plays a critical role in fiber formation. An optimized solvent system ensures

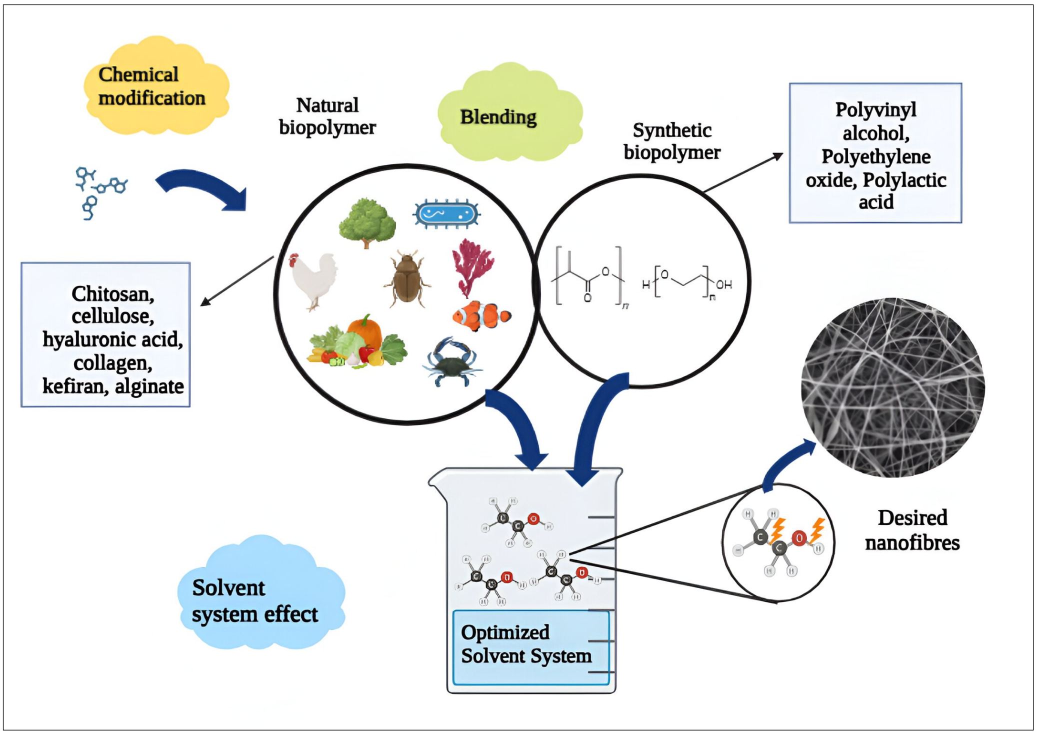

Fig. 1. Biopolymer and solvent system optimization for nanofiber production via electrospinning.

appropriate viscosity, conductivity and surface tension for successful electrospinning. The integration of all these components results in the fabrication of desired nanofibers with targeted structural and functional properties for various applications such as agriculture, medicine, or packaging. This review explores recent advancements in electrospinning for the development of controlled-release agrochemicals such as fertilizers, pheromone-loaded nanofibers, biodegradable mulching films and post-harvest preservation systems highlighting their potential in advancing sustainable agricultural practices.

Electrospinning

Electrospinning is a versatile technique that has garnered significant attention in the field of materials science, particularly for its ability to produce continuous fibres with diameters ranging from submicron to nanometre levels. This process, which has been rediscovered in the early 21st century, utilizes electrostatic forces to draw a polymer solution into fine fibres, making it distinct from traditional fibre spinning methods such as melt-spinning and dry-spinning. The unique properties of nanofibers, including their high surface area to volume ratio approximately a thousand times greater than that of human hair -enable a wide range of applications. These applications span various fields, including nano catalysis, tissue engineering, protective clothing, filtration and nano-electronics (8).

Fig. 2 illustrates a schematic diagram of a typical electrospinning unit, a spinneret with a heated nozzle tip, a high-voltage power supply and a rotating drum collector. The polymer solution is extruded through the nozzle, forming a droplet at the tip. Upon applying high voltage, electrostatic forces overcome the surface tension, forming a Taylor cone and ejecting a charged liquid jet. This jet initially travels in a straight path but quickly undergoes bending instabilities, forming a whipping motion. As the solvent evaporates, solid nanofibers are formed and deposited uniformly onto the rotating collector as a nanofiber mat. This technique enables the fabrication of uniform, tunable fibers with the potential for controlled release and functional agricultural applications.

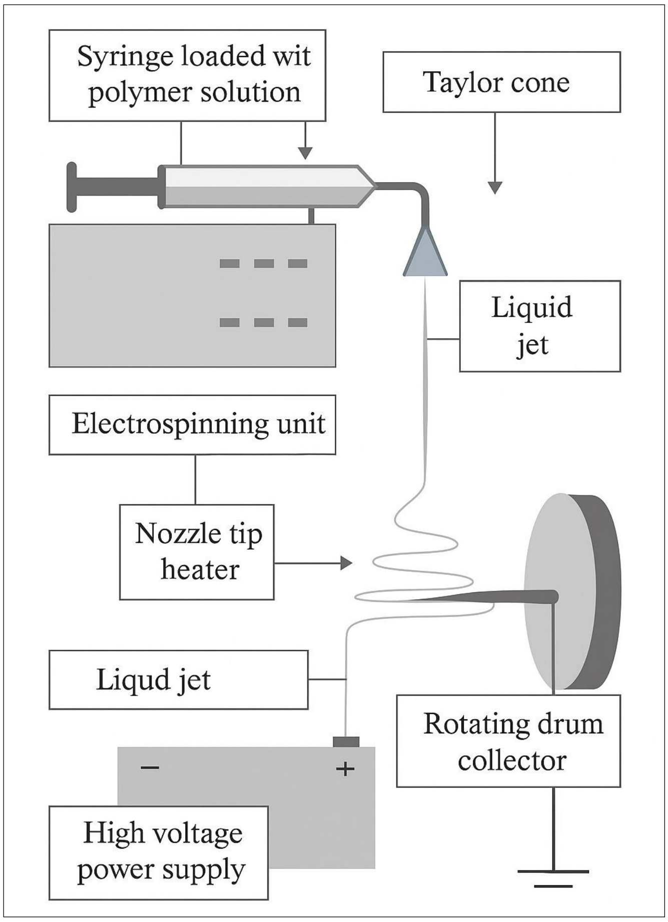

Fig. 2. Typical electrospinning set-up.

The flexibility of electrospinning allows for the fabrication of nanofibers from a diverse array of materials, including polymers, composites, ceramics and even metal nanofibers, either directly or through post-spinning processes. Despite the existence of alternative methods for nanofiber production, such as phase separation and template synthesis, electrospinning stands out due to its ease of use and adaptability (9). A typical electrospinning setup requires minimal equipment, including a high-voltage power supply, a syringe and a conducting collector. Recent advancements in electrospinning have focused on the creation of various fibrous assemblies, which are crucial for enhancing the performance of devices made from nanofibers. The arrangement of these fibres can significantly influence their functionality, making it essential to explore different electrospinning designs and setups (10).

Nanofiber loaded with fertilizer

A promising method for introducing plant nutrients is the application of electrospun polymeric fibers as controlled-release substrates. This is due to the very high surface area-to-volume ratio of these fibers compared to conventional polymer-coated fertilizers (4). The use of electrospun polymeric fibers as controlled-release substrates improves fertilizer use efficiency and addresses some environmental concerns associated with overuse (11). Among these fibers, electrospun PVA fibers are widely used for nutrient encapsulation (12). However, PVA is water-soluble and leads to the quick release of encased nutrients, necessitating the use of chemical cross-linking agents such as glutaraldehyde to enhance water resistance (13). To resolve this issue, coaxial electrospinning can be used, where the PVA fibers are arranged in core/shell configurations, with the outer phase being hydrophobic to improve structural stability (14). Coaxial electrospinning technology is favourable for fabricating fibrous membranes in core/shell configurations and can be successfully employed for the preparation of Slow-release fertilizers (SRFs) (15).

Fig. 3 illustrates the comparative effectiveness of ordinary fertilizers versus slow-release fertilizers in agricultural applications. On the left, ordinary fertilizers are shown to cause significant nutrient losses through volatilization, leaching and surface runoff, leading to reduced nutrient availability for crops and increased environmental pollution. In contrast, the right side demonstrates how slow-release fertilizers provide a controlled and targeted release of essential nutrients like nitrogen (N), phosphorus (P) and potassium (K). This method enhances nutrient use efficiency, supports sustained plant growth and minimizes environmental impact, highlighting the advantages of adopting slow-release fertilizers in precision agriculture.

Core/shell-structured fibers based on PVA have also gained attention in other industries. For instance, amoxicillin trihydrate-loaded silk fibroin/PVA core/shell nanofibers have been utilized for targeted drug release and improved wound healing (16). Similarly, to prevent corrosion, carbon steel surfaces have been coated with oleic acid and benzotriazole inhibitors embedded in PVA-core/shell nanofibers (17). Other applications include skin-graft PVA/gelatin core/shell fibers crosslinked with transglutaminase and PVA/polycaprolactone (PCL) fibers containing doxorubicin for sustained drug release in cancer treatment (18). This core/shell architecture significantly reduces burst release rates and prolongs the release of active substances, making it a valuable technique for various industries, including agriculture (19).

Pheromone-loaded nanofiber

Pheromones, or sex pheromones, are chemical signals produced by insects to communicate, particularly for mate attraction (20). Beyond their natural role in reproduction, they have emerged as eco-friendly alternatives to chemical pesticides in pest management. This is achieved by saturating fields with synthetic pheromones to confuse male insects and disrupt mating (21). However, their high volatility and susceptibility to environmental conditions like evaporation and rainfall limit their effectiveness (22). To overcome these limitations, researchers have explored encapsulating pheromones in polymeric carriers to enhance stability and enable controlled release.

Electrospun nanofibers, with their high porosity and surface area, have proven effective for pheromone delivery (22). Hellmann et al. demonstrated that polyamide (PA) nanofibers, unlike cellulose acetate (CA) ones, were bead-free and encapsulated pheromones efficiently. Despite bead formation, CA fibers offered higher loading capacity due to their solubility and biodegradability (23). Thermogravimetric

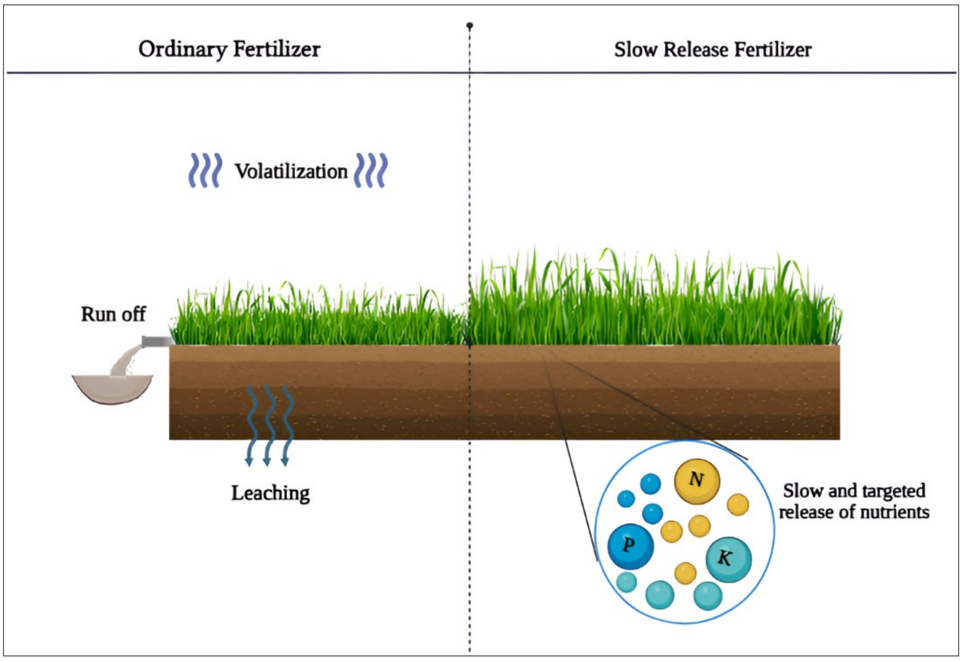

Fig. 3. Advantages of slow-release fertilizers (SRFs) in comparison to an ordinary fertilizer.

analysis (TGA) showed that CA and PA fibers sustained pheromone release for 55 and 31 days, respectively (24). Similarly, Bisotto-de-Oliveira et al. used electrospun polymers like PCL, PEG-PCL, ethyl cellulose and PVP to encapsulate *Trimedlure* for trapping *Ceratitis capitata*. These nanofiber formulations, containing 0.02-10% w/v of pheromones, performed significantly better than controls in field trials, with consistent trapping efficiency across different matrices (25). Their biodegradability and non-toxicity make pheromone-loaded electrospun fibers a sustainable and effective tool in integrated pest management (26).

Nanofiber loaded with biocontrol agents

The impacts of using chemicals for plant protection have led to serious health and ecological problems. To counter these challenges, bioprotectants have emerged as an alternative to synthetic pesticides, which pose risks to human health and the environment. These agents include beneficial microorganisms such as Trichoderma and *Bacillus subtilis*, which act against plant pathogens (27). The production of such microorganisms in the form of granules or capsules enhances their effectiveness by protecting them against environmental stresses, improving their stability during storage and processing and facilitating their incorporation into solid or semi-solid dosage forms for sustained release (28). Encapsulation also increases the convenience of applying biological agents in agricultural settings. Recent studies have explored the use of electrospun nanofibers for biocontrol applications. Fungal spores of Trichoderma were successfully electrospun into solutions of chitosan and PEO or chitosan and polyacrylamide (PAAm). The use of PEO was found to be more beneficial than PAAm due to its lower toxicity, although both polymers played a role in the electrospinning process (29). Viability tests indicated that fungal spores remained alive even after being spun in an electric field, highlighting the potential of electrospinning as a method for delivering bioactive microorganisms. The electrospun fibers also demonstrated effective antifungal activity against known phytopathogens such as *Fusarium* and *Alternaria* (30).

Moreover, biopolymer coatings were applied directly onto plant roots and leaves via electrospinning, providing protection and preserving plant nutrients. These findings support the potential of electrospun nanofibers as a sustainable and environmentally friendly method for plant protection. While electrospun nanofibers offer a promising strategy for pest and disease control, further research is needed to optimize the technology for large-scale agricultural applications. The development of improved electrospinning systems for industrial-scale nanofiber production could revolutionize pest management by enabling the widespread adoption of biodegradable, biopolymer-based solutions (30).

Nanofiber in pesticide delivery

Electrospinning enables the controlled release of pesticides, reducing the need for frequent applications while enhancing their efficacy. Nanofiber encapsulation protects pesticides from photodegradation and volatilization, improving their stability (4). Nanofibers, produced through electrospinning technology, are emerging as a promising solution for pesticide delivery systems. These nanofibers possess several advantageous properties that enhance their effectiveness in agricultural applications. Firstly, they have a high specific surface area, which allows for better interaction with active ingredients, leading to improved drug encapsulation rates and loading capacities

This characteristic is crucial for creating efficient pesticide carriers that can deliver active substances in a controlled and sustained manner, thereby enhancing the effectiveness of pesticides while minimizing environmental impact. Moreover, the flexibility of electrospinning technology enables the development of multifunctional nanofibers that can incorporate various agrochemicals, including insect pheromones and biopesticides, into their structure. This capability not only allows for the simultaneous delivery of multiple agents but also facilitates the design of environmentally responsive nanofibers, which are likely to be a focal point for future research in pesticide delivery systems (31).

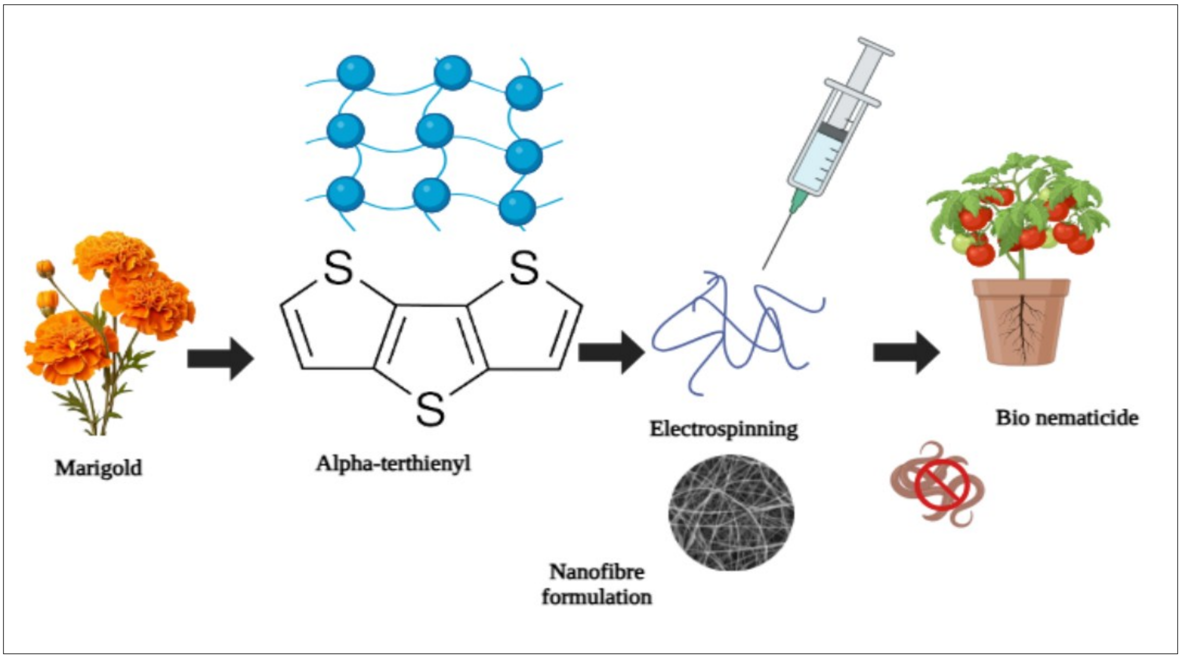

Fig. 4. Smart delivery of electrospun nanofiber-encapsulated botanical nematicide α-terthienyl from marigold for root-knot nematode control in tomato.

Fig. 4 illustrates the development of a bio-based nanofiber delivery system for nematode control. Bioactive α-terthienyl is extracted from marigold (*Tagetes spp.*), a plant known for its natural pesticidal properties. The compound is then encapsulated into nanofibers through electrospinning, forming a stable matrix for controlled release. Upon application to tomato plants, the nanofiber formulation acts as a bionematicide, targeting root-knot nematodes in the rhizosphere. This approach combines plant-based biopesticides with nanotechnology to enable smart, sustained and eco-friendly pest control in agriculture.

Additionally, the use of biodegradable polymer materials in the production of these nanofibers aligns with the global push towards green pesticides, reducing the ecological footprint associated with traditional pesticide formulations. However, challenges remain, such as optimizing the release profiles of these nanofibers and ensuring their safety and efficacy in real-world applications .Overall, the integration of nanofibers into pesticide delivery systems represents a significant advancement in agricultural technology, promising to enhance both the efficiency and sustainability of pesticide use (32).

Smart agrochemical release systems

Smart agrochemical release systems represent a significant advancement in agricultural practices, aiming to enhance the efficiency and sustainability of crop production. These systems utilize nanotechnology to create smart delivery mechanisms for agrochemicals, which can significantly reduce the negative impacts associated with conventional chemical applications. The integration of nanomaterials and nanocomposites allows for controlled release of active ingredients (AIs), minimizing the uncontrolled non-targeted release that often leads to environmental damage and toxicity to non-target species. For instance, studies have shown that encapsulating herbicides like atrazine in polyhydroxy butyrate-co-hydroxy valerate (PBHA) can reduce genotoxicity in plants, demonstrating the potential for these smart systems to improve crop health while mitigating adverse effects on surrounding ecosystems (33).

Furthermore, the binding ability of these nano compositions aids in understanding their distribution, bioavailability and toxicity levels, which are crucial for optimizing their use in agricultural settings. The development of smart agrochemical release systems also addresses the challenges posed by traditional agrochemical practices, such as the premature loss of growth-promoting ingredients and their extended degradation in soil. By utilizing nanotechnology, these systems can enhance nutrient utilization and improve disease resistance in crops, ultimately contributing to food security for a growing global population. However, the implementation of these systems is not without challenges. Concerns regarding the potential toxicity of nano pesticides and their effects on non-target organisms must be carefully evaluated. The balance between biodegradability, concentration and size of the incorporated AIs is critical in determining the safety and efficacy of these smart agrochemicals. As research continues to explore the interactions between nanoparticles and plant systems, it is essential to validate these technologies to ensure they lower agroecological risks while promoting sustainable agricultural practices. Overall, smart agrochemical release systems hold promise for revolutionizing crop protection and production, paving the way for a more sustainable agricultural future (34).

Electrospun sensors for precision farming

Nanofiber-based sensors have emerged as a promising tool for real-time monitoring of soil and crop conditions. Electrospun nanofibers functionalized with conductive polymers or metal nanoparticles can detect changes in soil moisture, nutrient levels and pH, allowing for optimized irrigation and fertilization (35). These sensors integrate with smart farming systems to enhance decision-making and resource efficiency. These sensors leverage electrospinning technology to create nanofibers that possess unique properties such as high surface area and porosity, which are crucial for effective sensing applications. The ability to fabricate composite nanofibers using a variety of materials, including polymers, carbon nanostructures and metal nanoparticles, enhances the performance of these sensors. This versatility allows for the development of sensors that can detect a wide range of analytes, from soil moisture levels to nutrient concentrations, thereby providing farmers with real-time data to optimize their farming practices. The integration of electrospun nanofibers into sensor designs not only improves sensitivity and response times but also enables the customization of sensors to meet specific agricultural needs, making them highly adaptable for different crops and environmental conditions.

Moreover, the structural characteristics of electrospun nanofibers contribute significantly to their effectiveness in precision agriculture. The interconnected porosity and predictable pore geometries of these nanofibers facilitate the rapid diffusion of analytes, reducing mass transport resistance and enhancing the overall sensing performance. This is particularly beneficial in applications where timely detection is critical, such as monitoring for pathogens or assessing crop health. Additionally, the ability to functionalize the surface of electrospun nanofibers with various nanomaterials allows for the creation of multifunctional sensors that can provide comprehensive data on multiple parameters simultaneously. As a result, electrospun sensors not only support precision farming by enabling more informed decision-making but also contribute to sustainable agricultural practices by minimizing resource waste and maximizing yield potential. The ongoing advancements in electrospinning technology and material science promise to further enhance the capabilities of these sensors, paving the way for smarter and more efficient farming solutions in the future (36).

Real-time soil monitoring

An analysis of Table 1 reveals electrospun nanofiber sensors improve soil health assessment by detecting changes in moisture levels, pH and nutrient concentrations (37). These sensors enable precision irrigation, reducing water waste and enhancing crop yields. Real-time soil monitoring (RTCSM) is an innovative approach that significantly enhances our ability to assess soil quality and manage agricultural practices effectively. Traditional soil measurement methods often rely on laboratory analyses, which can be time-consuming, costly and labour-intensive. These methods typically provide discrete data points that may not accurately reflect the dynamic nature of soil conditions. In contrast, RTCSM offers continuous, real-time data on various soil parameters, including physicochemical properties like moisture and nutrient levels, as well as biochemical factors such as microbial activity and

Table 1. Examples of nanotechnology-based sensors for soil nutrient and pH sensing

Sensor Category	Nanomaterial Employed	Target Analyte(s)	Working Mechanism
Electrochemical Sensor	Carbon Nanotubes (CNTs)	Nitrogen	Enhanced electron transfer boosts sensitivity to nitrate ions
Optical Sensor	Quantum Dots	Phosphorus	Fluorescence variation with changing phosphate concentration
Colorimetric Sensor	Gold Nanoparticles	Potassium	Color shift due to nanoparticle aggregation induced by potassium ions
Electrochemical Sensor	Graphene Oxide	Nitrate, Phosphate	High conductivity enables efficient nutrient ion detection
Fluorescence Sensor	Up conversion Nanoparticles	Micronutrients (Fe, Zn, Cu, Mn)	Fluorescence emission upon selective micronutrient ion binding
Ion-Selective Sensor	Nanoporous Membranes	Ammonium	Selective ion transport for detecting ammonium ions
Raman Sensor	Silver Nanoparticles	Nitrate, Phosphate	Surface-enhanced Raman scattering for precise nutrient detection
Conductometric Sensor	Zinc Oxide Nanorods	Nitrate, Ammonium	Conductivity changes upon interaction with nutrient ions
Electrochemical Sensor	Molybdenum Disulfide Nanosheets	Phosphate	High surface area promotes phosphate detection via electrochemical activity
Fluorescence Sensor	Carbon Dots	Potassium	Fluorescence quenching triggered by potassium ion presence
Electrochemical Sensor	Carbon Nanotubes (CNTs)	pH	Electron transfer enhancement improves pH sensitivity
Optical Sensor	Quantum Dots	pH	Quantum dot fluorescence properties shift with pH changes
Colorimetric Sensor	Gold Nanoparticles	pH	Color modification due to pH-induced nanoparticle aggregation
Field-Effect Transistor	Graphene	pH	High surface area of graphene increases pH detection sensitivity
Fluorescence Sensor	Up conversion Nanoparticles	pH	Fluorescence emission shifts with varying pH levels
Raman Sensor	Silver Nanoparticles	pH	Surface-enhanced Raman scattering enables pH detection
Conductometric Sensor	Zinc Oxide Nanorods	pH	Conductivity modulation based on pH response
Electrochemical Sensor	Molybdenum Disulfide Nanosheets	pH	High electroactivity and surface area enhance pH sensing
Fluorescence Sensor	Carbon Dots	pH	pH alters fluorescence intensity of carbon dots
Colorimetric Sensor	Polydiacetylene Nanofibers	pH	Color change of nanofibers in response to pH variation

the presence of contaminants like heavy metals and emerging contaminants (ECs) (38).

This continuous monitoring capability is crucial for timely decision-making in agricultural management, allowing for immediate adjustments to practices such as irrigation, fertilization and pest control, ultimately leading to improved soil health and crop yields. Despite its potential, the implementation of RTCSM faces several challenges. The complexity of soil properties, including texture, porosity and chemical composition, can interfere with monitoring accuracy and data interpretation. Additionally, current sensor technologies, such as potentiometric sensors, often struggle to meet the detection limits required for certain contaminants, leading to issues with accuracy and reliability. Furthermore, the integration of RTCSM data with existing agricultural models and practices is essential for maximizing its benefits. This integration can enhance our understanding of soil processes and improve strategies for soil management, food security and climate change mitigation. By addressing these challenges and advancing sensor technology, RTCSM can revolutionize how we monitor and manage soil, providing a more sustainable approach to agriculture and environmental stewardship (39).

Enhanced sensitivity and response time

Electrospun nanofiber-based sensors exhibit high sensitivity due to their large surface area and porous structure, leading to faster response times compared to conventional sensors (40). Electrospun nanofiber-based sensors have gained significant attention due to their enhanced sensitivity and rapid response capabilities. These sensors leverage the unique properties of nanofibers, which include a high surface-area-to-volume ratio, tailored pore structures and large stacking density. Such characteristics allow for effective surface modification, which is crucial for improving sensor performance. The high surface area facilitates greater interaction with target analytes, leading to increased sensitivity. This is particularly beneficial in applications where detecting low concentrations of contaminants is essential. Moreover, the design of electrospun nanofibers enables fast response and recovery times. The small diameter of the fibers allows for quicker diffusion of gases or liquids, which means that the sensors can detect changes in concentration almost instantaneously. This rapid response is vital in various applications, such as environmental monitoring and safety systems, where timely detection of hazardous substances is critical (41).

The versatility of electrospun nanofibers also extends to their use in different types of sensors, including acoustic wave sensors, resistive sensors, optical sensors, optoelectronic sensors and amperometric sensors. Each type utilizes the inherent properties of nanofibers to achieve specific detection mechanisms, further enhancing their applicability across various fields. In summary, the combination of high sensitivity and rapid response in electrospun nanofiber-based sensors makes them a promising solution for addressing global challenges related to contamination and safety. Their ability to provide quick and accurate readings positions them as a valuable tool in both research and practical applications, paving the way for advancements in sensor technology and environmental protection (42).

Biodegradable mulch film fabrication

Electrospun nanofibers, fragmented into sub pieces within extended polymeric solute drafting structures through atomization, have enabled the fabrication of biodegradable and biocompatible biomaterials. These nanofibers have recently been assembled for seed coating applications in agriculture, making them highly suited for enhancing germination and early plant development (43). Due to their diverse structural compositions, nanofibers offer numerous advantages, with vertical electrospinning emerging as the preferred method for fabrication. Vertical electrospinning provides a perfectly aligned electric field, leading to finer filament production (44). An innovative approach in seed coating involves the development of Colorado-coated seeds, which, when combined with a mechanical rotary method, improve coating uniformity and enhance seed interaction with acidic or basic agents, ultimately promoting better crop growth. Mechanically rotating coated seeds ensure even distribution of the nanofiber layer, facilitating respiration and water absorption for optimal germination (45). Palestinian civil society and agricultural experts have identified dissolvable, cross-linked, low -biodegradability nanofiber-coated seeds from Indonesia as advanced materials for enhancing crop cultivation across a wide range of vegetation. Unlike conventional thick grainy seed coatings, nanofiber coatings facilitate better oxygen exchange, improving aerobic respiration. This enhancement is crucial for energy production, cell division and seedling expansion, ultimately increasing seed strength and germination rates (46).

The primary goal of seed coating is to stimulate germination and aid in early seedling development. Seeds typically contain 5-15 % moisture, rendering them metabolically inactive. Upon water uptake (imbibition), seeds initiate metabolic processes, including the production of plant hormones such as abscisic acid (ABA) and gibberellic acid (GA_3), which regulate germination and energy utilization (47). Seed germination has been significantly improved by wire-based seed coatings due to their high fluid uptake ability (FUA). Research on hybrid nanofiber coatings has demonstrated remarkable increases in seedling growth, confirming that fibrous coatings support germination processes. Additionally, electrospun nanofibers provide mechanical benefits that allow plants to thrive in specific environments, including areas with limited arable land (43). These coatings not only promote germination but also provide long-term benefits during the early growth phases of plants.

Nanofibers in seed coatings

Polymers, sourced from natural raw materials or produced through biological processes, are highly adaptable materials for seed coating. Their biocompatibility, biodegradability and low toxicity make them ideal for agricultural applications. Additionally, they function as controlled-release carriers of agrochemicals, ensuring a sustained and efficient nutrient supply to plants (48). Several biopolymers, including polysaccharides, polypeptides and semi-synthetic biopolymers, have been studied for seed coating applications. Among these, polysaccharides stand out due to their broad availability, excellent gas barrier properties and mechanical strength. Examples include cellulose, chitin, starch, pectin, gums and alginates unbranched polymers of monosaccharides linked by glycosidic bonds. Cellulose, in particular, is valued for its high biocompatibility and thermal and mechanical stability (49). Chitosan, another commonly used polysaccharide, has demonstrated excellent seed-coating properties, improving germination rates and seedling health (50).

Fig. 5 shows a seedling coated with electrospun nanofibers containing embedded nutrients. The nanofiber network acts as a delivery system, slowly releasing nutrients to support early plant growth. This method enhances germination and seedling vigor while minimizing nutrient loss.

Though semi-synthetic polymers such as PHB, PHV and PHA show promise, their high-cost limits usage. In contrast, starch-based biopolymers offer a more affordable and eco-friendly solution (51). Electrospun nanofibers (NFs) and biopolymer nanoparticles (NPs) outperform traditional coatings by enabling targeted, sustained nutrient release through their porous, nanoscale structure (43).

Biopolymer coatings such as nanocellulose, gelatin and PVA improve oxygen and moisture transfer, supporting better germination and yield (52). These nanofibers also reinforce coating integrity, reduce peeling and ensure uniform distribution of active compounds. Examples include cellulose acetate for weed control and gelatin composites for nutrient delivery (47). Thus, biopolymer-based seed coatings offer a sustainable and effective solution aligned with modern agricultural needs (53).

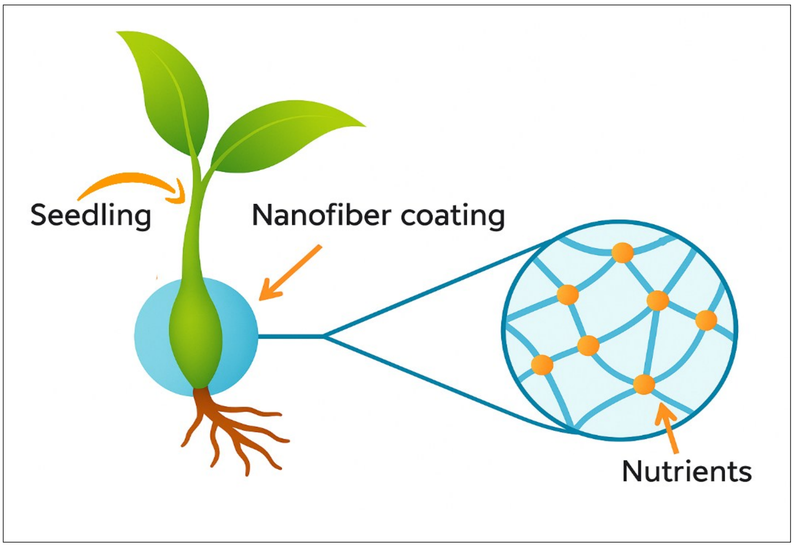

Fig. 5. Electrospun nanofibers as a seed coating.

Antimicrobial electrospun materials for post-harvest storage

Over the past decade, the global vegetable and fruit market has grown due to population increases, improved living conditions and rising social awareness about health and nutrition. However, maintaining post-harvest quality remains a major challenge, primarily due to inadequate storage and microbiological contamination. To address these issues, innovative antimicrobial materials incorporating metal oxide nanoparticles such as silver (Ag), titanium dioxide (TiO_2) and zinc oxide (ZnO) have been developed (54). Among these materials, nano-silver (nano-Ag) is particularly effective due to its large surface area and broad-spectrum antibacterial properties against *E. coli*, *S. aureus* and *L. monocytogenes*. Nano-Ag disrupts microbial growth by binding to phosphorus and sulfur in cell membranes, proteins and DNA, leading to structural breakdown and impaired cellular functions. Additionally, it triggers the synthesis of reactive oxygen species (ROS), which oxidize cell walls and membranes, further damaging the bacteria (55). Nano-TiO_2 also exhibits strong antimicrobial activity, particularly due to its photocatalytic properties under UV light. When exposed to photons with sufficient energy (greater than its 3.2 eV band gap), TiO_2 generates ROS capable of destroying a broad spectrum of microorganisms (56).

Natural antimicrobials such as essential oils (EOs), chitosan, lysozyme and lactoferrin inhibit microbial growth through membrane disruption and interference with metabolic processes (57, 58). Electrospun nanofibers effectively incorporate these agents due to their high surface area and controlled release capabilities (59). Yet, challenges remain in humid environments, which are mitigated through cross-linking to enhance structural stability (60).

Ethylene, a key ripening hormone, causes fruit softening. Electrospun films with essential oils like thyme or jasmine delay this by preserving cell wall integrity. PLA submicrofibers with eugenol improved cucumber firmness by boosting lignin and proline levels (61, 62). In mushrooms, cinnamon oil-infused nanofiber membranes provided antimicrobial protection and maintained respiration balance (63).

Although traditional polyethylene films retain firmness, they can trap moisture and promote spoilage. Electrospun nanofiber films offer superior antimicrobial and moisture control (64). Managing ethylene via photocatalytic TiO_2 nanofibers reduces ripening and spoilage by degrading ethylene gas into CO_2 and O_2 (65). The effectiveness of ethylene control through electrospun nanofiber technology has been demonstrated in various studies, particularly for climacteric fruits such as tomatoes and bananas. By incorporating TiO_2-based coatings, fruit degradation can be minimized, maintaining freshness and reducing odour during storage (66). These advancements indicate that electrospun nanofiber mats can revolutionize post-harvest food storage by improving antimicrobial efficacy, ethylene management and overall food preservation. However, further research is needed to enhance the scalability, stability and mechanical properties of nanofiber-based packaging materials for widespread commercial adoption.

Electrospun nanofibers for water purification

Water scarcity is a major challenge in agriculture and electrospun nanofibers have shown significant potential for water filtration and purification. These nanofibers can be functionalized with metal oxides such as titanium dioxide (TiO_2) and silver nanoparticles (AgNPs) to enhance antimicrobial activity and remove contaminants from irrigation water (67). The high porosity of electrospun membranes allows for efficient water filtration while maintaining soil hydration and minimizing waterborne plant diseases (68). Electrospun polymeric nanofibrous membranes provide an effective means of water treatment due to their large surface area, high permeability and ability to be modified for specific contaminant removal (69). Additionally, these membranes have been used to filter wastewater, removing heavy metals, bacteria and organic pollutants. The integration of nanofibers with antimicrobial agents, such as silver nanoparticles, enhances their potential for preventing microbial contamination in irrigation systems.

Fig. 6 shows a nanofiber-based water filtration system where polluted water passes through an electrospun membrane to yield clean water. These membranes, fabricated by

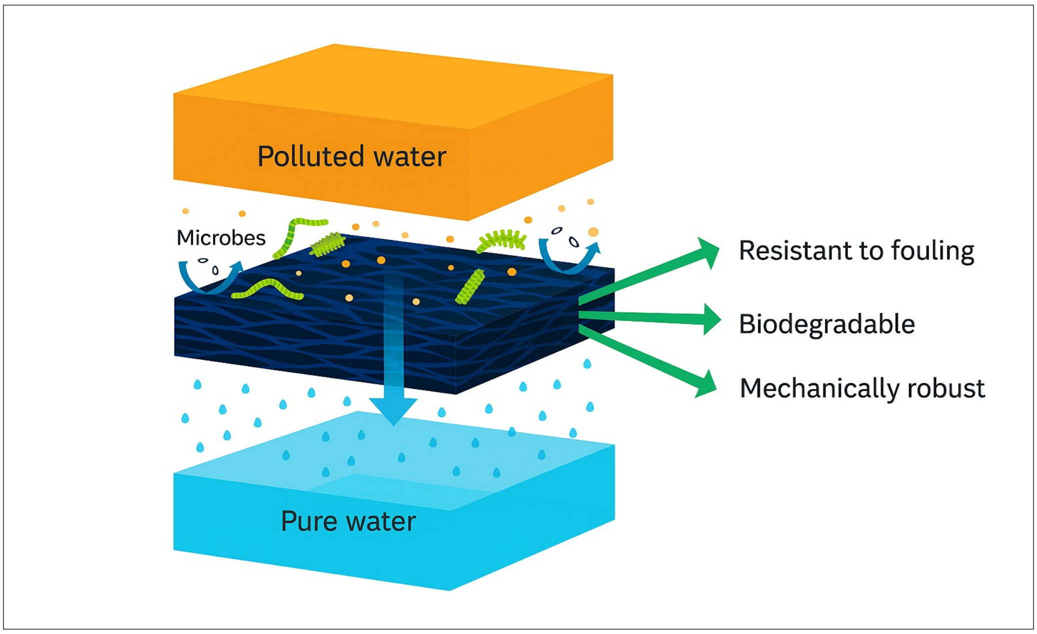

Fig. 6. Schematic representation of removal of micro-pollutants from water by filtration through an ideal electrospun nanofiber membrane (ENM).

electrospinning, offer uniform pore size (<0.2 µm), strong mechanical properties and biodegradability. They effectively remove fine particles and microorganisms, making them a superior alternative to conventional membranes for sustainable water purification. These advancements demonstrate that electrospun nanofiber technology has the potential to revolutionize water purification methods, making them more effective, cost-efficient and environmentally friendly (70).

Addressing challenges and advancing electrospinning in precision agriculture

Electrospinning holds great promise for agricultural applications; however, it faces several critical challenges. These include high production costs, difficulties in scaling up and environmental concerns due to the use of toxic solvents (71). Recent research has explored green electrospinning approaches using biodegradable polymers and eco-friendly additives as potential solutions (72). Electrospun nanofibers are especially attractive for agriculture because of their unique characteristics such as a high surface-area-to-volume ratio and porosity which enable the controlled release of agrochemicals, enhancing their efficiency and minimizing environmental impact (4, 73). Despite these advantages, practical limitations persist, particularly in scaling up production, achieving consistency in fiber quality and navigating regulatory hurdles (73). Addressing these challenges will require interdisciplinary efforts and continued innovation in materials science and engineering to develop sustainable, scalable and economically viable electrospinning techniques for broad agricultural use (72).

As shown in Table 2 Electrospinning is an emerging technology with significant potential in precision agriculture, offering sustainable solutions to enhance productivity while protecting the environment. It enables the creation of nanofiber-based systems for controlled agrochemical delivery, pest management, seed treatment and soil remediation. Electrospun nanofibers can encapsulate fertilizers, pesticides and herbicides for targeted release, improving nutrient use efficiency and reducing pollution. Coaxial electrospinning, which produces core-shell fibers, allows precise regulation of active ingredient

Table 2. Various applications of nanofiber in agriculture (75-92)

Nanofiber Material	Solvent	Application	Reference
Nylon 6 (PA6)	Formic acid	Pesticide biosensor for aquatic crops	(75)
Polyamide 6	Formic acid	Mating disruption by (Z)-9-dodecenyl acetate encapsulation for European grape moths	(76)
PVA	DW	*P. agglomerans* and *B. caribensis* encapsulation for seed treatment	(77)
PLLA	Chloroform/MetOH	Thiram fungicide-controlled release formulation	(78)
PVAc	DMF	Pheromone delivery system for pest deterrence	(79)
PA6/PPy/RGO	Formic acid	Electrochemical sensing of malathion pesticide	(80)
PVA	DW	Detection of pesticide residues	(81)
PVP/TiO2	DMF	Water crop pesticide biosensor	(82)
PVA/PVP/Glycerol (Gly)	DW	Soil biostimulant and biofertilizer with Bacillus and Serratia species	(83)
PVA/AChE/IA	DW	Sensor for pesticide detection	(84)
CA and gelatin	Ac:DW	Nanocomposite seed cover with CuO and Cu^{2+} ions for fungicidal action	(85)
SBS	DW	Sustained pheromone elution system	(79)
Cellulose (Innofresh™)	Cellulose NF/plasticizers/ surfactant mixture/KSb	Protective cherry coating film	(86)
PVA	DW	Bradyrhizobium-based seed encapsulation for soybeans	(87)
CA	Ac	Controlled pheromone delivery for *Grapholita molesta*	(79)
PVP	THF	Nanofiber-based pheromone release	(79)
PCL	EtOH	Slow-release pheromone encapsulation	(79)
Co-polyester PHA-b-MEG and Poly (ethylene oxide) PEO	Brij S20	Encapsulation system for pheromone OLA release	(88)
Fe_3O_4 NPs/PMMA NFs/carbon horns (CNHs)	DMF	Biosensor for detecting Aflatoxin (AFB1)	(89)
PCL	Chloroform/EtOH	3D nanoscaffold for Burkholderia strain-based biofilm	(90)
Ethyl cellulose (EC), solution Toluene/ethanol 80:20	DCM	Encapsulation of Vitavax and Carbex fungicides for rice seed coating	(91)
CA	DCM	Encapsulation of *Grapholita molesta* pheromone	(79)
Blends of (PEG)/(PCL) and blends of (PVAc)/(PVP)	Acetone	Controlled release encapsulation for *Ceratitis capitata* management	(92)
(PEDOT)/Graphene oxide (GO)	EtOH	Impedimetric device for detecting soil nitrate levels	(75)

NPs: nanoparticles; NFs: nanofibers; PEDOT: poly(3,4-ethylenedioxythiophene); PCL: polycaprolactone; PEO: polyethylene oxide; PVP: polyvinylpyrrolidone; PANI: polyaniline; PA6: polyamide-6; PS: polystyrene; PEG: polyethylene glycol; CA: cellulose acetate; CDA: Cellulose diacetate; PVAc: polyvinyl acetate; PVA: polyvinylalcohol; PPZ: poly (diethoxy) phosphazene; PLA: polylactic acid; PHB: polyhydroxybutyrate; DMF: N,N dimethyl formamide; THF: tetrahydrofuran; DCM: dichloromethane; EtOH: ethanol; MetOH: methanol; DW: deionized water; DDA: double distilled water; DMAc: dymethyl acetamide; Ac: acetic acid; PBAT: poly(butyleneadipate-co-terephthalate; PHMG: polyhexamethylene guanidine; PLGA: lactide/glycolide copolymer; KSb: potassium sorbate; PVDF: polyvinylidene fluoride; SBS: styrene-butadiene-styrene copolymer; PPy: polypyrrole; RGO: reduced graphene oxide; HP-β-CD-hydroxypropyl-β-cyclodextrin; NPK: nitrogen-phosphorus-potassium; AChE: acetylcholinesterase; IA: indolyl acetate.

release, potentially responsive to pH, moisture, or microbial signals. In pest control, nanofibers embedded with pheromones or biopesticides offer eco-friendly alternatives by disrupting pest cycles. Biodegradable polymers further minimize environmental impact. Electrospun seed coatings enhance germination by retaining water, oxygen and nutrients and can deliver growth regulators or microbes effectively. Soil health can also benefit from functionalized nanofibers combined with biochar and beneficial microbes, while integrated nanofiber-based sensors allow real-time monitoring of moisture, pH and nutrients.

Future advancements may merge electrospinning with 3D printing and nanolithography to develop smart agricultural tools and biodegradable films (74). However, scaling up production, reducing costs and addressing environmental and regulatory challenges require collaborative efforts. Technological progress in materials science and precision agriculture will be key to mainstreaming electrospinning in sustainable farming (72).

Conclusion

The integration of electrospinning technology in sustainable agriculture presents a transformative approach to enhance soil health, seed coatings and post-harvest antimicrobial protection. This innovative method not only improves nutrient delivery and utilization but also addresses critical challenges such as plant disease management and environmental sustainability. The following sections will explore the multifaceted applications of electrospinning in agriculture, highlighting its potential to revolutionize farming practices. Controlled Nutrient Release: Electrospun nanofibers can encapsulate fertilizers, allowing for a slow and controlled release, which minimizes nutrient leaching and enhances soil health. Microbial Encapsulation: The use of electrospun biocomposites that incorporate beneficial microbes can improve nutrient acquisition and disease resistance in crops, promoting a healthier rhizosphere. Seed coatings made from electrospun nanofibers, such as those incorporating cobalt nanoparticles and urea, have shown significant improvements in germination rates and seed protection. The materials used in these coatings are often biocompatible, reducing environmental impact while enhancing crop yield through better nutrient management. Antimicrobial Properties: Electrospun nanofibers can be engineered to include antimicrobial agents, providing protective coatings for fruits and vegetables that extend shelf life and reduce spoilage. The development of smart nanotextiles for food packaging can further enhance food safety and quality, addressing post-harvest losses.

In conclusion, while the applications of electrospinning in sustainable agriculture are promising, challenges remain in scaling these technologies for widespread adoption. The need for further research into the long-term effects and economic viability of these innovations is essential to fully realize their potential in transforming agricultural practices.

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Authors' contributions

KR conceptualized the review and developed the initial framework. RA conducted the comprehensive literature search, data collection and writing the original draft. IJ critically analysed the technological aspects of electrospinning applications in agriculture. SM contributed to the sections on seed coating and post-harvest protection. AS reviewed the manuscript for scientific accuracy and provided valuable insights on sustainability implications. All authors read and approved the final manuscript.

Compliance with ethical standards

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