NANOFIBER TECHNOLOGY AND ITS POTENTIAL USE FOR SUSTAINABLE AGRICULTURAL DEVELOPMENT: A BIBLIOMETRIC REVIEW

TECNOLOGÍA DE NANOFIBRAS Y SU USO POTENCIAL PARA EL DESARROLLO AGRÍCOLA SOSTENIBLE: UNA REVISIÓN BIBLIOMÉTRICA

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ABSTRACT:

Contemporary agriculture requires innovative materials capable of increasing productivity and improving resource-use efficiency without compromising sustainability. This review analyzes the potential of polyvinyl alcohol (PVA) nanofibers produced by electrospinning from a structural design perspective. Through a systematic review based on the PRISMA methodology and a bibliometric analysis of 170 articles published between 2020 and 2026, a current predominance of applications in coatings and packaging for the food industry was identified, although scientific interest has increased since 2023. PVA stands out as a strategic polymer due to its ease of processing and compatibility with blends and hybrid systems, enabling applications in water retention, bioactive delivery, microbial support, and sensing. Despite challenges such as water solubility, field validation, and regulatory barriers, emerging areas such as controlled nutrient release and agricultural sensing show high potential. Overall, the review proposes a conceptual framework linking material architecture to agricultural performance and highlights the importance of integrating these technologies within social, economic, and territorial contexts to promote sustainable and equitable agriculture.

Keywords: Polyvinyl alcohol, Anofibers, Sustainable agriculture, Fibrous materials.

RESUMEN:

La agricultura contemporánea requiere materiales innovadores que aumenten la productividad y mejoren la eficiencia en el uso de recursos sin comprometer la sostenibilidad. Esta revisión analiza el potencial de las nanofibras de alcohol polivinílico (PVA) obtenidas por electrospinning desde una perspectiva de diseño estructural. Mediante una revisión sistemática basada en la metodología PRISMA y un análisis bibliométrico de 170 artículos publicados entre 2020 y 2026, se identificó un predominio actual de aplicaciones en recubrimientos y empaques para la industria alimentaria, aunque el interés científico ha aumentado desde 2023. El PVA se destaca como un polímero estratégico por su facilidad de procesamiento y compatibilidad con mezclas y sistemas híbridos, lo que permite aplicaciones en retención de agua, liberación de bioactivos, soporte microbiano y sensores. A pesar de

desafíos como su solubilidad en agua, la validación en campo y las barreras regulatorias, áreas emergentes como la liberación controlada de nutrientes y el sensado agrícola muestran alto potencial. En conjunto, la revisión propone un marco conceptual que relaciona la arquitectura del material con el desempeño agrícola y destaca la importancia de integrar estas tecnologías dentro de contextos sociales, económicos y territoriales para promover una agricultura sostenible y equitativa.

Palabras clave: Polivinil alcohol, Nanofibras, Agricultura sustentable, Materiales fibrosos.

INTRODUCTION

Agriculture faces major social, economic, and environmental challenges, particularly for smallholder farmers, including limited access to technology, rising production costs, and climate variability. Therefore, agricultural innovations must be evaluated not only for technical performance but also for their ability to promote sustainability and reduce technological gaps. In this context, polyvinyl alcohol (PVA)-based nanofibrous materials have emerged as promising tools for controlled-release systems and improved resource-use efficiency.

Modern agriculture functions as a complex system where physical, chemical, and biological processes interact, especially at the soil–root–microorganism interface that regulates water and nutrient availability and biochemical signaling essential for plant growth (Górski et al., 2025; Makhado et al., 2025). Early crop stages such as germination depend strongly on environmental factors like moisture, temperature, and microbial activity, making this interface crucial for nutrient uptake, water retention, and gas exchange (Górski et al., 2025).

PVA-based multifunctional polymeric materials have gained attention due to their biocompatibility, hydrophilicity, and structural versatility. These materials can create stable humid microenvironments that support biological activity and protect sensitive structures, acting as active platforms rather than passive carriers (Akram et al., 2023). The incorporation of biological or photosynthetic components into PVA matrices can further regulate interactions with water and light, strengthening their role as functional interfaces in agricultural systems (Chen et al., 2020).

The effectiveness of these materials depends not only on chemical composition but also on their architecture and environmental interaction. PVA fibrous matrices can balance water absorption and mechanical stability under variable conditions. Among nanomaterials explored for agricultural applications, fibrous structures stand out due to their high surface area and interconnected porosity, promoting water retention, stable microenvironments, and interactions with seeds, roots, and microorganisms (Akram et al., 2023; Makhado et al., 2025; Xue et al., 2025).

Overall, PVA-based materials have potential not only as nutrient carriers but also as active interfaces that regulate physical, hydric, and biological processes. However, current research remains fragmented and often lacks integration between material architecture and agricultural performance. Therefore, this study systematically analyzes the literature on PVA nanofibers from a socio-technical perspective, evaluating their potential as enabling technologies for sustainable agriculture, technological accessibility, and rural innovation.

MATERIALS AND METHODS

The present study was conducted as a systematic literature review following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines to ensure transparency and methodological rigor in the identification, selection, and analysis of studies (Page et al., 2021).

The search strategy focused on scientific literature related to polyvinyl alcohol (PVA)-based materials in agricultural applications, particularly nanomaterials, fibrous structures, and interactions with the soil–plant interface. Searches were performed in the Scopus, Web of Science, and Google Scholar databases, considering publications from 2020 to 2026 to capture recent developments.

In the identification phase, 5,386 records were retrieved using keywords such as *PVA*, *agriculture*, *nanomaterials*, *fibrous matrices*, *seed coating*, and *soil interface*. After removing duplicates, titles and abstracts were screened to exclude studies unrelated to agricultural applications, particularly those focused on biomedicine or packaging without agronomic relevance, as well as non-research documents. Full-text evaluation was then conducted, including only studies addressing agricultural uses of PVA in films, coatings, or fibrous matrices and analyzing relevant functional properties such as interactions with seeds, soil, water, or microorganisms. The final selection was integrated into a qualitative synthesis and documented using a PRISMA flow diagram (Figure 1).
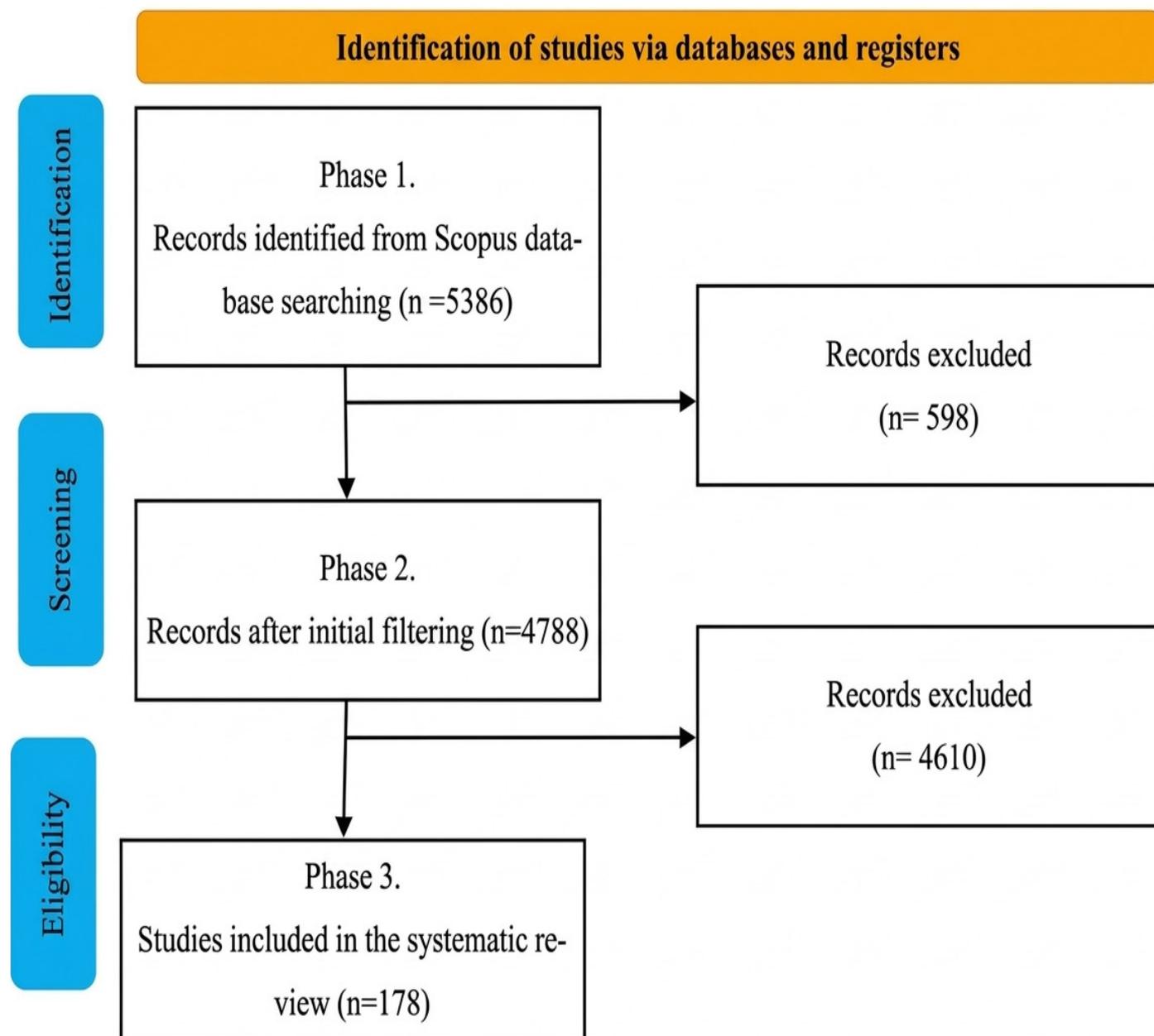
Fig 1. PRISMA flow diagram for the identification and selection of studies on electrospun polyvinyl alcohol nanofibers applied in agriculture.

DEVELOPMENT

Bibliometric analysis and research trends

A bibliometric analysis using VOSviewer was conducted to understand the evolution of research on PVA electrospinning and its potential agricultural applications. The resulting network (Figure 2) reveals a multidisciplinary landscape linking fields such as chemistry, nanotechnology, microbiology, and materials science. Central nodes including *nanofibers*, *electrospinning*, *antibacterial activity*, *cellulose*, and *food packaging* indicate that electrospun nanofibers are widely studied as multifunctional materials with tunable physical and biochemical properties.

Fig 2. Bibliometric network of research on electrospun polyvinyl alcohol and its agricultural applications, generated with VOSviewer using a keyword co-occurrence threshold of 7.

The proximity of terms such as *PVA*, *chitosan*, *biopolymers*, and *encapsulation* reflect increasing interest in sustainable and biocompatible polymer matrices capable of performing active functions. The network also shows a recent shift toward bioactive and environmentally responsive systems associated with biodegradability and biocompatibility.

Two main research trajectories emerge: biomedical and pharmaceutical applications (e.g., drug delivery and wound healing) and food–agricultural systems, including food packaging, antimicrobial materials, cellulose nanofibers, and biopolymer composites. This convergence suggests that properties such as controlled release, hydrophilicity, and microbial regulation can also be adapted for agricultural interfaces between soil, roots, and microorganisms.

Methodologically, the field relies on techniques such as scanning electron microscopy, X-ray diffraction, and Fourier transform infrared spectroscopy (FTIR), which connect material structure with functionality. Recent studies also incorporate bioactive compounds, essential oils, and polyphenols into electrospun PVA matrices, creating hybrid materials with antimicrobial and antioxidant properties. These materials show potential for applications such as seed coatings, soil conditioners, and delivery systems for microorganisms and micronutrients.

Overall, the bibliometric landscape indicates that electrospinning research has evolved into an interdisciplinary field integrating materials science, biology, and environmental engineering. This transition toward biopolymer-based systems highlights electrospun PVA not only as a carrier material but also as a structural platform capable of regulating water dynamics, microbial colonization, and biochemical exchange at the soil–root interface.

Social impact and socio-technical assessment of PVA-based electrospun materials in agriculture

In addition to systematic and bibliometric analyses, this study includes a qualitative socio-technical review to examine the potential social implications of adopting electrospun polyvinyl alcohol (PVA) materials in agricultural systems. This assessment explores how emerging material technologies interact with structural aspects of agriculture, including technological accessibility, knowledge transfer, economic feasibility, and the ability of different producer groups—specially to integrate advanced materials into their practices. The review was conducted through an interpretative analysis of literature on agricultural innovation diffusion, sustainability transitions, and technology adoption barriers. It identifies key themes such as equitable access to innovation, institutional support, regulatory environments, and environmental benefits. Rather than relying on quantitative indicators, the approach emphasizes the systemic positioning of PVA-based nanofibrous technologies within broader agroecological and socio-economic transformations.

This perspective connects developments in material science with sustainability-oriented agricultural frameworks, recognizing that the real-world impact of electrospun PVA systems depends not only on physicochemical performance

but also on the social conditions that enable responsible deployment and inclusive adoption. Consequently, this social analysis complements the PRISMA-based evidence synthesis and bibliometric mapping, providing a multidimensional basis for understanding the future role of electrospun PVA materials in sustainable agriculture.

Nanofibrous as active design tools

The conceptual framework indicates that modern agriculture requires materials capable of actively interacting with the soil–root–microorganism interface rather than acting only as passive nutrient carriers. Bibliometric and systematic analyses highlight material architecture as a key factor linking polymer science with agricultural functionality. In this context, fibrous architectures are particularly relevant because processes such as water regulation, gas exchange, mechanical protection, and microbial interactions occur at this interface during early plant establishment (Górski et al., 2025; Makhado et al., 2025). Their structure enables the formation of stable microenvironments, moisture redistribution, and direct contact with biological surfaces.

The use of nanofibers in agriculture has expanded due to the need for materials that interact efficiently with the soil–plant–atmosphere system. Unlike conventional dense films or coatings, nanofibrous materials rely on architecture-based functionality, where spatial organization is as important as chemical composition (Greiner & Wendorff, 2007; Xue et al., 2019). Among fabrication methods, electrospinning stands out as a versatile technique capable of producing continuous fibers with submicrometric diameters, high surface area, and interconnected porosity (Ramakrishna et al., 2005; Xue et al., 2019). These features allow control over parameters such as fiber diameter, density, orientation, and mat thickness, enabling the design of microenvironments that retain moisture, regulate diffusion processes, and protect seeds and young roots (Chen et al., 2021; Greiner & Wendorff, 2007; Xue et al., 2019).

Electrospinning also allows the creation of advanced architectures such as core–shell fibers, multilayer structures, and hybrid systems, enabling multiple functions within a single fibrous network (Haider et al., 2018). In agriculture, these nanofibers have been applied in nutrient delivery systems, where release is controlled by diffusion and degradation mechanisms (Chen et al., 2021); in seed coatings, where they provide mechanical protection while facilitating water and oxygen exchange (Haider et al., 2018); and in soil applications as temporary matrices for moisture retention, surface stabilization, and microbial support (Xue et al., 2019).

Overall, electrospinning should be understood not only as an encapsulation technique but as a structural engineering platform capable of translating material architecture into agricultural functions. Its potential lies in the design of active interfaces that regulate physical, hydric, and biological processes, linking polymer science with sustainable agriculture (Chen et al., 2021; Greiner & Wendorff, 2007; Xue et al., 2019). Table 1 summarizes the main agricultural applications of electrospun nanofibers, their functions, commonly used materials, and key references, providing an integrated overview of their role as active interfaces in agricultural systems.

Table 1. Applications of electrospun nanofibers in agriculture.

Application	Function	Role of nanofibrous	Materials	References
Fertilizer and nutrient delivery	Release modulation and loss reduction	High surface area and controlled diffusion through fibrous networks	Biodegradable polymers (PLA, PCL), natural biopolymers	Chen et al. (2021); Xue et al. (2019)
Seed coating	Physical and microenvironmental protection	Semipermeable barrier, moisture and oxygen retention	Chitosan, gelatin, alginates, plant proteins	Haider et al. (2018);
Functional agricultural films and mats	Surface protection and microclimate regulation	Multilayer architectures and open fibrous networks	PLA, PBAT, PCL, polymer blends	Haider et al. (2018); Xue et al. (2019)
Support for beneficial microorganisms	Microbial immobilization and protection	Extended surface for adhesion and colonization	Chitosan, gelatin, hybrid matrices	Chen et al. (2021)

The evidence presented in Table 1 indicates that the value of electrospun nanofibers in agriculture extends beyond technical performance to their ability to integrate with social dynamics related to sustainability, equity, and productive resilience. Although nanofibrous architectures can regulate water, nutrients, and biological processes at the microscale, their real impact depends on factors such as technological access, economic feasibility, and the inclusion of small-holder farmers in innovation processes (Klerkx et al., 2012). Applications such as nutrient delivery and seed coatings can improve efficiency and early crop establishment, helping reduce production risks and increase yield stability—key aspects for food security under climate vulnerability and limited resources (Geels, 2011). However, these benefits contribute to sustainability only if technologies remain accessible, affordable, and compatible with local agricultural practices, avoiding the widening of technological gaps (Klerkx et al., 2012). Applications at the soil–plant interface and in microbial support systems align with agroecological approaches that promote soil health, reduced chemical

inputs, and long-term ecosystem stability (FAO, 2017). Their adoption, however, will depend on environmental safety perceptions, regulatory frameworks, and the governance of emerging technologies. Therefore, electrospun nanofibers should be understood as socio-technical innovations whose contribution to sustainable agriculture will depend not only on agronomic performance but also on their capacity to support resilient and inclusive agroecosystems (Geels, 2011; Klerkx et al., 2012).

Polyvinyl alcohol; a strategic material

Among the polymers used for the fabrication of nanofibers in agricultural and active packaging applications, PVA has emerged as a strategic material due to its biocompatibility, water solubility, low cost, and ease of processing in aqueous solutions. These properties allow the production of electrospun structures with a high surface-to-volume ratio suitable for controlled nutrient release, encapsulation of bioactive agents, and smart sensors for agricultural and food monitoring (Matinfar et al., 2024). In addition, its high hydrophilicity, ability to form continuous fibrous networks, and stability during electrospinning make it a widely used polymer for agricultural applications where water management and structural stability under wet conditions are essential (Karnwal et al., 2025).

From a functional perspective, PVA nanofibers enable the generation of highly hydrated microenvironments capable of retaining large amounts of water without structural collapse, particularly when combined with chemical crosslinking strategies or natural biopolymers.

Recent advances also show that incorporating PVA into composite structures improves key properties such as mechanical strength, thermal stability, and moisture resistance. Navaei et al. (2025) developed bilayer films based on electrospun PVA/gelatin containing Fe_3O_4 nanoparticles that exhibited significant improvements in water vapor barrier performance and swelling resistance. Likewise, the chemical versatility of PVA enables its combination with natural biopolymers such as chitosan, alginate, gelatin, or zein, generating biodegradable hybrid materials with antimicrobial, antioxidant, and sustained-release properties (Tadele et al., 2025).

PVA has also been integrated into nanofibers derived from plant biomass such as industrial hemp, where it acts as a fiber-forming phase and binding agent in nanocellulose-based systems, producing structures with high crystallinity, enhanced thermal resistance, and low permeability, suitable for sustainable packaging and controlled-release matrices (Górski et al., 2025). In the context of sustainable agriculture, PVA offers additional advantages including compatibility with biofertilizers, moisture retention at the soil–plant interface, and ease of electrospinning processing, facilitating the incorporation of microorganisms, enzymes, or encapsulated nutrients (Karnwal et al., 2025). Furthermore, PVA nanofibers functionalized with metallic nanoparticles or biosensors can detect pesticides, pathogens, and heavy metals, providing added value for monitoring in smart agricultural systems (Matinfar et al., 2024).

Nevertheless, the use of PVA also presents limitations, particularly its high-water solubility and the variability of its biodegradation in real soil environments, which has driven the development of blends, crosslinked systems, and hybrid architectures to improve stability. Overall, the evidence indicates that the true potential of electrospun PVA in agriculture lies not only in its role as a carrier but as an active structural platform capable of regulating water availability, protecting biological entities, and modulating interactions at the soil–plant interface, which justifies its analysis from an architectural and functional design perspective. Table 2 summarizes representative studies on the use of PVA nanofibers in agricultural, biological, and agri-food contexts, highlighting their versatility for functions such as water retention, biological protection, controlled release, and sensing in agricultural systems.

Table 2. Applications for PVA nanofiber.

Applications	Functions	Materials	References
Biomass-based functional films	Water retention, light and moisture barrier, valorization of biological residues	PVA / cellulose nanofibers / cyanobacteria	Chen et al. (2020)
Support for microorganisms or probiotics	Biological protection and maintenance of cell viability	PVA / apple pectin	Nawaz et al. (2023)
Active films reinforced with natural fibers	Improvement of mechanical and hydrophilic properties	PVA / nanocellulose	Chen et al. (2020)
Encapsulation and release platforms	Diffusion control and protection against environmental moisture	PVA and hydrophilic blends	Ramachandraiah et al. (2025)
Sustainable bilayer films	Enhancement of barrier properties and thermal stability	PVA/gelatin + Fe_3O_4 nanoparticles + plant-derived mucilage	Navaei et al. (2025)

Biodegradable hybrid nanofibers	Controlled release of bioactives with high biocompatibility	PVA blended with zein or chitosan	Tadele et al. (2025)
Hemp-based biocellulose nanofibers	Structural reinforcement and reduction of water sorption	PVA + Cannabis sativa lignocellu-losic nanofibers	Górski et al. (2025)
Electrospun sensing systems	Monitoring of agricultural and food contaminants	PVA nanofibers functionalized with metallic nanoparticles (Au/Ag)	Matinfar et al. (2024)

The evidence synthesized in Table 2 allows polyvinyl alcohol (PVA) to be understood not only as a functional polymer but as a strategic material within socio-technical transitions toward agricultural and food sustainability, contributing to food security, the reduction of production losses, and the adaptation of smallholders to climate variability (FAO, 2017; Klerkx et al., 2012). In this context, applications such as water retention, controlled release of inputs, and microbial protection act as risk-mitigation mechanisms in vulnerable agroecosystems, strengthening the productive and economic resilience of small-scale agriculture (FAO, 2017; Nawaz et al., 2023).

Complementarily, the development of biodegradable materials, hybrid nanofibers, and biomass-based systems reflects a transition toward rural circular economies, generating environmental benefits and local socioeconomic opportunities (Geels, 2011; Górski et al., 2025; Tadele et al., 2025). Likewise, electrospun PVA-based sensors expand their role into food-security governance and digital agriculture, although their social impact depends on technological accessibility, regulatory frameworks, and knowledge transfer (Klerkx et al., 20132; Matinfar et al., 2024). Nevertheless, challenges of social legitimacy persist—such as soil biodegradation, production costs, and regulatory acceptance—highlighting that technological sustainability requires institutional alignment and social inclusion (Geels, 2011). Overall, PVA nanofibers should be understood as transition platforms whose future value will depend on their integration into resilient, circular, and inclusive agri-food systems (FAO, 2017; Klerkx et al., 2012).

Social impact and socio-technical assessment of controlled-release PVA polymer in agriculture

Contemporary agriculture faces structural social challenges such as the vulnerability of smallholder farmers to climate change, unequal access to inputs, and environmental degradation caused by the intensive use of fertilizers. In this context, controlled-release systems based on PVA emerge as technologies with potential within broader processes of socio-technical innovation and socio-ecological transitions. Fertilizers encapsulated in electrospun PVA fibers improve nutrient-use efficiency and reduce losses through leaching or volatilization. For example, PVA/PLA core–shell structures enable sustained NPK release with a single application, decreasing contamination and improving production stability, particularly in small-scale agricultural systems (Nooeaid et al., 2020). However, the real impact of these technologies depends on their integration into productive systems. In this regard, biopolymers and biodegradable materials represent alternatives to petroleum-based plastics and promote new value chains based on biological resources and agro-industrial residues, linked to circular economy strategies and sustainable territorial development. The adoption of PVA-based controlled-release systems depends on factors such as regulatory frameworks, institutional capacities, knowledge transfer, and economic accessibility. Although they offer advantages such as biodegradability, biocompatibility, and functional versatility, challenges remain regarding production costs, industrial scalability, behavior in real soils, and social acceptance. Overall, these systems show high potential to improve input efficiency, reduce production risks, and decrease environmental impacts, thereby contributing to agricultural sustainability. Their future impact will depend on the articulation between material innovation, technological governance, and the social needs of agricultural systems (Nooeaid et al., 2020).

Trends in agricultural applications of nanofiber

The analysis of the 170 selected articles allowed their classification into six main application areas: seed coatings, food industry applications (coatings and packaging), essential oil encapsulation, fabrication of novel agricultural materials, controlled-release systems for nutrients or fertilizers, and sensor development. Studies addressing isolated applications, such as water treatment using agricultural residues, were grouped under the "others" category.

The results show (Figure 3a) that most studies focus on packaging and coating materials for food applications, representing 41.18% of the publications. This is followed by research on essential oil encapsulation (21.18%) and the fabrication of novel materials (18.82%). In terms of temporal distribution, the largest number of publications appeared in 2025 (Figure 3b), accounting for about 41% of the analyzed studies. Since 2023, interest in nanofiber applications in agriculture has steadily increased, indicating the consolidation of this research field. In contrast, applications related to agricultural sensing and controlled nutrient release remain the least represented, likely due to higher technical complexity, the need for field validation, and regulatory barriers. However, during 2025 these areas began to show initial growth, suggesting strong potential for future sustainable agricultural technologies.

Overall, these trends indicate that nanofiber-based technologies in agriculture are moving from an exploratory stage toward more application-oriented and system-integrated solutions. Although applications related to the food industry currently dominate due to their greater technological maturity and closer industrial alignment, the growing interest observed since 2023 shows a broadening of the research focus. Emerging areas such as controlled nutrient release and agricultural sensing, although still less represented, are gaining momentum and are expected to play a key role in future developments. As technical challenges, field validation, and regulatory aspects are progressively addressed, nanofibers are likely to become fundamental platforms for the development of sustainable, efficient, and precision-based agricultural.
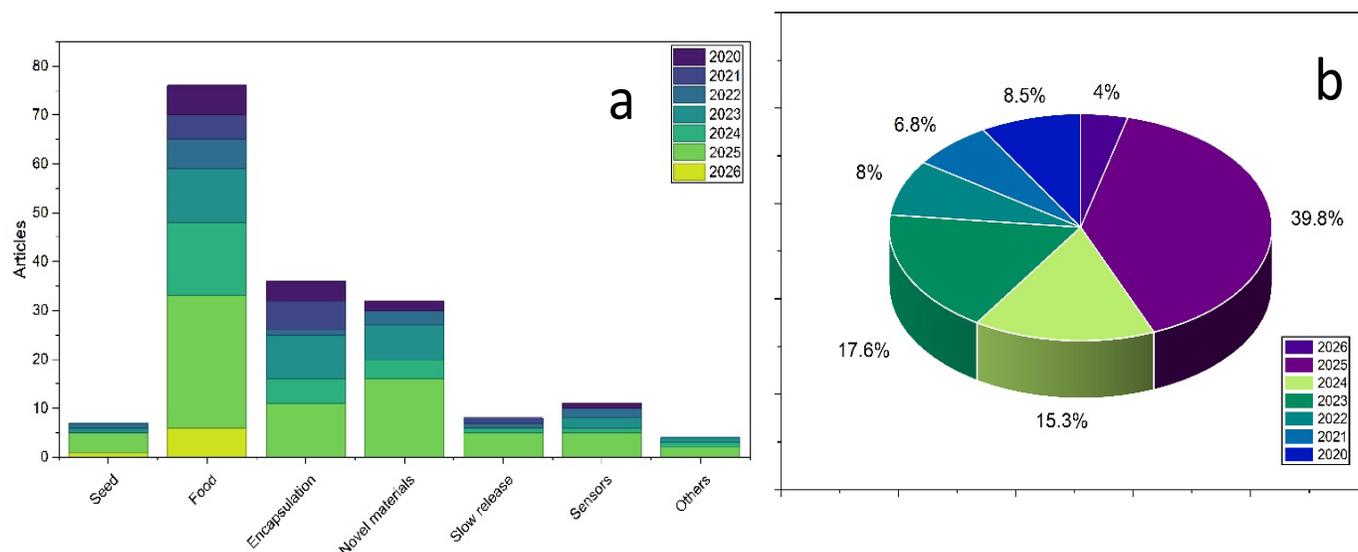
Fig 3. a) Evolution of research topics by year b) Percentage of publications on nanofiber in agriculture by year.

CONCLUSIONS

This review presents an architecture-oriented analysis of PVA-based materials in agricultural applications, moving beyond a nutrient-delivery perspective to examine how material structure and interfacial design influence functionality at the soil–root–microorganism interface. Through a systematic and bibliometric evaluation of 170 studies, the results show that nanofibrous systems are increasingly considered active interfacial platforms rather than passive carriers. Although much research still focuses on food-related coatings and packaging, interest has expanded rapidly since 2023 toward applications involving deeper interactions with biological and environmental processes.

Within this framework, fibrous architectures offer high surface area, interconnected porosity, and effective moisture regulation, helping stabilize microenvironments during germination and early plant establishment. These characteristics position electrospun nanofibers as promising platforms for regulating hydric, gaseous, and biological exchanges in agroecosystems. Polyvinyl alcohol stands out as a versatile polymer due to its biocompatibility, hydrophilicity, processability, and compatibility with blends and hybrid systems capable of supporting bioactive delivery, microbial protection, and sensing functions relevant to sustainable and precision agriculture. However, limitations related to water solubility, degradation dynamics, field validation, and regulatory uncertainty highlight the importance of architectural and composite design in translating laboratory performance into real agricultural functionality.

The identification of controlled nutrient release and agricultural sensing as emerging yet underexplored areas suggests that future research will likely move from material development toward system integration and field-scale validation. Consequently, the significance of PVA-based nanofibrous systems must be interpreted not only through physicochemical efficiency but also within broader socio-technical contexts that influence accessibility, governance, environmental acceptance, and adoption by different farming systems. Overall, this review proposes an architecture-centered framework linking polymer science with agroecosystem performance while incorporating a socio-technical perspective. From this integrated view, next-generation nanofibrous materials should be evaluated by their capacity to enhance efficiency, sustainability, and resilience while supporting inclusive agricultural development. The future impact of

electrospun PVA systems will depend on their ability to function both as advanced material interfaces and as technologies integrated into real agricultural systems

REFERENCES

Akram, N., Afzaal, M., Saeed, F., Ahmad, A., Imran, A., Ahmed, A., Shah, Y. A., Islam, F., Alomar, S. Y., Manoharadas, S., & Nawaz, A. (2023). Fabrication and characterization of PVA–WPI based nanofiber mats for improved viability of *Lactobacillus rhamnosus* GG. *Foods, 12*(21), 3904. https://doi.org/10.3390/foods12213904

Chen, S., Liu, D., Qian, M., Xu, L., Li, Y., Sun, H., Wang, X., Zhou, H., Bao, J., & Xu, C. (2020). Preparation of cyanobacteria-enhanced poly(vinyl alcohol)-based films with resistance to blue-violet light/red light and water. *PLOS ONE, 15*(2), e0228814. https://doi.org/10.1371/journal.pone.0228814

FAO. (2017). *The future of food and agriculture: Trends and challenges*. Food and Agriculture Organization of the United Nations.

Geels, F. W. (2011). The multi-level perspective on sustainability transitions: Responses to seven criticisms. *Environmental Innovation and Societal Transitions, 1*(1), 24–40. https://doi.org/10.1016/j.eist.2011.02.002

Górski, K., Kowalczyk, T., Gładys, A., Muskała, M., Picot, L., & Sitarek, P. (2025). Industrial applications of *Cannabis sativa* L.: Exploring its biological and nanotechnological potential. *Industrial Crops and Products, 225*, 120566. https://doi.org/10.1016/j.indcrop.2025.120566

Greiner, A., & Wendorff, J. H. (2007). Electrospinning: A fascinating method for the preparation of ultrathin fibers. *Angewandte Chemie International Edition, 46*(30), 5670–5703. https://doi.org/10.1002/anie.200604646

Haider, A., Haider, S., & Kang, I. K. (2018). A comprehensive review summarizing the effect of electrospinning parameters and potential applications of nanofibers in biomedical and agricultural fields. *Arabian Journal of Chemistry, 11*(8), 1165–1188. https://doi.org/10.1016/j.arabjc.2015.11.015

Karnwal, A., Rauf, A., Jassim, A. Y., Selvaraj, M., Al-Tawaha, A. R. M. S., Kashyap, P., Kumar, D., & Malik, T. (2025). Advanced starch-based films for food packaging: Innovations in sustainability and functional properties. *Food Chemistry: X, 29*, 102662. https://doi.org/10.1016/j.fochx.2025.102662

Klerkx, L., van Mierlo, B., & Leeuwis, C. (2012). Evolution of systems approaches to agricultural innovation: Concepts, analysis and interventions. En *Farming Systems Research into the 21st Century: The New Dynamic* (pp. 457–483). Springer. https://doi.org/10.1007/978-94-007-4503-2_20

Li, R., Mei, X., Jin, W., Yang, Z., Liu, Y., Li, Z., Xu, X., & Wang, P. (2025). Perfect balance between the water absorption and mechanical properties of carboxymethyl cellulose/polyvinyl alcohol electrospun nanofibre pads through citric acid cross-linking. *Food Production, Processing and Nutrition, 7*, 62. https://doi.org/10.1186/s43014-025-00341-0

Makhado, E., Seleka, W. M., Glory, L. M., Selowa, K., Abu Elella, M. H., Botlhoko, O. J., & Hato, M. J. (2025). Comparative extraction and characterization of cellulose nanostructures from agricultural biomass sources. *International Journal of Biological Macromolecules, 329*, 147842. https://doi.org/10.1016/j.ijbiomac.2025.147842

Matinfar, G., Ye, H., Bashiry, M., Hashami, Z., & Yang, T. (2024). Electrospinning-based sensing technologies: Opportunities for food applications. *Comprehensive Reviews in Food Science and Food Safety, 23*, e13415. https://doi.org/10.1111/1541-4337.13415

Navaei, F., Zandi, M., Ganjloo, A., & Dardmeh, N. (2025). Fabrication of magnetic nanoparticle-enhanced bi-layer films: Fe_3O_4-loaded electrospun PVA/gelatin nanofibers on a balangu seed mucilage–gelatin base. *Industrial Crops & Products, 229*, 121037. https://doi.org/10.1016/j.indcrop.2025.121037

Nawaz, A., Irshad, S., Walayat, N., Khan, M. R., Iqbal, M. W., & Luo, X. (2023). *Fabrication and characterization of apple-pectin–PVA-based nanofibers for improved viability of probiotics*. Foods, 12, 3194. https://doi.org/10.3390/foods12173194

Nooeaid, P., Chuysinuan, P., Pitakdantham, W., Aryuwananon, D., Techasakul, S., & Dechtrirat, D. (2020). Eco-friendly polyvinyl alcohol/polylactic acid core/shell structured fibers as controlled-release fertilizers for sustainable agriculture. *Journal of Polymers and the Environment*. https://link.springer.com/article/10.1007/s10924-020-01902-9

Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., … Moher, D. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ, 372*, n71. https://doi.org/10.1136/bmj.n71

Ramachandraiah, K., Martin, E. M., & Limayem, A. (2025). Nanofiber-enabled rapid and non-destructive sensors for meat quality and shelf-life monitoring: A review. *Foods, 14*(22), 3842. https://doi.org/10.3390/foods14223842

Ramakrishna, S., Fujihara, K., Teo, W. E., Lim, T. C., & Ma, Z. (2005). *An introduction to electrospinning and nanofibers*. World Scientific Publishing.

Tadele, D. T., Islam, M. S., & Mekonnen, T. H. (2025). Zein-based nanoparticles and nanofibers: Structure–function relationships and applications in food and agriculture. *Trends in Food Science & Technology, 155*, 104809. https://doi.org/10.1016/j.tifs.2024.104809

Xue, J., Jiang, L., Qin, R., Liu, T., Li, H., & Wang, H. (2025). Chitin nanofiber–reinforced chitosan aerogels for smart food packaging applications. *LWT – Food Science and Technology, 233*, 118542. https://doi.org/10.1016/j.lwt.2025.118542

Xue, J., Wu, T., Dai, Y., & Xia, Y. (2019). Electrospinning and electrospun nanofibers: Methods, materials, and applications. *Chemical Reviews, 119*(8), 5298–5415. https://doi.org/10.1021/acs.chemrev.8b00593

Conflict of interest Authors declare that there is no conflict of interest.

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