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Review Paper

Sustainable nanofiber-based strategies for improving quality and safety in meat systems

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A B S T R A C T

Nanofiber technology has emerged as a sustainable strategy to improve the quality and safety of meat systems. With their high surface area, tunable porosity, and encapsulation efficiency, nanofibers enable applications in active packaging, intelligent sensing, and functional reformulation. Biopolymer-based nanofiber films, particularly from plant (pea and mungbean) proteins, enhance oxygen and moisture barriers, extend shelf life, and provide mechanical stability. When combined with natural antimicrobials or antioxidants, they allow controlled release systems that reduce microbial growth and lipid oxidation without compromising sensory attributes. Moreover, intelligent nanofiber packaging contributes to real-time spoilage detection, while functional reformulation supports phosphate and nitrite replacement. Recent advances highlight protein isolates as promising materials for nanofiber production, aligning with sustainability and circular economy principles. Although challenges remain in scalability, cost, and regulatory approval, nanofibers represent a versatile platform for developing clean-label and eco-friendly meat systems.

1. Introduction

Meat and meat products are highly perishable due to their nutrient-rich composition, high water activity, and vulnerability to microbial spoilage and oxidative deterioration. These factors not only shorten shelf life but also compromise quality and safety. Conventional preservation methods rely heavily on synthetic additives such as phosphates, nitrites, and antioxidants, which have been effective but are increasingly criticized due to potential health risks and rising consumer demand for clean-label and sustainable alternatives. In parallel, concerns over non-biodegradable packaging materials further drive the search for innovative and eco-friendly solutions (*Mills*, 2014; *Amna et al.*, 2015).

Nanofiber technology has emerged as a promising strategy to address these challenges. Owing to their high surface-to-volume ratio, tunable porosity, and ability to encapsulate and release bioactive compounds in a controlled manner, nanofibers enable multifunctional applications in meat systems (*Lim*, 2017). They have been shown to enhance oxidative stability, inhibit microbial growth, improve texture, and extend shelf life, while also serving as carriers for natural antimicrobials and antioxidants (*Arkoun et al.*, 2017; *Liu et al.*, 2022). In addition, nanofiber-based films can improve barrier properties of packaging, function as freshness indicators, and contribute to the reformulation of low-additive meat products (*Jiang et al.*, 2024).

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From a sustainability perspective, the utilization of renewable biopolymers, such as proteins and polysaccharides, in nanofiber production reduces reliance on fossil-derived polymers and aligns with consumer expectations for environmentally friendly processing. Collectively, these advances highlight nanofibers as versatile tools capable of simultaneously improving quality, safety, and sustainability in modern meat systems.

2. Production strategies for nanofibers

Nanofibers can be produced by various methods, such as phase separation, ball-milling, homogenization, self-assembly, freeze-drying, electrospinning, and other spinning techniques, including air and force spinning (*Henriksson et al*., 2007; *Piras et al*., 2019; *Delgado-Aguilar et al.*, 2015). Electrospinning remains the most versatile and extensively applied technique in food systems. Applying a high-voltage electric field to polymer solutions or melts generates ultrafine fibers with high surface area and interconnected pore structures (*Ji et al*., 2024). Electrospinning enables precise control over fiber morphology and the incorporation of bioactive compounds, such as antioxidants, antimicrobials, and colorants. Advanced variants—including coaxial, needleless, and multi-jet electrospinning—enhance encapsulation efficiency and scalability, though equipment cost and throughput remain challenges (*Zahmatkeshan et al*., 2019; *Sofi et al*., 2020). Other strategies, such as self-assembly, interfacial polymerization, and freeze-drying, offer opportunities for designing functional nanostructures, but are less established for food applications due to technical and economic constraints (*Wei et al*., 2012). Overall, mechanical methods are advantageous for bulk nanofiber production, whereas electrospinning provides unmatched versatility for developing functional nanofibers tailored for preservation, active packaging, and reformulation of meat products (*Jiang et al*., 2014).

3. Functional applications in meat systems

3.1 Control of lipid oxidation

Lipid oxidation is one of the most critical factors leading to meat quality deterioration, resulting in rancidity, discoloration, and nutrient loss (*Serdaroğlu et al*., 2024). Nanofiber-based systems can effectively encapsulate and gradually release natural antioxidants, thereby prolonging oxidative stability during storage (*Ansarifar et al*., 2022). Electrospun nanofibers loaded with compounds, such as α-tocopherol, polyphenols, and essential oils, have demonstrated significant reductions in thiobarbituric acid reactive substance (TBARS) and peroxide values in beef, chicken, and fish products (*Aytac et al*., 2017; *Khaledian et al*., 2019; *Lin et al*., 2019). In addition, the intrinsic antioxidant potential of whey protein isolate-based nanofibers further supports their potential as clean-label strategies to delay oxidative rancidity (*Carvalho et al*., 2018).

3.2 Antimicrobial effects

Microbial spoilage remains a major concern for meat safety and shelf life. Nanofibers incorporated with antimicrobial agents—including essential oils, organic acids, polyphenols, or bacteriocins—exhibit strong inhibitory effects against foodborne pathogens, such as *E. coli, Salmonella* spp., and *Listeria monocytogenes*. Electrospinning allows efficient encapsulation of these compounds, preventing premature volatilization or deactivation and ensuring sustained release during storage. Chitosan- and gelatin-based nanofibers, in particular, have been shown to extend the microbial stability of fresh meat and poultry products while maintaining sensory attributes (*Arkoun et al*., 2017; *Lin et al*., 2018b; *Liu et al*., 2022).

3.3 Functional reformulation and additive replacement

Beyond preservation, nanofibers contribute to the functional reformulation of meat products by improving water-holding capacity, emulsification, and textural properties (*Jiang et al*., 2024). This makes them attractive as natural alternatives to conventional additives such as phosphates and nitrites. For instance, nanofibers incorporating cinnamic aldehyde, thyme oil, and plant or animal protein sources have shown potential to replace nitrites while maintaining color and microbial safety (*Aytac et al*., 2017; *Ceylan et al*., 2022; *Dogan et al*., 2022). Recent studies investigating nanofiber-based applications in meat systems are summarized in Table 1.

3.4 Sensory quality and consumer acceptance

The integration of nanofibers into meat systems should not compromise sensory quality. Studies indicate that antioxidant- and antimicrobial-loaded nanofibers enhance juiciness, preserve color stability, and reduce off-flavors associated with lipid oxidation (*Dogan et al*., 2022; *Yilmaz et al*., 2022). Moreover, the use of biopolymer-based nanofibers aligns with consumer expectations for sustainability, naturality, and clean-label production, thereby improving market acceptance (*Jiang et al*., 2014).

Table 1. Applications of Nanofiber-Based Systems in Meat Products

Nanofiber Type	Active Components/ Biological Activity	Meat Product	Findings	References
Chitosan and Poly(ethylene oxide) Nanofibers	Chitosan	Fresh beef slices	Increased bioavailability of chitosan; antibacterial effects against *E. coli*, *L. innocua*, *S. aureus*, and *S.* Typhimurium	*Arkoun et al*. (2017)
Gelatin, Chitosan, and 3-Phenyllactic Acid (GCP) Nanofibers	Chitosan and PLA	Chicken breast	Controlled release of antibacterial agents; enhanced antibacterial effect against *Staphylococcus aureus* and *Escherichia coli*	*Liu et al.* (2022)
Gelatin, Glycerin, and ε-Polylysine Nanofiber-Coated Wraps	ε-Polylysine	Beef	Improved mechanical properties; antibacterial effect against *Listeria monocytogenes*	*Lin et al.* (2018a)
ε-PL and Chitosan Electrospun Nanofibers	ε-PL, Chitosan	Fresh chicken slices	Reduced growth of *S.* Typhimurium and *S. enteritidis*; use of nanofiber-coated aluminum foil	*Lin et al.* (2018b)
Polyurethane Nanofibers	Olive oil (VOO) and zinc oxide (ZnO)	Fresh meat	Inhibition of *Staphylococcus aureus* and *Salmonella*; potential replacement for PVC film	*Anma et al*. (2015)
Chitosan Nanofibers	Tea tree oil	Chicken meat	Increased bioavailability and sustained release; enhanced antibacterial effect against *Salmonella*	*Cui et al*. (2018)
Glycyrrhiza Polysaccharide Nanofibers	Tea tree oil, encapsulated with gliadin nanoparticles	Chicken and pork meat	Efficient encapsulation and release of tea tree oil; reduction of *Salmonella* Typhimurium	*Cai et al*. (2021)
PVA Nanofibers	Black seed oil and curcumin	Salmon fillet	Sous vide (SV) cooking with nanofiber-coated fillet; reduced bacterial growth (TMAB and TPB), lowered TBA values	*Ceylan et al*. (2022)
Chitosan Nanofibers	Chrysanthemum essential oil	Fresh beef slices	Slow release of essential oil; long-term antibacterial effects; reduced TBARS values	*Lin et al*. (2019)
Polyvinylpyrrolidone Nanofibers	Lavender essential oil	Minced meat	Slow release of essential oil; reduction of aerobic mesophilic bacteria, psychrotrophic bacteria, yeast, and molds	*Dogan et al*. (2022)
Gelatin Nanofibers	Eugenol	Beef samples	Reduced bacterial growth (TMAB and TPB) and TBA; improved organoleptic and textural properties	*Yilmaz et al*. (2022)
Chitosan Nanofibers	Liquid smoke	Sea bass fillet	Slow and sustained release of liquid smoke; reduction of TPB, YM, and TMAB	*Ceylan et al*. (2017)
Cellulose Nanofibers	Ginger essential oil and stearic acid	Ready-to-cook chicken meat	Reduced growth of lactic acid bacteria, psychrotrophic bacteria, yeast, and molds; lowered peroxide values	*Khaledian et al*. (2019)
PLA Nanofibers	α-Tocopherol and cyclodextrin complex	Beef samples	Improved solubility and preservation of α-TC; reduced TBARS values	*Aytac et al*. (2017)
Cellulose Nanofibers	Anthocyanin	Meat and fish	Increased hydration peroxide RSA	*Hazarika et al*. (2023)

4. Conclusion

Nanofiber technology represents a sustainable and multifunctional approach for enhancing the quality and safety of meat systems. By enabling controlled release of natural antimicrobials and antioxidants, nanofibers can effectively reduce microbial growth, delay lipid oxidation, and maintain desirable sensory properties. Their application extends beyond preservation, providing opportunities for functional reformulation, such as phosphate and nitrite replacement, in line with clean-label expectations. Moreover, the utilization of plant-derived proteins for nanofiber production aligns with sustainability goals and circular economy principles. Despite existing challenges related to large-scale production, cost-efficiency, and regulatory frameworks, nanofibers offer significant potential as next-generation solutions that integrate active, intelligent, and eco-friendly functions into meat systems. Their future adoption in industrial practice will contribute to healthier, safer, and more sustainable meat products.

5. Future perspectives

Although nanofiber technologies are highly promising for meat preservation and reformulation, several barriers hinder their large-scale adoption. Key challenges include scaling up electrospinning processes, managing production costs, and ensuring compliance with food safety regulations. Future research should prioritize the development of multifunctional nanofibers with combined antioxidant, antimicrobial, and sensing capabilities, enabling both protection and real-time monitoring of meat quality and safety. Furthermore, the utilization of renewable biopolymers, such as plant-derived proteins and polysaccharides, not only supports sustainability, but also adds value to agricultural by-products, aligning with clean-label and circular economy principles (*Singh et al*., 2023).

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