

NONWOVEN COVERS FOR AGRICULTURAL APPLICATIONS: MATERIALS ENGINEERING, FUNCTIONAL PERFORMANCE, AND SUSTAINABLE TRANSITION

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Abstract: Nonwoven materials have become indispensable in modern agriculture due to their structural versatility, cost-effectiveness, and multifunctional performance. This review provides a comprehensive analysis of nonwoven covers used in agricultural applications, including row covers, mulch fabrics, frost protection systems, and greenhouse shading materials. The relationship between fiber composition, manufacturing technology, and functional performance is critically examined, with emphasis on air and water permeability, thermal insulation, light transmission, and mechanical durability. Conventional petroleum-based nonwovens, predominantly polypropylene, continue to dominate the market; however, increasing environmental concerns related to plastic accumulation and microplastic formation have accelerated the development of biodegradable and bio-based alternatives such as polylactic acid, cellulose-based fibers, and natural fiber composites. The review further explores emerging innovations, including functional coatings, smart nonwovens with sensing capabilities, and AI-assisted structural optimization. Finally, current challenges and future directions are discussed within the framework of sustainable agriculture and circular economy principles. The integration of advanced material design with environmental responsibility positions nonwoven agricultural covers as a key enabling technology for next-generation farming systems.

Keywords: nonwoven agricultural covers, crop protection textiles, structure-property relationships, thermal and optical performance, biodegradable nonwoven, sustainable agriculture.

NETKANI POKRIVNI MATERIJALI ZA POLJOPRIVREDNE PRIMENE: INŽENJERSTVO MATERIJALA, FUNKCIONALNA SVOJSTVA I ODRŽIVA TRANZICIJA

Apstrakt: Netkani materijali postali su nezamenljivi u savremenoj poljoprivredi zahvaljujući svojoj strukturalnoj svestranosti, isplativosti i multifunkcionalnim performansama. Ovaj pregledni rad pruža sveobuhvatnu analizu netkanih pokrivki koje se koriste u poljoprivrednim primenama, uključujući pokrivače za redove, malč tkanine, sisteme za zaštitu od mraza i materijale za zasenjivanje plastenika. Kritički se razmatra odnos između sastava vlakana, tehnologije proizvodnje i funkcionalnih svojstava, sa posebnim naglaskom na propusnost za vazduh i vodu, toplotnu izolaciju, propusnost svetlosti i mehaničku izdržljivost. Konvencionalni netkani materijali na bazi nafte, pretežno polipropilen, i dalje dominiraju tržištem; međutim, sve veća zabrinutost za životnu sredinu u vezi sa akumulacijom plastike i stvaranjem mikroplastike ubrzala je razvoj biorazgradivih i bio-baziranih alternativa, kao što su polilaktična kiselina, celulozna vlakna i kompoziti od prirodnih vlakana. Rad dalje

razmatra nove inovacije, uključujući funkcionalne premaze, pametne netkane materijale sa senzorskim mogućnostima i optimizaciju strukture uz pomoć veštačke inteligencije. Na kraju, aktuelni izazovi i budući pravci razvoja razmatraju se u okviru principa održive poljoprivrede i cirkularne ekonomije. Integracija naprednog dizajna materijala sa odgovornošću prema životnoj sredini pozicionira netkane poljoprivredne pokrivke kao ključnu tehnologiju za poljoprivredne sisteme naredne generacije.

Ključne reči: netkane poljoprivredne pokrivke, tekstili za zaštitu useva, odnosi struktura–svojstva, toplotne i optičke performanse, biorazgradivi netkani materijali, održiva poljoprivreda.

1. INTRODUCTION

The global transition toward sustainable and climate-resilient agricultural systems has intensified the demand for advanced materials capable of enhancing crop productivity while minimizing environmental impact [1-3]. Among available solutions, textile-based materials—particularly nonwovens—have emerged as highly adaptable and efficient tools for modern agriculture [4]. Unlike conventional woven and knitted textiles, nonwoven materials are engineered through controlled fiber bonding, enabling precise manipulation of structural parameters such as porosity, fiber diameter, thickness, and surface morphology. This structural tunability allows the design of application-specific functional properties, positioning nonwovens as key materials for agricultural cover systems.

Nonwoven covers are widely used across diverse agricultural applications, including row covers for frost protection and pest exclusion, mulch fabrics for weed suppression and soil moisture conservation, and shading materials for greenhouse environments [5]. Their multifunctionality arises from the ability to simultaneously regulate heat transfer, air and water permeability, and light transmission—properties that directly influence plant growth, crop yield, and resource efficiency [6]. Compared to conventional polyethylene films, nonwoven materials offer enhanced breathability, reduced condensation, and improved adaptability to fluctuating environmental conditions, making them particularly suitable for precision and sustainable agriculture [7].

Despite their widespread use, the performance of nonwoven agricultural covers is governed by complex interdependencies between material structure, functional behavior, and environmental conditions. Experimental studies show that parameters such as basis weight, pore size distribution, and fiber orientation play a decisive role in determining thermal insulation, optical characteristics, and mechanical durability. However, these properties cannot be optimized independently. Increasing basis weight improves thermal protection and mechanical strength but of-

ten reduces light transmission and air permeability, while enhancing durability through UV stabilization may compromise biodegradability. These inherent trade-offs highlight the need for a more integrated understanding of structure–property–performance relationships in nonwoven systems [8].

In parallel, growing concerns regarding plastic waste accumulation and microplastic pollution have accelerated the development of biodegradable and bio-based nonwoven materials, including polylactic acid (PLA), regenerated cellulose, and natural fiber-based systems [9,10]. Although these materials offer promising sustainable alternatives, their performance under real agricultural conditions remains insufficiently understood, particularly in terms of durability, degradation kinetics, and functional stability. Furthermore, the lack of standardized testing methodologies for evaluating thermal, optical, and environmental performance limits comparability across studies and hinders the establishment of universal design principles [11].

Within this context, the present review provides a comprehensive and critical synthesis of current research on nonwoven agricultural covers, focusing on the relationships between material structure, functional properties, and environmental performance. It systematically examines permeability, thermal insulation, optical behavior, mechanical durability, and barrier functionality, integrating experimental findings through comparative and meta-analysis-style evaluation. Particular emphasis is placed on identifying trade-offs and interdependencies that govern performance, as well as assessing the potential of biodegradable alternatives. Additionally, the review highlights key knowledge gaps, including the absence of standardized testing protocols and the limited application of multi-objective design strategies. Future directions emphasize advanced material engineering, functional surface modifications, and data-driven optimization, including the integration of smart functionalities and digital tools [12].

2. TYPES OF NONWOVEN COVERS IN AGRICULTURE

Nonwoven agricultural covers represent a versatile class of engineered materials designed to enhance crop protection and optimize microclimatic conditions in both open-field and controlled-environment agriculture. Their functionality arises from a combination of structural parameters, including porosity, fiber diameter, basis weight, and thickness, which collectively govern heat transfer, air and water permeability, and light transmission. These properties allow nonwoven materials to simultaneously act as protective barriers and environmental regulators, distinguishing them from conventional impermeable plastic films [13,14]. Depending on the specific agricultural application, nonwoven covers are generally categorized into row covers, mulch fabrics, frost protection covers, and shading or greenhouse systems.

2.1. Row Covers

Row covers are lightweight, permeable nonwoven fabrics placed directly over crops to create a controlled microenvironment that promotes plant growth and protection. Typically produced from spunbond polypropylene, these materials combine low density with high porosity, enabling efficient transmission of air, water, and light while providing a physical barrier against pests and environmental stressors. As shown in Figure 1, row covers are applied directly over crops in floating systems, forming a protective layer that modifies the local microclimate. Experimental studies indicate that row covers transmit approximately 70–90% of incident solar radiation and can increase near-surface temperatures by 1–3 °C, which is particularly beneficial for early-season cultivation and frost-sensitive crops [15]. Their breathable structure reduces condensation and excessive humid-

ity, thereby minimizing fungal disease development. In addition, row covers significantly reduce insect infestation by acting as a physical barrier, contributing to decreased pesticide use and improved crop quality [16]. However, the performance of row covers is strongly influenced by structural design. Increasing basis weight enhances thermal insulation and mechanical resistance but may reduce light transmission and airflow. Therefore, optimization of fiber structure and porosity is essential to balance protection and growth conditions [17].

2.2. Mulch Nonwoven Fabrics

Mulch nonwoven fabrics are applied directly to the soil surface to regulate soil conditions, suppress weeds, and improve crop productivity. As illustrated in Figure 2, these materials form a continuous layer over the soil, effectively blocking sunlight while allowing water infiltration and air exchange. The primary function of mulch nonwovens is weed suppression, achieved by limiting light availability for weed germination. Studies report suppression efficiencies exceeding 85–95%, depending on material opacity and thickness [18]. Additionally, these materials significantly improve soil moisture retention by reducing evaporation, which is particularly advantageous in water-scarce environments. Unlike polyethylene films, nonwoven mulches allow water penetration, preventing surface runoff and promoting soil aeration [19]. Thermally, mulch nonwovens contribute to stabilization of root-zone temperature, reducing extreme fluctuations between day and night. This leads to improved root development and overall plant growth. However, long-term environmental concerns related to synthetic polymer accumulation and microplastic formation remain significant, driving research toward biodegradable alternatives [20].



Figure 1: Nonwoven row covers applied directly over crops, illustrating floating cover systems, pest protection and microclimate modification in agricultural fields.



Figure 2: Application of nonwoven mulch fabrics for weed suppression and soil moisture conservation, showing ground coverage and crop growth improvement.

2.3. Frost Protection Covers

Frost protection covers are specialized nonwoven materials designed to protect crops from low-temperature stress by reducing heat loss and maintaining a stable microclimate. As shown in Figure 3, these covers are used to shield crops during cold periods, forming an insulating layer that traps air within the fibrous structure. The insulating performance of frost covers is primarily governed by air entrapment within the porous structure, which reduces convective and radiative heat loss. This mechanism allows for measurable increases in plant-level temperature and effective frost protection [21].

The effectiveness of these materials depends on parameters such as basis weight, thickness, and fiber arrangement, as well as external factors including wind speed and humidity. Field studies demonstrate that frost protection covers can significantly reduce

crop damage in sensitive plants such as vegetables and fruit crops, particularly during early growth stages. However, excessive material density may limit light transmission, and prolonged exposure to UV radiation can lead to degradation, reducing long-term performance.

2.4. Shade and Greenhouse Covers

Nonwoven shading and greenhouse covers play a critical role in controlled-environment agriculture by regulating solar radiation and optimizing plant growth conditions. As illustrated in Figure 4, these materials are used to diffuse incoming light and reduce thermal stress within greenhouse systems. These materials are engineered to provide light diffusion, which enhances the distribution of photosynthetically active radiation within the plant canopy and improves photosynthetic efficiency [22]. At the same



Figure 3: Nonwoven frost protection covers used in agriculture, demonstrating insulation effects and protection of crops under low-temperature conditions.

time, they reduce excessive solar heating, preventing thermal stress and maintaining optimal growth conditions. The breathable structure of nonwoven shading covers facilitates air circulation and heat dissipation, unlike impermeable plastic materials. Advanced nonwoven systems may also incorporate UV-protective properties, increasing durability and providing additional crop protection. As greenhouse technologies advance, such materials are increasingly integrated into climate-control systems for sustainable agricultural production [23].

high flexibility allow good conformity to plant surfaces, while its barrier properties contribute to moisture retention. However, like PP and PET, PE is non-biodegradable and contributes to long-term environmental accumulation. Despite their technical advantages, polymer-based nonwovens present environmental challenges, particularly related to plastic waste persistence and recycling limitations. Therefore, ongoing research focuses on improving recyclability and reducing environmental impact while maintaining performance characteristics [26].

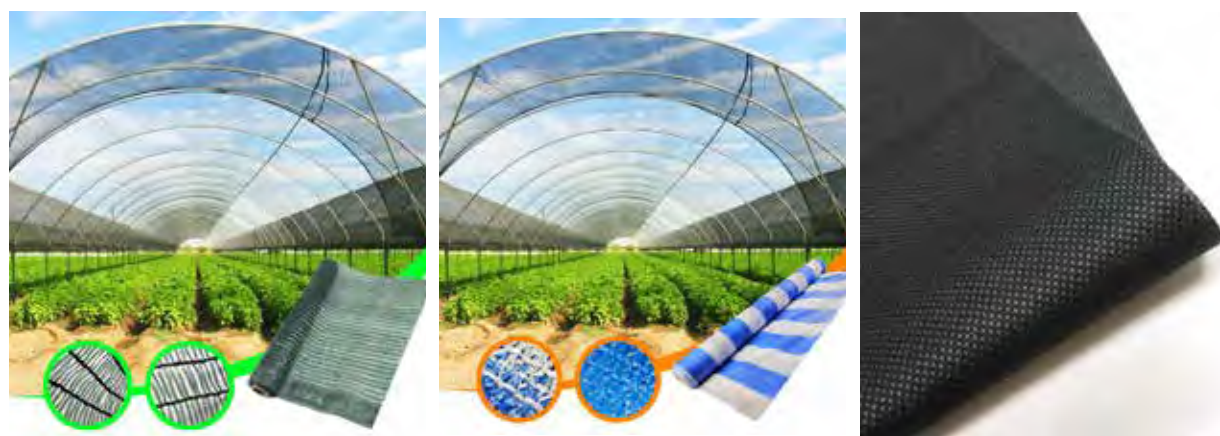


Figure 4: Nonwoven shading and greenhouse covers illustrating light diffusion, temperature control, and improved crop uniformity in controlled-environment agriculture.

3. MATERIALS AND MANUFACTURING TECHNOLOGIES

3.1. Polymer-Based Nonwovens

Polymer-based nonwoven materials dominate agricultural applications due to their favorable balance between cost, performance, and processability. Among these, polypropylene (PP) is the most widely used polymer, particularly in spunbond nonwoven covers, owing to its low density, chemical resistance, and ease of processing. PP fibers exhibit hydrophobic behavior and good resistance to environmental conditions, making them suitable for crop protection applications such as row covers and mulch fabrics [24].

Polyester (PET) is also utilized where higher mechanical strength and dimensional stability are required. Compared to PP, PET-based nonwovens demonstrate improved tensile properties and resistance to thermal and UV degradation, which enhances their durability in outdoor conditions. However, the higher cost and density of PET limit its use in disposable agricultural products [25].

Polyethylene (PE) is applied in flexible and moisture-resistant nonwoven systems. Its low stiffness and

3.2. Biodegradable and Bio-Based Nonwovens

The environmental concerns associated with synthetic polymer accumulation have led to increased interest in biodegradable and bio-based nonwoven materials for agricultural applications. Polylactic acid (PLA) is one of the most extensively studied biodegradable polymers, derived from renewable resources such as corn starch. PLA-based nonwovens offer the advantage of biodegradability under controlled composting conditions while maintaining sufficient mechanical strength for short-term use. However, their performance is sensitive to environmental factors such as temperature and moisture, which can affect degradation rates [27].

Cellulose-based fibers, including viscose and lyocell, represent another important class of biodegradable materials. These fibers exhibit high moisture absorption capacity and natural compatibility with soil environments, enabling gradual degradation without harmful residues. Their hydrophilic nature also enhances water distribution in soil-cover applications, contributing to improved plant growth conditions.

Natural fibers, conventional (such as jute, hemp, and flax) and unconventional (such as banana, corn husk, sisal), are increasingly incorporated into nonwoven structures due to their renewability and low environmental impact [28]. These fibers can improve soil organic matter after degradation, supporting circular agricultural systems. However, variability in fiber quality and lower durability compared to synthetic polymers remain key limitations. The main challenge in biodegradable nonwoven development is achieving a balance between functional stability during use and controlled degradation after disposal, which is essential for practical agricultural applications.

3.3. Production Technologies

The manufacturing technology used in nonwoven production plays a critical role in determining structural characteristics and functional performance. Among the available techniques, spunbond technology is the most widely used for agricultural applications. In this process, continuous filaments are extruded, stretched, and thermally bonded to form a uniform web. Spunbond nonwovens exhibit relatively large fiber diameters, high mechanical strength, and good air permeability, making them suitable for row covers and protective applications [29]. Figure 5a-c illustrates the main production routes for nonwoven agricultural covers, highlighting the differences between spunbond, meltblown, and needle punching

technologies, as well as their structure–property–application relationships.

The meltblown process produces nonwoven materials with significantly finer fibers, typically in the micrometer or submicron range. This results in high surface area and small pore sizes, which are advantageous for controlling airflow and filtration. Although meltblown nonwovens are primarily used in filtration, their structural properties can be adapted for specialized agricultural applications requiring barrier functionality.

Needle punching is a mechanical bonding technique used to produce thicker and more robust nonwoven fabrics. The entanglement of fibers through barbed needles creates materials with high bulk, durability, and resistance to mechanical stress, making them particularly suitable for mulch applications. However, these materials tend to have less uniform pore distribution compared to spunbond nonwovens.

The selection of manufacturing technology directly influences fiber diameter, porosity, permeability, and mechanical properties, highlighting the importance of process optimization for specific agricultural applications [30,31].

A comparative overview of the key structural and functional differences between these technologies is presented in Table 1, where fiber diameter, porosity, permeability, and mechanical properties are correlated with their agricultural applications.



Figure 5: Production technologies for nonwoven agricultural covers and their structure–property–application relationship.

Table 1: Comparison of production technologies for nonwoven agricultural covers, their structural characteristics, key properties, advantages, limitations and suitable applications

Technology	Spunbond	Meltblown	Needle Punched
Fiber Diameter (μm)	10-40	0.1-2	5-50
Porosity (%)	70-90	60-85	75-95
Air Permeability (Lm ⁻¹ s ⁻¹)	500-2000	50-500	100-800
Tensile Strength (N/5 cm)	20-40	5-15	15-35
Thickness (mm)	0.1-0.5	0.05-0.2	0.5-3.0
Pore Structure Uniformity	High	Very High	Low-Moderate
Typical Advantages	High strength, good permeability, uniform structure	Excellent barrier, high surface area, fine filtration	High bulk and durability, excellent puncture resistance
Typical Limitations	Lower barrier properties than meltblown	Lower strength, high pressure drop	Less uniform pores, Lower air permeability than spunbond
Best-Suited Agricultural Use	Row covers, crop protection, frost protection	Insect nets, barrier covers, specialized applications	Mulch fabrics, erosion control, heavy-duty

4. FUNCTIONAL PROPERTIES

4.1. Structural Properties
(Porosity, Fiber Diameter, Basis Weight)

Structural parameters are the primary determinants of nonwoven performance in agricultural applications, governing mass transfer, thermal behavior, and mechanical integrity. Experimental studies show that porosity, pore size distribution, fiber diameter, and basis weight collectively control functional efficiency. Typical porosity ranges between 70% and 95%, enabling effective gas exchange while maintaining protective functionality. Fine-fiber structures, such as meltblown nonwovens, exhibit smaller pores and superior barrier properties, whereas spunbond

materials provide a balanced combination of permeability and strength. As illustrated in Figure 6, increasing fiber diameter leads to a systematic shift in pore size distribution from small and narrow pores toward larger and broader pore structures, directly influencing permeability and protective performance. Basis weight further modulates performance: low values (15–25 g/m²) enhance permeability but reduce insulation, medium values (25–50 g/m²) ensure balanced functionality, and higher values (>50 g/m²) improve durability and thermal resistance at the expense of light transmission. A critical insight is that structural optimization outweighs polymer selection, emphasizing the importance of engineering design in performance tuning [32,33].

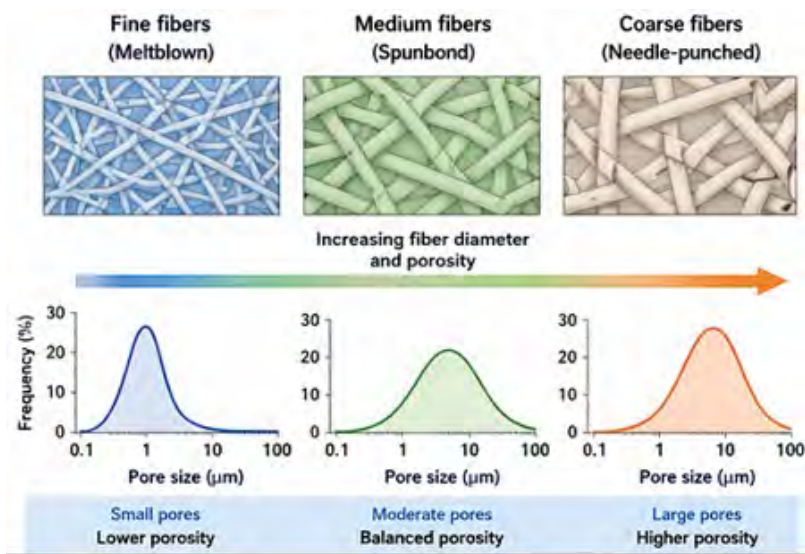


Figure 6: Effect of fiber diameter and porosity on pore size distribution in nonwoven structure.

4.2. Air and Water Permeability

Air and water permeability are pivotal functional parameters in nonwoven agricultural covers, as they directly control plant respiration, moisture transport, and microclimate regulation. Experimental evidence consistently demonstrates that nonwovens exhibit significantly higher air permeability than woven textiles, while maintaining controlled water permeability that enables infiltration and minimizes evaporation losses. As illustrated in Figure 7, permeability follows Darcy-type porous media flow, increasing with porosity and pore size and decreasing with fiber packing density.

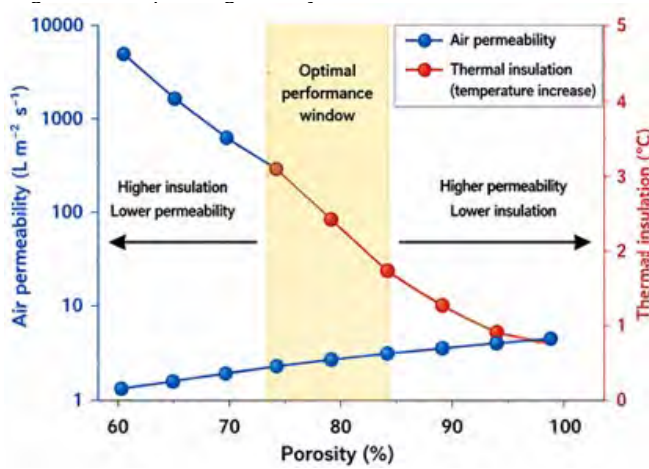


Figure 7: Trade-off between air permeability and thermal insulation in nonwoven agricultural covers.

However, this behavior introduces a fundamental trade-off: higher permeability enhances gas exchange and reduces humidity accumulation, but compromises thermal insulation; conversely, lower permeability improves heat retention and crop protection, yet increases the risk of condensation and overheating. The figure highlights a distinct optimal performance window where these competing effects are balanced. This underscores that permeability should not be maximized, but precisely engineered through structural design to meet specific crop requirements, climatic conditions, and seasonal variations, ensuring both protection and productivity [34,35].

4.3. Thermal Insulation and Heat Transfer Properties

Thermal insulation is a critical functional property of nonwoven agricultural covers, particularly for frost protection and season extension. Experimental studies report temperature increases of 1–4 °C beneath covers, driven by reduced heat loss and the presence

of trapped air layers that act as the primary insulating medium. As illustrated in Figure 8, heat transfer occurs through conduction along fibers, convection through interconnected pores, and radiation exchange with the environment. Among these, air entrapment within the porous structure dominates insulation performance and contributes to the stabilization of diurnal temperature fluctuations. However, excessive insulation—especially in dense nonwovens—can result in overheating under intense solar radiation. This highlights that thermal performance must be carefully balanced through structural design, ensuring sufficient heat retention without compromising ventilation. Therefore, optimized rather than maximal insulation is essential for maintaining crop health under varying climatic conditions [36,37].

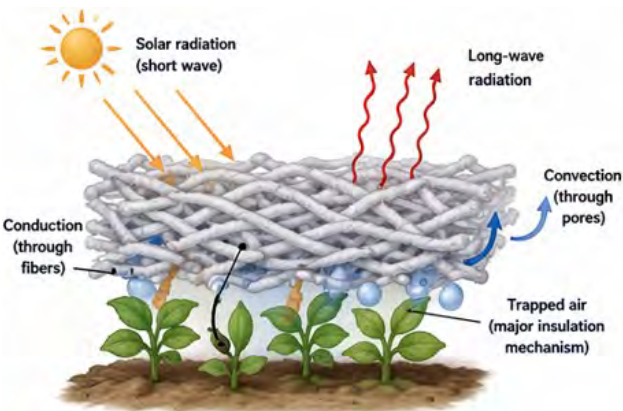


Figure 8: Heat transfer mechanisms in nonwoven agricultural covers: condition, convection, and radiation.

4.4. Optical Properties (Light Transmission and Diffusion) and Crop Yield

Optical properties are essential for plant growth, directly affecting photosynthesis. Nonwoven covers typically provide 70–90% light transmission in the PAR (photosynthetically active radiation) region while promoting strong light diffusion through fiber scattering. As illustrated in Figure 9, diffused light enhances canopy (the collective layer of plant leaves) penetration and improves photosynthetic efficiency in lower plant layers. However, increased basis weight reduces transmission, and excessive scattering can lower effective irradiance [38]. Therefore, optimal performance requires a balance between transmission and diffusion, ensuring efficient light distribution without significant energy loss [39,40].

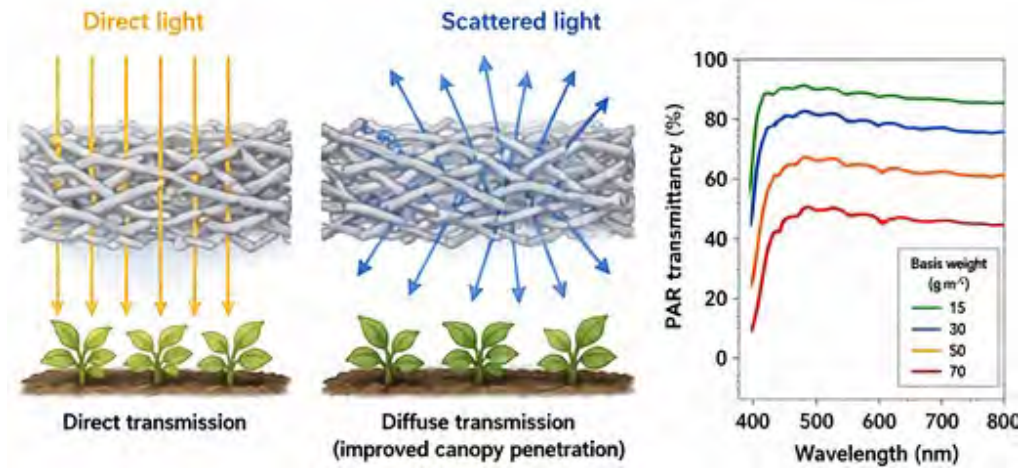


Figure 9: Light transmission and scattering behavior in nonwoven agricultural covers.

4.5. Soil Moisture Retention and Weed Suppression Efficiency

Studies on nonwoven mulch systems demonstrate superior soil water conservation compared to bare soil and impermeable polyethylene films, with reported moisture retention increases of 15–40%, primarily due to reduced evaporative flux and controlled vapor permeability. Weed suppression efficiencies of 85–95% are achieved through effective attenuation of photosynthetically active radiation, limiting weed germination. Unlike polyethylene films, nonwoven structures enable liquid water infiltration while maintaining gaseous exchange, thereby reducing surface runoff and enhancing soil aeration. However, performance is highly dependent on structural parameters, including basis weight, thickness, opacity, and fiber packing density, as well as external factors such as rainfall intensity and soil texture. Low-density nonwovens often exhibit insufficient optical blocking and pore coverage, allowing penetration of light and weed emergence. These findings highlight that functional performance is governed by structure–property relationships, necessitating precise engineering optimization rather than simple material substitution [41,42].

4.6. Mechanical Properties (Strength, Durability, UV Resistance)

Mechanical properties constitute a critical determinant of the service lifetime and functional reliability of nonwoven agricultural covers, governing their response to tensile, tearing, and puncture stresses under field conditions. Typical tensile strength values range from 10 to 40 N/5 cm, with elongation at break between 20% and 80%, depending on fiber type, bonding mechanism, and structural architecture. These parameters are highly sensitive to environmental exposure, with ultraviolet (UV) radiation identified as the dominant degradation pathway. UV-induced photo-oxidative reactions and laundering lead to polymer chain scission, crosslinking, and embrittlement, resulting in a progressive loss of mechanical integrity and structural cohesion [43–46]. As illustrated in Figure 10, a fundamental trade-off exists between mechanical durability and biodegradability. Synthetic polymers such as polypropylene (PP) and polyethylene terephthalate (PET) exhibit superior mechanical performance and long-term stability, particularly when stabilized with UV absorbers and antioxidants, yet demonstrate low biodegradability. In contrast,

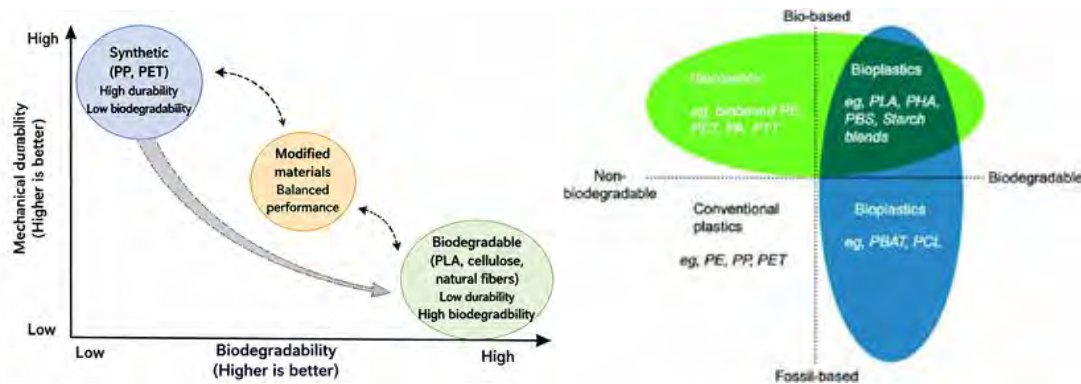


Figure 10: Trade-off between mechanical durability and biodegradability in nonwoven materials.

biodegradable alternatives such as polylactic acid (PLA) and cellulose-based fibers offer enhanced environmental compatibility but are characterized by reduced mechanical strength and accelerated degradation kinetics. Consequently, the development of sustainable nonwoven systems necessitates advanced material engineering approaches, including hybrid fiber systems, surface modification, and controlled degradation design, to reconcile durability with ecological performance [47-49].

4.7. Degradation and Environmental Behaviour

Biodegradable nonwoven materials are increasingly explored as sustainable alternatives to conventional synthetic polymers in agricultural applications. Recent studies indicate that PLA-based nonwovens exhibit controlled degradation within 6–24 months, while cellulose-based materials degrade more rapidly but with reduced mechanical stability. Natural fiber nonwovens further contribute to soil organic matter following decomposition. As illustrated in Figure 11, degradation proceeds through moisture uptake, microbial colonization, enzymatic activity, and polymer chain scission, ultimately resulting in mineralization

into CO₂, H₂O, and biomass. However, under field conditions, particularly in environments with high moisture and microbial activity, premature degradation can occur, leading to loss of functional performance before the end of the agricultural cycle. This limitation highlights the necessity for precisely engineered degradation kinetics, where the material lifetime is aligned with crop requirements, ensuring both functional reliability and environmental compatibility [50,51].

4.8. Barrier Properties (Pest and Weed Protection)

Barrier functionality is crucial for minimizing pesticide use and ensuring effective crop protection in nonwoven systems. As illustrated in Figure 12, insect exclusion efficiency approaches 100% at small pore sizes, while weed suppression reaches 85–95% due to effective light blocking. However, reducing pore size significantly decreases air permeability, limiting ventilation and potentially affecting plant microclimate. This demonstrates a fundamental structure–property trade-off, where optimal performance requires balancing pore size to achieve both high barrier efficiency and adequate air exchange for healthy crop growth [52].

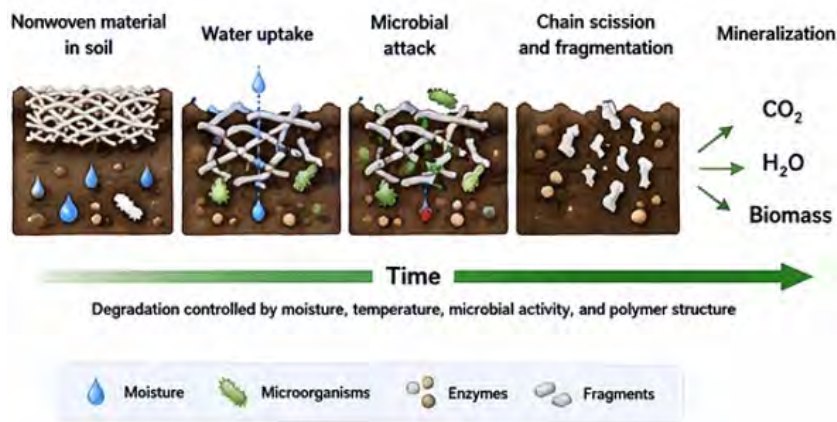


Figure 11: Degradation pathways of biodegradable nonwoven materials in soil environments.

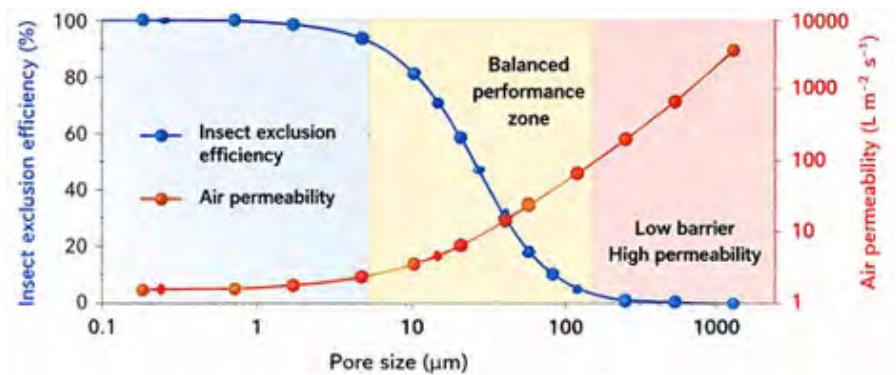


Figure 12: Relationship between pore size, barrier efficiency, and air permeability.

Table 2: Typical performance range.

Pore size (µm)	Barrier efficiency (%)	Air permeability	Application suitability
<1	>95	Low	Insect netting, pest protection
1-10	85-95	Moderate	Row covers, crop protection
10-100	50-85	High	Ventilated covers, shade nets
>100	<50	Very high	Mulch mats, soil covers

5. ADVANTAGES OVER CONVENTIONAL MATERIALS

Nonwoven agricultural covers present several significant advantages over conventional materials such as polyethylene (PE) films and woven textiles, primarily due to their engineered porous structure and multifunctional performance. One of the most important benefits is their high breathability, which enables efficient air exchange between the crop and the surrounding environment. Unlike impermeable PE films, nonwoven materials allow gas diffusion, reducing the risk of excessive humidity and promoting healthier plant respiration. This permeability also minimizes the formation of condensation, a common issue in plastic films that can lead to fungal growth and plant diseases [53].

Another key advantage is their lightweight structure and ease of handling, which facilitate installation, removal, and reuse in field conditions. Nonwoven covers can be directly placed over crops without requiring complex support systems, making them particularly suitable for row cover applications and small-scale farming systems. Their flexibility also reduces mechanical stress on plants compared to heavier woven materials.

In addition, nonwoven covers contribute to improved crop quality and yield by creating a more stable microclimate. Studies have shown that their ability to moderately increase temperature, diffuse light, and maintain soil moisture can accelerate plant growth and enhance early harvest yields. The diffused light transmission characteristic of nonwovens further promotes uniform canopy development, which is beneficial for photosynthetic efficiency [54].

Despite these advantages, certain limitations must be considered. Nonwoven materials, particularly those based on polypropylene, generally exhibit lower long-term durability compared to woven textiles, especially under prolonged UV exposure. Furthermore, the widespread use of synthetic polymers presents challenges in terms of recycling and environmental impact, including the potential generation of microplastics in soil systems. These issues highlight the need for the development of more durable, recyclable, or biodegradable alternatives [55].

6. SUSTAINABILITY CHALLENGES AND CIRCULAR SOLUTIONS

Despite their functional advantages, synthetic nonwoven agricultural covers—primarily based on polypropylene and polyethylene—pose significant environmental challenges related to plastic waste accumulation and long-term ecological impact. One of the most critical issues is the limited recyclability of agricultural textiles, as these materials are often contaminated with soil, agrochemicals, and biological residues after use. Such contamination complicates collection, sorting, and reprocessing, resulting in low recycling rates and frequent disposal in landfills or through incineration [56].

Another major concern is the fragmentation of nonwoven materials into microplastics during use and degradation. Exposure to ultraviolet radiation, mechanical stress, and environmental factors leads to progressive breakdown of polymer structures, generating micro- and nano-scale particles that can accumulate in soil ecosystems. These microplastics may affect soil structure, water retention, and microbial activity, with potential implications for crop productivity and environmental health [57]. Furthermore, the inherent environmental persistence of conventional synthetic polymers means that these materials can remain in the soil for extended periods, contributing to long-term pollution.

To address these challenges, research has increasingly focused on the development of biodegradable nonwoven materials based on polylactic acid (PLA), cellulose, and other bio-based polymers. These materials are designed to degrade under specific environmental conditions, reducing long-term accumulation. However, achieving a balance between durability during use and controlled degradation after disposal remains a key challenge [58].

In parallel, design for recyclability has emerged as an important strategy. The use of mono-material systems, where the entire nonwoven structure is composed of a single polymer type, facilitates mechanical recycling by eliminating the need for material separation. Additionally, the integration of recycled fibers into nonwoven production is gaining attention as a

means of reducing reliance on virgin raw materials and lowering the overall environmental footprint [59].

Beyond material innovations, circular economy approaches are increasingly being explored to close material loops in agricultural textiles. These approaches include improved collection systems, material recovery strategies, and the development of reuse and recycling pathways tailored to agricultural applications. Life cycle assessment (LCA) studies highlight that combining biodegradable materials with circular design principles can significantly reduce environmental impacts compared to conventional systems [60,61].

7. FUTURE TRENDS AND RESEARCH DIRECTIONS

The next generation of nonwoven agricultural covers is increasingly shaped by the convergence of advanced materials engineering, digital technologies, and sustainability-driven design. In particular, the development of smart nonwovens represents a transformative direction, where textile structures evolve from passive protective layers into active systems capable of sensing and responding to environmental stimuli. Recent studies report the integration of flexible sensing elements within nonwoven matrices for real-time monitoring of soil moisture, temperature, and crop health indicators. These sensor-enabled systems, often based on conductive coatings, printed electronics, or fiber-integrated sensing components, enable continuous data acquisition and support precision irrigation and crop management strategies [62, 63].

In parallel, functional surface modifications have emerged as an effective approach to extend and tailor the performance of nonwoven covers. Functional coatings, including antimicrobial, UV-responsive, and wettability-tunable finishes, can be applied to modify surface interactions without altering the bulk structure. Hydrophobic treatments, for example, reduce water accumulation and microbial growth, while hydrophilic finishes improve water distribution and soil moisture regulation. UV-responsive coatings further enable adaptive behavior under varying radiation conditions, contributing to improved durability and thermal management [64].

A particularly promising direction is the integration of digital tools and data-driven methodologies into material design and characterization. Image processing methods allow quantification of porosity, fiber orientation, and surface morphology, providing critical insights into structure–property relationships [65]. Recent studies have demonstrated the effectiveness of digital image-based approaches, including gray-level co-occurrence matrix (GLCM) texture anal-

ysis and process parameter evaluation, for assessing structural irregularities and their influence on textile performance [66–68]. These techniques enable rapid, non-destructive evaluation and represent an important step toward the digitalization of textile characterization. When combined with machine learning algorithms, such data-rich approaches facilitate AI-driven optimization of nonwoven structures, allowing simultaneous consideration of multiple performance criteria such as permeability, thermal insulation, and optical behavior [69].

Furthermore, the development of hybrid material systems combining nonwovens with biodegradable polymers or bioactive agents is gaining significant attention. Composite structures based on polylactic acid (PLA), cellulose fibers, or natural polymers offer the potential for controlled degradation while maintaining functional integrity during use. The incorporation of bioactive components, such as antimicrobial agents or plant-growth-promoting substances, further enhances the functional scope of these materials, transforming them into active contributors to crop protection and soil health [70].

These emerging innovations reflect a shift toward intelligent, multifunctional, and environmentally responsive nonwoven systems. By integrating sensing capabilities, advanced surface functionalities, and digital design tools, nonwoven agricultural covers are becoming key components of precision agriculture and digital farming paradigms. Future research will need to address challenges related to scalability, cost-efficiency, and long-term field performance, while ensuring compatibility with circular economy principles and environmental sustainability.

4. CONCLUSION

Nonwoven agricultural covers represent a critical convergence of textile engineering and sustainable agricultural practices, offering versatile solutions for improving crop productivity and environmental performance. Their engineered structure enables precise control over key functional properties, including air and water permeability, thermal insulation, light transmission, and mechanical durability. This multifunctionality allows nonwoven materials to effectively regulate microclimatic conditions, protect crops from biotic and abiotic stresses, and enhance resource efficiency in modern farming systems. However, the performance of these materials is governed by complex interdependencies between structural parameters and functional outcomes, often involving trade-offs that require careful optimization. In particular, the balance between durability and biodegradability re-

mains a central challenge, especially in the context of increasing environmental concerns related to plastic waste and microplastic formation. Future developments in this field will be driven by advances in biodegradable and bio-based materials, the integration of smart functionalities such as sensing and responsiveness, and the application of data-driven design approaches for structural optimization. Additionally, the adoption of lifecycle thinking and circular economy principles will be essential for reducing environmental impact. Overall, nonwoven agricultural covers are positioned as key enabling technologies for the development of sustainable, efficient, and resilient next-generation agricultural systems.

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