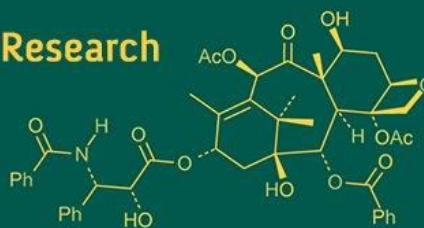


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Agro-textiles for sustainable agriculture: Materials, manufacturing, applications, and future prospects

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Abstract

Agro-textiles are specialized technical fabrics created to improve farming efficiency and boost agricultural production. They play a significant role in crop protection, resource conservation, soil stabilization, and post-harvest management. Utilizing both natural fibers such as jute, coir, hemp, and *Grewia optiva* (Bhimal), and synthetic polymers like polypropylene and polyester, agro-textiles offer functional benefits including UV protection, moisture retention, and pest control. These textiles are widely employed in horticulture, forestry, aquaculture, and crop production systems, offering solutions to environmental stresses and reducing the need for chemical inputs. Technological advancements in materials engineering, smart textiles, and biodegradable fibers have further improved their performance and sustainability. This review provides an overview of agro-textile materials, manufacturing methods, diverse applications, and emerging trends, while highlighting their environmental implications and future prospects.

Keywords: Agro-textiles, sustainable materials, technical textiles, smart agro-textiles, crop protection

1. Introduction

Agro-textiles, or Agro-tex, are specialized technical fabrics designed to support sustainable agricultural practices by improving productivity and resource efficiency. These woven, knitted, or nonwoven materials serve vital roles in crop protection, soil stabilization, water conservation, and post-harvest handling (Palamutcu & Devrent, 2017) ^[17]. Their applications extend across agriculture, horticulture, forestry, and aquaculture, helping to mitigate environmental stresses and reduce dependence on chemical fertilizers and pesticides. It is manufactured from both natural fibers (such as jute, coir, hemp, and *Grewia optiva*) and synthetic polymers (like polypropylene and polyester). It provide benefits such as UV protection, temperature regulation, and moisture control (Horrocks & Anand, 2000) ^[1]. Common products include shade nets, windbreak fabrics, mulch mats, and protective nets, which enhance crop quality, minimize weed growth, and prevent soil erosion.

Recent advancements in material science and textile engineering have driven innovations in biodegradable and smart agro-textiles, balancing durability with environmental sustainability (Saini *et al.*, 2023) ^[42]. Moreover, growing interest in natural and agricultural waste-based fibers offers a pathway toward eco-friendly production and circular economy models (Ramesh *et al.*, 2022) ^[33]. Overall, agro-textiles represent a crucial technology for promoting sustainable agriculture and adapting farming systems to climate and resource challenges.

2. Materials

Materials used in Natural fibers such as jute, coir, hemp, flax, sisal, *Grewia optiva* (Bhimal), wool, banana, and pineapple fibers are extensively used in agro-textiles due to their biodegradability, eco-friendliness, and cost-effectiveness (Basu & Roy, 2021; Horrocks & Anand, 2000) ^[23, 1]. Jute is widely applied in seedbed covers, sapling sleeves, mulching, and soil stabilization, where it enhances soil fertility and prevents erosion. Coir, derived from coconut husks, is valued for its high strength, rot resistance, and water retention capacity, making it ideal for erosion control mats, mulch blankets, and coastal agriculture (Sanyal, 2010) ^[5]. Hemp and flax offer high tensile strength and breathability, suitable for reinforcement and vineyard applications, while sisal and agave fibers, known for their durability and salt resistance, are used in twines and mulching in semi-arid and coastal

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regions. Wool-based agro-textiles provide moisture resistance, insulation, and UV protection, reducing frost damage and improving soil temperature regulation for organic farming. *Grewia optiva* (Bhimal), a Himalayan fiber, is strong, flexible, and biodegradable, used for ropes, mats, and bags that support soil stabilization and plant growth, with emerging applications in bio-composite materials (Patel *et al.*, 2023) ^[41]. Additionally, banana and pineapple fibers, extracted from agricultural waste, are rich in cellulose and suitable for mulching and sustainable packaging (Kumar *et al.*, 2023) ^[43]. Overall, these natural fibers form the foundation of agro-textiles by promoting sustainability, enhancing soil health, and providing functional benefits in various agricultural applications.

Synthetic fibers such as polypropylene (PP), polyethylene (PE), polyester (PET), and polyamide (PA) are widely used in agro-textiles due to their high tensile strength, UV resistance, durability, and longevity. These fibers are employed in products like shade nets, greenhouse films, insect screens, and protective covers, which help regulate temperature, sunlight, and humidity for optimal plant growth (Briassoulis, 2007; Max *et al.*, 2012) ^[2, 8]. Shade nets, made from HDPE or PP, are available in various colors and shade levels (25-90%) to protect crops from excessive sunlight and wind, while anti-frost covers made from spun-bonded polypropylene fabrics protect plants from cold stress (Patel *et al.*, 2021; Briassoulis, 2007) ^[27, 41]. Windshields, typically warp-knitted from high-density PP yarns, safeguard crops from wind damage and fruit drop. Similarly, harvesting nets made from polyethylene simplify fruit collection and reduce labor costs. Bird protection nets and anti-hail nets made from HDPE or PP shield crops from pests and hailstorms, respectively, without blocking sunlight or airflow. Despite their performance advantages, synthetic fibers pose environmental challenges due to non-biodegradability, prompting research into biodegradable coatings and natural-synthetic fiber blends to enhance sustainability without compromising durability (Singh *et al.*, 2020) ^[22].

3. Manufacturing Techniques of Agro-Textiles

Agro-textiles are manufactured using diverse techniques to tailor their properties for specific agricultural applications. The choice of manufacturing technique influences the fabric's strength, porosity, elasticity, and durability, thereby determining its suitability for different environmental conditions and crop protection needs. The main manufacturing techniques include woven, knitted, nonwoven, and coated agro-textiles.

3.1 Woven Agro-Textiles

Woven Agro-Textiles are reproduced by interlacing yarns in crisscross patterns, offering dimensional stability and strength. These are used in windbreaks, shade nets, and fencing barriers due to their dimensional stability, strength, and controlled porosity (Patel *et al.*, 2021) ^[27]. The tight weave structure offers resistance against mechanical stresses and provides effective shading and wind reduction in agricultural fields. Woven polypropylene and polyester fabrics are widely used for long-lasting shade nets, while jute and coir woven fabrics are applied in temporary erosion control and seed protection. The porosity of woven

structures is critical in determining airflow and light transmission, making them suitable for greenhouses and mulching (Briassoulis, 2007; Koerner, 2012) ^[2, 7, 8].

3.2 Knitted Agro-Textiles

Knitted Agro-Textiles provides elasticity and flexibility, suitable for bird nets and anti-hail nets. This open-loop structure enhances air permeability and mechanical adaptability (Briassoulis, D., *et al.* (2007) ^[2]. The elasticity of knitted fabrics also helps in maintaining their structural integrity under tension. Knitted polyethylene monofilament fabrics are especially popular in anti-bird and hail protection nets. Their flexibility reduces yarn breakage compared to woven designs, thereby increasing service life in orchards and vineyards (Max *et al.*, 2012) ^[8].

3.3 Nonwoven Agro-Textiles

Nonwoven Agro-Textiles are manufactured by bonding fibers mechanically, chemically, or thermally. These are used in mulching sheets, erosion control mats, and crop covers due to their porous structure. These fabrics exhibit high porosity, light weight, and cost-effectiveness, making them ideal for mulching sheets, weed control mats, soil erosion blankets, and crop covers (Kothari & Das, 2021) ^[25]. Their porous structure facilitates moisture retention, soil aeration, and temperature regulation, promoting plant growth. Spun-bonded polypropylene nonwovens are dominant in frost-protection covers due to their lightweight and breathability. Studies also showed that natural-fiber nonwovens, such as coir and jute felts, retain soil moisture and gradually decompose into organic matter, providing added agronomic value (Horrocks & Anand, 2000; Max *et al.*, 2012) ^[1, 8]. Sanyal (2010) ^[5] reported that nonwoven coir mats are particularly effective in preventing soil crusting and enhancing seed germination. Basu & Roy (2021) ^[23] also pointed out that nonwoven jute felts have been successfully tested in road embankment stabilization while simultaneously promoting vegetation growth.

3.4 Coated Agro-Textiles

Coated Agro-Textiles are specialized fabrics treated with functional coatings that significantly enhances their performance characteristics including UV resistance, water repellency, and flame retardancy. These are also used in pond liners, greenhouse films, and protective barriers (Singh *et al.*, 2020, Kothari & Das, 2021) ^[22, 25]. Coated agro-textiles are developed by applying functional coatings—such as polyethylene, polypropylene, UV-stabilizers, or water-repellent agents—onto textile substrates to enhance specific properties like UV resistance, water impermeability, chemical resistance, and flame retardancy (Singh *et al.*, 2020) ^[25]. Applying biodegradable polymer coatings (e.g., PLA blends) on natural fabrics such as jute or hemp has been shown to extend durability in outdoor conditions while maintaining eco-friendly disposal (Briassoulis, 2007) ^[2]. Horrocks & Anand (2000) ^[1] further highlighted the use of flame-retardant and antimicrobial finishes in coated agro-textiles, improving their safety in storage and greenhouse applications. Patel *et al.* (2023) ^[41] discussed hybrid coated systems combining natural fiber fabrics with bio-resins to achieve extended service life while meeting sustainability goals.

4. Applications in Agro-Textiles

Agro-textiles serve multiple functions in modern agriculture, offering protection, resource conservation, and improved post-harvest management (Patel *et al.*, 2021; Vinod *et al.*, 2023) [27, 44]. They act as an effective interface between plants and their environment, promoting growth, yield, and sustainability. For crop protection, shade nets and insect-proof fabrics shield plants from excessive sunlight, pests, and birds, reducing pesticide use and crop damage. In soil erosion control, jute and coir-based geotextiles stabilize slopes and riverbanks while biodegrading to enrich the soil. For water conservation, mulch mats made from jute, coir, or biodegradable polymers help retain soil moisture, suppress weeds, and regulate soil temperature. In greenhouse applications, agro-textiles such as shade nets, thermal screens, and nonwoven covers maintain optimal microclimatic conditions, extending growing seasons and improving crop quality. Finally, for post-harvest handling, materials like jute bags, polypropylene sacks, and coir-based packaging protect produce during storage and transport, reducing spoilage and maintaining freshness. Overall, agro-textiles significantly enhance agricultural productivity and sustainability through their diverse and eco-friendly application.

5. Emerging Trends and Future Prospects

Agro-textiles are evolving rapidly with the integration of advanced technologies, addressing the growing need for sustainable, efficient, and high-performance agricultural solutions. Among the most promising developments is the emergence of smart agro-textiles, nano technology, biodegradable textile.

- **Smart Agro-Textiles:** The incorporation of smart technologies into agro-textiles is an advancing field that supports the principles of precision agriculture. These textiles are being designed with integrated sensors and IoT-enabled systems to monitor critical environmental parameters such as soil moisture, temperature, nutrient levels, and pest infestations in real-time. Such smart textiles facilitate data-driven decision-making, optimizing resource usage and improving crop yields. Future developments may focus on energy-efficient, wireless, and AI-powered smart textiles to automate farm management systems (Sharma & Verma, 2025; Saini *et al.*, 2023) [46, 42]. Furthermore, some smart agro-textiles are being combined with solar-powered energy harvesters to operate autonomously in remote fields. The integration of flexible electronics and biodegradable circuits is also being explored, allowing the textiles to degrade naturally after their service life, reducing environmental impact. In the near future, these innovations could enable fully automated farm management systems that dynamically adjust microclimatic conditions for crops, enhance resource-use efficiency, and minimize chemical inputs.
- **Nanotechnology:** The integration of nanotechnology into agro-textile production is revolutionizing the sector by enhancing the functional attributes of fabrics. Application of nanoparticles and nano-coatings enables agro-textiles to acquire antimicrobial resistance, UV-blocking efficiency, enhanced durability, water repellency, and even self-cleaning properties. These advancements not only extend the service life of agro-textiles but also reduce maintenance costs.

Nanotechnology-based agro-textiles are being increasingly researched for controlled release of agrochemicals to reduce environmental pollution (Patra & Gouda, 2022) [32]. According to Choudhary & Bajaj (2016), nanocoated jute fabrics exhibited improved UV resistance and reduced microbial growth, extending their service life in field conditions. Similarly, Sampath *et al.* (2017) [15] highlighted the potential of nanostructured biodegradable polymers to deliver agrochemicals in a controlled manner, minimizing losses and leaching.

- **Biodegradable Textiles:** The shift towards sustainable and eco-friendly agro-textiles is driving research into biodegradable materials derived from natural fibers (jute, coir, hemp) and bio-polymers (PLA, PHA). These textiles are being developed to offer comparable mechanical and functional performance to synthetic counterparts, while ensuring they decompose naturally after their life cycle, minimizing environmental impact. Innovations are focusing on biocomposite agro-textiles with enhanced durability, yet ensuring soil and ecological safety after degradation (Kumar *et al.*, 2023; Ramesh *et al.*, 2022) [43, 33]. Chaudhary *et al.* (2018) [16], PLA-based nonwovens used in mulching and crop covers provided effective weed suppression while safely degrading into soil. Mishra *et al.* (2015) [11] also demonstrated that coir composites blended with starch-based polymers could serve as effective biodegradable packaging materials for perishable produce.

6. Current Challenges in Agro-Textiles

The agro-textile sector faces several economic, technical, and environmental challenges that limit its large-scale adoption and sustainability. For natural fibers like jute and coir, key issues include low durability, as they degrade quickly under UV light, moisture, and microbial attack, leading to a short service life. Their susceptibility to pests and microbes, inconsistent quality, and lack of standardization make industrial production difficult. Additionally, high processing costs, limited large-scale infrastructure, and seasonal availability hinder commercialization. A lack of awareness and education among farmers and stakeholders also slows the adoption of eco-friendly alternatives, emphasizing the need for better outreach, training, and labeling initiatives.

For synthetic fibers such as polypropylene and polyethylene, the main challenges stem from non-biodegradability and microplastic pollution, which threaten soil health and the environment. Recycling and waste disposal are difficult due to contamination with soil and pesticides, while volatile raw material prices tied to fossil fuels affect economic stability. Furthermore, the high end-of-life costs of disposal and pollution make these materials less sustainable in the long term. Overall, balancing durability, cost-effectiveness, and environmental responsibility remains the central challenge for advancing agro-textile innovation.

7. Policy and Industry Initiatives in Agro-Textiles

The accelerated growth and adoption of agro-textiles globally are significantly shaped by a combination of governmental policies, industry innovation, international cooperation, and public-private partnerships (PPPs). These initiatives not only promote the development and

deployment of sustainable agro-textile solutions but also help in building awareness, reducing costs, and expanding access to smallholder and commercial farmers.

- **Government Policies and Subsidies:** Governments worldwide are promoting the use of eco-friendly agro-textiles through subsidies, awareness programs, and inclusion in agricultural development schemes. In India, the Ministry of Textiles and the Ministry of Agriculture have supported agro-textiles under the National Technical Textile Mission, with financial aid for mulching, shade nets, and crop covers (Ministry of Textiles, 2021) ^[26]. Similarly, the European Union has implemented policies encouraging biodegradable mulching films to reduce plastic waste in agriculture (European Commission, 2020) ^[20].
- **Industry-Led Innovations:** Private industries and startups are investing in biodegradable and smart agro-textiles. Companies are developing natural fiber-based mulching mats, coir geotextiles for soil erosion control, and biodegradable films. Collaborative projects between research institutions and industries have accelerated the commercialization of PLA-based nonwoven fabrics, jute-based agro-textiles, and nanofiber mats with controlled-release fertilizers (Vinod *et al.*, 2023) ^[44].
- **International Organizations:** Global organizations such as the FAO and UNEP emphasize sustainable agricultural practices, encouraging the reduction of plastic in farming. Their reports highlight agro-textiles as vital tools for reducing food loss, enhancing water-use efficiency, and improving climate resilience (FAO, 2023) ^[39].
- **Public-Private Partnerships:** Public-private partnerships play a critical role in strengthening agro-textile supply chains. Collaborative ventures in countries like China and India have supported the production of shade nets, greenhouse covers, and biodegradable mulch films, making them more affordable for smallholder farmers (Sharma & Verma, 2025) ^[46].

8. Conclusion

Agro-textiles have emerged as indispensable tools in modern agriculture, offering solutions for crop protection, soil conservation, water management, and yield enhancement. Their growing role in climate-smart agriculture underscores their potential in ensuring sustainable farming practices. However, challenges such as cost competitiveness, durability of biodegradable alternatives, limited recycling infrastructure, and lack of standardized benchmarks hinder widespread adoption. Addressing these issues requires technological innovation, supportive policies, and greater farmer awareness.

The future of agro-textiles lies in the integration of sustainability with advanced technologies. Biodegradable natural fiber-based products, combined with smart agro-textiles equipped with sensors and IoT systems, promise to revolutionize agricultural practices by enhancing productivity while minimizing environmental impacts. Strengthened by policy support, industry-research collaborations, and international sustainability goals, agro-textiles are set to play a transformative role in the global agricultural landscape.

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