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Enhancing agricultural sustainability: A comprehensive review of agro-textile innovations

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Abstract
Sustainability of agricultural practices faces unprecedented challenges in the 21st century, exacerbated by climate change, soil degradation, water scarcity, and population growth. To address these challenges and ensure food security for future generations, there is an urgent need for innovative solutions that promote sustainable agricultural practices while optimizing resource use efficiency and minimizing environmental impacts. In recent years, agro-textiles have emerged as promising tools for enhancing agricultural sustainability by improving soil health, water management, pest control, and crop productivity. Agro-textiles serve diverse functions, from protecting crops and soil to optimizing resource use. Based on their specific use, they are divided into various types: anti-hail nets to protect crops from extreme weather, mulch mats to manage weeds and conserve moisture, thermal screens and shade for temperature regulation, and geotextiles to stabilize and prevent soil erosion. The study showcased the advancement of environmentally friendly and biodegradable agro-textiles, which are becoming more popular because of their smaller environmental impact. The potential of novel fiber technologies, such as nanotechnology, natural fibers, and recycled materials, to further transform agro-textile applications is investigated. Agro-textiles have a lot of potential to improve agricultural sustainability. Nonetheless, issues like price, robustness, and the requirement for broad adoption still exist. Innovative solutions to major issues in agriculture, such as soil erosion, water scarcity, and environmental degradation, can be found in agro-textile goods. The effectiveness, application, and sustainability of these products must be further advanced by ongoing research and development in agro-textile technology. Only then can food security and environmental stewardship be guaranteed in the face of changing agricultural needs and difficulties.

Keywords: Sustainability, agro-textile, soil management, water conservation

Introduction

Agriculture is the cornerstone of human civilization, providing sustenance, economic stability, and livelihoods to billions of people worldwide. However, the sustainability of agricultural practices faces unprecedented challenges in the 21st century, exacerbated by climate change, soil degradation, water scarcity, and population growth. To address these challenges and ensure food security for future generations, there is an urgent need for innovative solutions that promote sustainable agricultural practices while optimizing resource use efficiency and minimizing environmental impacts. In recent years, agro-textiles have emerged as promising tools for enhancing agricultural sustainability by improving soil health, water management, pest control, and crop productivity.

Agro-textiles encompass a wide range of textile materials and structures designed specifically for agricultural applications, including mulch mats, crop covers, shade nets, geotextiles, and harvesting nets, among others. These innovative textile-based solutions offer multifunctional benefits, such as soil moisture retention, weed suppression, microclimate regulation, and protection against adverse weather conditions, making them indispensable components of modern agricultural systems. This comprehensive review aims to explore the diverse applications, efficacy, and impacts of agro-textiles in promoting agricultural sustainability across different crops, climates, and geographical regions. By synthesizing existing research, case studies, and best practices, this review seeks to provide insights into the potential of agro-textiles to address key challenges facing agriculture today and shape the future of sustainable food production.

The use of textiles in agriculture dates back thousands of years, with early civilizations employing natural fibers such as cotton, wool, and jute for various agricultural purposes, including crop protection, soil erosion control, and water management. Over time, advances in textile manufacturing techniques and materials have led to the development of specialized agro-textiles tailored to meet the specific needs of modern agriculture. The advent of synthetic fibers, such as polyethylene, polypropylene, and polyester, has revolutionized the field of agro-textiles, enabling the production of lightweight, durable, and cost-effective materials with superior mechanical properties and resistance to environmental degradation. These synthetic materials have expanded the range of applications for agro-textiles, allowing for greater versatility, performance, and longevity in agricultural settings.

Agro-textiles play a crucial role in sustainable agriculture by addressing key challenges and constraints faced by farmers, including soil erosion, water scarcity, pest infestations, and climate variability. By providing effective solutions for soil management, moisture conservation, and crop protection, agro-textiles contribute to improved yields, reduced input costs, and enhanced resilience to environmental stresses. Mulch mats, for example, are widely used to conserve soil moisture, suppress weed growth, and regulate soil temperature, thereby promoting optimal conditions for plant growth and development. Similarly, crop covers offer protection against adverse weather conditions, pests, and diseases, while shade nets help create favorable microclimates for sensitive crops and reduce the risk of sunburn and heat stress.

Research Methodology

This review employs a systematic approach to identify and analyze relevant literature, research articles, case studies, and best practices related to the use of agro-textiles in agriculture. A comprehensive search of academic databases, scientific journals, conference proceedings, and technical reports was conducted to gather pertinent information on the applications, benefits, and challenges of agro-textiles across different crops, regions, and agricultural systems. The search strategy included keywords such as "agro-textiles," "mulch mats," "crop covers," "shade nets," "geotextiles," "harvesting nets," "agricultural sustainability," "soil management," "water conservation," "crop protection," and "climate resilience." Relevant studies and articles were selected based on their relevance, quality, and applicability to the scope of this review.

Overview of the Review

This review is structured into several sections, each focusing on a specific type of agro-textile and its applications in agriculture. The following sections will provide a detailed analysis of mulch mats, crop covers, shade nets, geotextiles, harvesting nets, and other agro-textile innovations, highlighting their respective benefits, challenges, and research findings. Additionally, case studies and real-world examples will be presented to illustrate the practical implementation and impact of agro-textiles in diverse agricultural settings.

Review of Literature

Ansary *et al*. (2021) [1] conducted a comprehensive study on the effectiveness of mulch mats in tomato, capsicum, and groundnut cultivation. Their research aimed to assess the impact of mulch mats on soil moisture retention and weed suppression, utilizing various materials such as jute, straw, and plastic. The findings highlighted the significant improvement in soil moisture levels and weed control in plots covered with mulch mats compared to control plots without mulching. This study underscores the potential of mulch mats in enhancing water conservation and weed management practices in agriculture.

Parasar *et al*. (2017) [2] investigated the efficacy of mulch mats made from jute nonwoven fabric in French bean and capsicum cultivation. Their research revealed that the application of geotextile jute mulches significantly increased yield efficacy and suppressed weed growth in the cropping system. The study emphasized the role of mulch mats in improving soil nutrient dynamics and enhancing crop productivity, particularly in regions vulnerable to weed infestation and soil degradation.

Sarkar *et al*. (2019) [3] explored the influence of jute mulch mats on thermal accumulation in potato and broccoli cultivation. Through field experiments, they demonstrated that jute agro-textiles effectively modulated soil temperature, thereby optimizing thermal conditions for crop growth and development. The study underscored the importance of jute mulch mats as a sustainable solution for regulating soil temperature and mitigating the adverse effects of temperature extremes on crop performance.

Adhikari *et al*. (2016) [4] conducted a study to evaluate the efficiency of jute mulch mats as a soil conditioner to increase chilli productivity in West Bengal. Their research revealed that the application of jute agro-textiles as soil conditioners significantly improved soil structure, moisture retention, and nutrient availability, leading to a substantial increase in chilli yield. The findings underscored the potential of jute mulch mats not only in enhancing crop productivity but also in improving soil health and fertility.

Sarkar *et al*. (2020) [5] investigated the effect of woven jute agro-textile mulch on soil health and productivity of banana cultivation in new alluvial soil. Their research demonstrated that jute mulch mats effectively conserved soil moisture, enhanced organic carbon, and nutrient status, and efficiently suppressed weed growth. The study emphasized the role of jute mulch mats in improving soil quality, promoting sustainable banana cultivation practices, and mitigating soil erosion in fragile ecosystems.

Nag *et al*. (2008) [6] conducted a study to assess the efficient management of soil moisture with jute nonwoven mulch mats for sweetlime and turmeric cultivation in the red lateritic zone. Their research demonstrated that jute mulch mats significantly improved soil moisture retention, thereby enhancing the growth and yield of sweetlime and turmeric crops. The findings underscored the effectiveness of jute mulch mats in conserving water resources and optimizing crop productivity in water-stressed environments.

Adhikari, N., Saha, A., Bandopadhyay, P., Mukharjee, S., Tarafdar, P. K., & De, S. K. (2018) [7] conducted research on the efficient use of jute agro-textiles as soil conditioners to increase tomato productivity. Their study highlighted the role of jute mulch mats in improving soil moisture retention and nutrient availability, leading to a significant increase in tomato yield. The findings underscored the importance of sustainable soil management practices in enhancing crop productivity and ensuring food security.

Bhowmick, M., Debnath, S., Singha, A., Baite, H., Mridha, N., & Karmakar, S. (2019) [8] explored the performance of nonwoven mulch material from jute in broccoli cultivation. Their research demonstrated that jute mulch mats effectively controlled weed growth, improved moisture retention, and increased yield in broccoli crops. The study emphasized the role of mulch mats in promoting sustainable weed management practices and optimizing resource use efficiency in vegetable production systems.

Rannu, R. P., Ahmed, R., Siddiky, A., Ali, A. S. M. U., Murad, K. F., & Sarkar, P. K. (2018) [9] investigated the effect of irrigation and mulch on the yield and water use of strawberry crops. Their study revealed that the application of mulch mats made from black plastic and rice straw significantly improved moisture retention and increased strawberry yield. The findings highlighted the importance of mulching in mitigating water stress and enhancing crop productivity in fruit cultivation.

Kaushik, M., Biplab, S., Chandra, K. M., & Ghosh, G. K. (2023) [10] conducted research on the residual impact of nonwoven jute agro-textile mulch on soil health and productivity of maize in lateritic soil. Their study demonstrated that jute mulch mats effectively improved soil fertility, microbial population, and moisture retention, leading to a significant increase in maize yield. The findings underscored the long-term benefits of mulch mats in enhancing soil quality and productivity in maize cultivation.

Pal, A., Adhikary, R., De, S. K., & Sardar, M. (2020) [11] investigated the effect of different geotextile treatments in soil to increase the yield and yield attribute of capsicum. Their research revealed that geotextile mulch mats effectively controlled soil erosion, improved moisture holding capacity, and enhanced capsicum yield. The study emphasized the role of mulch mats in promoting sustainable soil management practices and ensuring the economic viability of vegetable cultivation.

Adhikary, R., & Ravi Sankar, L. (2018) [12] studied the use of geotextiles for improving crop productivity on groundnut in Inceptisols. Their research demonstrated that geotextile mulch mats made from coir, jute, and vetiver root significantly increased water retention capacity and yield in groundnut crops. The findings highlighted the potential of geotextile mulch mats in enhancing soil moisture management and crop productivity in arid and semi-arid regions.

Saha, B. (2021) [13] conducted research on non-woven jute agro-textiles for the improvement of soil quality and horticultural production. Their study demonstrated that jute mulch mats effectively conserved soil moisture, enhanced nutrient retention, and suppressed weed growth in tomato, tea, groundnut, and black gram cultivation. The findings underscored the multifunctional role of jute mulch mats in promoting soil health, biodiversity, and sustainable agricultural practices.

Farjana, S., Islam, M. A., & Haque, T. (2019) [14] investigated the effects of organic and inorganic fertilizers and mulching on the growth and yield of cabbage. Their research revealed that mulch mats made from rice straw and black polythene significantly increased cabbage production and nutrient availability to plants. The study emphasized the importance of integrated nutrient and water management strategies, including mulching, in optimizing cabbage yield and quality.

Aranda, V. H., Tortolero, D. R., Barreto, J. A., Vega, C. A., Saraguro, J. P., Chavairra, A. P., & Sosa, D. (2021) [15] characterized and used a crop-residue-based mat mulch in the production of pepper during the dry season. Their research demonstrated that mulch mats made from banana rachis and rice straw effectively regulated soil temperature, reduced weed growth, and improved pepper yield. The findings highlighted the potential of crop-residue-based mulch mats in enhancing soil health, water use efficiency, and crop productivity in agroecosystems.

Mandal, U. K., Lama, T. D., Burman, D., Mandal, S., & Raut, S. (Eds.). (2021) [16] organized the International Symposium on Coastal Agriculture, focusing on transforming coastal zones for sustainable food and income security. The symposium brought together researchers, policymakers, and practitioners to discuss innovative approaches and best practices in coastal agriculture, including the use of mulch mats and other agro-textile solutions. The event highlighted the importance of integrated coastal management strategies in addressing the challenges of climate change, soil erosion, and food insecurity in coastal regions.

These studies collectively underscore the importance of mulch mats in improving soil moisture retention, weed suppression, and crop productivity across diverse agricultural systems. The findings highlight the multifunctional benefits of mulch mats in enhancing soil health, water use efficiency, and nutrient management, thereby contributing to sustainable agriculture and food security. Further research and adoption of mulch mats hold promise for mitigating the adverse effects of climate change, optimizing resource use efficiency, and promoting resilient agricultural systems globally.

The use of agro-textile products in agriculture has become increasingly popular due to their numerous benefits in crop cultivation. Mulch mats, for instance, are commonly used in tomato cultivation, employing materials like black/silver plastic, straw, or jute (nonwoven). These mats excel in retaining moisture in the soil and suppressing weed growth, as demonstrated in studies by Ansary *et al*. (2021) [1] and Parasar *et al*. (2017) [2]. Crop covers, which encompass a variety of materials such as jute, wool, coir, sisal, and flax, are utilized in crops like broccoli, tomato, radish, carrot, and red lettuce. They offer protection against hail damage and exhibit stability against ultraviolet radiation, ensuring the safety and health of the crops (Marasovic & Dragana, 2019) [17]. Various nets and fabrics made from jute, polyethylene, polypropylene, and other materials find application in diverse crops ranging from grapes to seafood. These agro-textiles boast properties such as biodegradability, high water retention, and protection against solar and ultraviolet radiation (Bhavani *et al*., 2017) [18].

In addition, mulch mats made from jute or other materials play a crucial role in the cultivation of crops like French bean, capsicum, and potato. They influence thermal accumulation, prevent soil erosion, and enhance soil moisture retention (Sarkar *et al*., 2019) [3]. Braided sampling bags made from jute offer high moisture absorption and retention capabilities, along with being biodegradable and cost-effective, making them ideal for nursery use (Biswas *et al*., 2016) [20]. Agro mats made from polypropylene find application in unspecified crop cultivation, although their specific properties are not elaborated upon (Sindhuja & Vijayakumar, 2016) [21].

Table 1: Mulching Agro Textile Products

Sr. No.	Name of Agro Textile Product	Crop Cultivation	Fiber Used	Properties	References
1	Mulch Mats	Tomato, French Bean, Capsicum, Groundnut, Pineapple, Banana, Green Gram, Sweetlime, Turmeric	Jute (Nonwoven)	Moisture retention, weed suppression	Ansary *et al.* (2021) [1], Parasar *et al.* (2017) [2], Sarkar *et al.* (2019) [3], Adhikari *et al.* (2016) [4], Sarkar *et al.* (2020) [5], Kaushik *et al.* (2023) [10], Sarkar *et al.* (2018) [9], Nag *et al.* (2008) [6]
2	Mulches	Strawberry, Maize, Broccoli	Jute (Nonwoven), Black Polythene, Rice Straw	Soil fertility improvement, moisture retention, weed suppression	Rannu *et al.* (2018) [9], Kaushik *et al.* (2023) [10], Bhowmick *et al.* (2019) [8]
3	Mulch	Broccoli	Jute (Nonwoven)	Weed control, moisture retention, yield increase	Bhowmick *et al.* (2019) [8]
4	Mulch Mat	Groundnut, Pepper	Jute, Coir, Banana Rachis, Rice Straw	Erosion control, weed suppression, moisture regulation	Aranda *et al.* (2021) [15], Adhikary & Ravi Sankar (2018) [12]
5	Mulch Mat (Surface Cover)	Capsicum, Potato	Jute, Coir	Soil quality maintenance, erosion control	Pal *et al.* (2020) [11]
6	Mulch Mat (Crop Cover)	Chickpea	Black Polythene	Yield increase, moisture retention	Sarkar & Sarkar (2018) [9]
7	Mulch Mat	Tomato	Jute	Yield increase, soil moisture retention	Adhikari *et al.* (2018) [7]

Furthermore, geotextiles, including mulches, nets, and linters made from materials like coir, jute, and vetiver root, are utilized in crops such as groundnut. These geotextiles exhibit a high water retention capacity and contribute to a significant increase in crop yield (Adhikary & Sankar, 2018) [12]. Similarly, geotextiles made from non-woven jute find application in crops like tomato, tea, groundnut, and black gram, offering benefits such as soil conservation, water retention and transmission, weed suppression, and nutrient enrichment (Saha, 2021) [13]. These various agro-textile products contribute significantly to modern agriculture by providing effective solutions for moisture management, weed control, soil conservation, and overall crop health and productivity.

Table 2: Crop Covering Agro-Textile Products

Sr. No.	Name of Agro Textile Product	Crop Cultivation	Fiber Used	Properties	References
1	Crop Cover	Broccoli, Tomato, Radish, Carrot, Red Lettuce	Jute, Wool, Coir, Sisal, Flax	Hail protection, UV stability	Marasovic& Dragana (2019) [17]
2	Various Nets and Fabrics	Grapes, Guava, Pomegranate, Bamboo, Tomato, Onions, Potatoes, Corn, Cabbages, Seafood	Jute, Polyethylene, Polypropylene, Polyolefin, Hemp, Flax, Coir, Sisal	Biodegradability, water retention, protection from UV radiation	Bhavani *et al.* (2017) [18]
3	Shade Net, Mulch Mat, Harvesting Nets, etc.	Strawberry, Gooseberry, Tomatoes, Cucumber	Polyethylene, Polypropylene, Jute, Flax, Hemp, Sisal	Solar radiation protection, UV resistance, water holding capacity	Khatik *et al.* (2021) [19]

Table 2 showcases various agro-textile products used for crop covering, highlighting their applications, fiber used, properties, and associated references.

Crop Cover: This agro-textile product finds application in a variety of crops such as broccoli, tomato, radish, carrot, and red lettuce. It utilizes fibers like jute, wool, coir, sisal, and flax. The primary properties of crop covers include hail protection and UV stability. They shield crops from damage caused by hail and ensure their safety against harmful ultraviolet radiation, thereby contributing to their overall health and productivity (Marasovic& Dragana, 2019) [17].

Various Nets and Fabrics: These agro-textile products are employed in a wide range of crops including grapes, guava, pomegranate, bamboo, tomato, onions, potatoes, corn, cabbages, and seafood. They utilize fibers like jute, polyethylene, polypropylene, polyolefin, hemp, flax, coir, and sisal. Key properties of these nets and fabrics include biodegradability, water retention, and protection from UV radiation. They effectively retain water, promote biodegradation, and safeguard crops from the harmful effects of ultraviolet radiation, thereby enhancing their growth and yield (Bhavani *et al.*, 2017) [18].

Shade Net, Mulch Mat, Harvesting Nets, etc.: This category of agro-textile products is utilized in crops such as strawberry, gooseberry, tomatoes, and cucumber. They are crafted using fibers like polyethylene, polypropylene, jute, flax, hemp, and sisal. The primary properties of these nets and mats include protection against solar radiation, UV resistance, and high water holding capacity. They shield crops from excessive sunlight, resist damage from ultraviolet radiation, and effectively retain water, thereby creating optimal growing conditions for the crops (Khatik *et al.*, 2021) [19].

These crops covering agro-textile products play a crucial role in modern agriculture by providing essential protection and support to a wide range of crops. They contribute to the sustainability and efficiency of agricultural practices by mitigating

Table 3: Agro Geotextile Textile Products

Sr. No.	Name of Agro Textile Product	Crop Cultivation	Fiber Used	Properties	References
1	Geotextiles (Mulches, Nets, Linters)	Groundnut	Coir, Jute, Vetiver Root	High water retention, yield increase	Adhikary & Sankar (2018) [12]
2	Geotextiles	Tomato, Tea, Groundnut, Black Gram	Jute (Nonwoven)	Soil conservation, water retention, weed suppression, nutrient enrichment	Saha (2021) [13]

Table 3 outlines geotextiles agro-textile products and their applications, fiber compositions, properties, and references.
Geotextiles (Mulches, Nets, Linters): These geotextiles find utility in groundnut cultivation and are composed of fibers like coir, jute, and vetiver root. They excel in retaining water and enhancing yield. Geotextiles play a crucial role in groundnut farming by effectively retaining moisture in the soil, which contributes to improved plant growth and increased yields (Adhikary & Sankar, 2018) [12].
Geotextiles: Utilized in various crops including tomato, tea, groundnut, and black gram, these geotextiles are predominantly made from nonwoven jute fibers. They offer a multitude of benefits such as soil conservation, water retention, weed suppression, and nutrient enrichment. Geotextiles help in maintaining soil structure and fertility, minimizing water runoff, controlling weed growth, and enriching the soil with essential nutrients, thereby promoting healthy crop growth and higher yields (Saha, 2021) [13].
Geotextiles agro-textile products serve as versatile tools in agriculture, offering solutions for soil management, moisture retention, weed control, and nutrient enrichment, thereby contributing to sustainable and productive farming practices.

Table 4: Properties of Mulching Materials

Mulching Material	Tenacity	GSM	Air Permeability	Thickness	Width
Jute Nonwoven fabric produced from fresh jute (M/C direction)	0.21	365	24.18		100±10 cm
Jute Nonwoven fabric produced from fresh jute (Cross direction)	0.72				100±10 cm
Nonwoven from waste jute fibre	0.02	391	25.76		100±10 cm
Jute (nonwoven)				3-6 cm	100±10 cm

The table provides a comprehensive overview of the properties of various mulching materials, focusing on parameters like tenacity, GSM (grams per square meter), air permeability, thickness, and width.

Jute Nonwoven Fabric Produced from Fresh Jute (Machine/Cross Direction): This material exhibits different tenacity values depending on the direction of production. In the machine direction, it has a tenacity of 0.21, while in the cross direction, it is higher at 0.72. The GSM values are 365 and not specified, respectively, indicating the weight of the material per square meter. The air permeability for the machine direction is 24.18, although it is not specified for the cross direction.

Nonwoven from Waste Jute Fiber: This material has a lower tenacity of 0.02 compared to the fresh jute nonwoven fabric. However, it has a higher GSM of 391 and air permeability of 25.76, indicating its potential suitability for specific applications.

Jute (Nonwoven): The thickness of this material ranges from 3-6 cm, with varying GSM values from 250-750. The width is standardized at 100±10cm, ensuring consistency in application.
These properties are crucial considerations for selecting the appropriate mulching material based on the specific requirements of the agricultural environment, including soil type, climate conditions, and crop type. High tenacity and appropriate GSM values ensure durability and effectiveness in weed suppression and moisture retention, while air permeability influences soil aeration and water drainage. Thickness and width specifications contribute to ease of handling and installation in the field.

Conclusion

In conclusion, the extensive review of mulching agro-textile products, crop covering agro-textile products, and geotextiles agro-textile products highlights their significant contributions to modern agriculture. These specialized textile solutions offer a wide array of benefits, including moisture retention, weed suppression, soil conservation, and protection against environmental stressors like hail, UV radiation, and excessive solar radiation. Mulching agro-textile products, such as mulch mats and mulches, play a crucial role in maintaining soil moisture levels, controlling weeds, and enhancing soil fertility. They have been shown to improve crop yields and promote sustainable farming practices in various crop cultivation scenarios.
Crop covering agro-textile products provide essential protection to crops against adverse weather conditions and environmental factors. By offering hail protection, UV stability, and water retention capabilities, these products contribute to the overall health and productivity of crops, ensuring optimal growing conditions and higher yields. Geotextiles agro-textile products serve as effective tools for soil management, water retention, and nutrient enrichment. They play a vital role in enhancing soil structure, suppressing weeds, and promoting nutrient uptake in crops, thereby fostering sustainable agricultural practices and increasing crop resilience.
Overall, agro-textile products represent innovative solutions for addressing key challenges in agriculture, including water scarcity, soil degradation, and environmental degradation. Continued research and development in agro-textile technology are essential for further advancing these products' efficacy, applicability, and sustainability, ultimately ensuring food security and environmental stewardship in the face of evolving agricultural needs and challenges.

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