

Sustainable Agriculture with Biodegradable Mulching Films: Polyvinyl Alcohol and Starch-Based Solutions

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Abstract

In this review, the environmental effects of conventional non-biodegradable polyethylene mulching films are specifically examined, alongside the growing issue of plastic pollution in agriculture. It emphasizes the urgent need for environmentally friendly substitutes and concentrates on biodegradable materials like starch-based films and polyvinyl alcohol (PVA). PVA is unique because it forms a strong film, is biodegradable, and works well to retain soil moisture, suppress weeds, and increase crop yields - especially when mixed with natural polymers like starch. Conversely, starch-based films are attractive due to their renewable nature, abundance, and environmental friendliness; however, they often exhibit lower mechanical strength and durability. Additionally, the study examines current research aimed at improving these materials through mixing, crosslinking, and nanofillers. In addition, it examines their field performance, their impact on soil health, and their potential economic and environmental benefits. In general, mulching films made from PVA and starch are viable, environmentally friendly substitutes for traditional plastics, helping reduce waste and promote sustainable farming methods. According to the review, more multidisciplinary research is necessary to further improve these materials for widespread, useful application in contemporary farming.

Keywords: *Biodegradable, polyvinyl alcohol (PVA), starch, crosslinking.*

1. Introduction

Plastic manufacturing and use have increased at an unprecedented rate since the end of World War II, becoming a necessary component of daily living and industrial advancement [1]. Particularly, plastic products including films, foams, pipes and containers are now widely used in the horticulture and agricultural industries. These plastics are frequently utilized for greenhouse construction, crop protection and storage, weed and insect management, and fertilizer transportation [2]. With an estimated 2.25 million tons used annually worldwide, plastics today serve a crucial role in every step of the agricultural production chain, from the nursery stages to postharvest processing [2].

However, the extensive and on-going use of plastics in agriculture has led to a significant accumulation of waste and an increase in environmental concerns. Because of its superior mechanical strength and barrier qualities, low-density polyethylene (LDPE) is one of the most widely used polymers among these materials, particularly for mulching and greenhouse applications [3–5]. Despite these benefits, the majority of petroleum-based polymers, including polyethylene (PE), polyvinyl chloride (PVC), and polypropylene (PP), disintegrate relatively slowly and have a long half-life in the environment [6–10]. These polymers' durability causes soil contamination, the production of microplastics, and the spread of dangerous particles across ecosystems, all of which pose major dangers to human and environmental health. Worldwide, PE films are estimated to cover 130,000 square kilometres of agricultural land annually [11, 12]. Their accumulation in the soil over time alters its natural composition, decreasing aeration and porosity, impeding root growth,

and eventually decreasing crop yield [13–15]. These problems underscore the need to develop environmentally benign, sustainable substitutes for conventional plastic mulching materials [16, 17].

Mulching, which involves covering the soil surface with either organic or inorganic materials, has long been used to control soil temperature, reduce erosion, suppress weeds, preserve moisture, and increase crop yields [18, 19]. From a resource management perspective, mulching supports more sustainable, productive farming by improving the use of water and nutrients [20].

Biodegradable and bio-based mulching materials have gained popularity recently as affordable substitutes for conventional polymers derived from fossil fuels. One significant development among them is liquid mulch films, which are sprayable coatings created from film-forming polymers derived from biomass [21, 22]. After crops are harvested, these films can be immediately put to the soil's surface and gradually decompose into non-toxic substances that lessen their negative effects on the environment [23, 24]. However, the high water content (about 50–70 weight per cent) in conventional liquid mulch formulations raises the energy required for storage and transportation. In addition to increasing expenses, this also lessens their carbon neutrality and suitability for widespread usage [22, 25]. Therefore, creating water-soluble, fully biodegradable, next-generation mulching films has become essential to implementing more sustainable farming methods.

This paper highlights the potential of biodegradable mulching films derived from PVA and starch as sustainable substitutes for traditional PE films, providing a thorough analysis of these films. Recent research on their effects on the environment, degrading behaviour, and agricultural performance is compiled and examined. The review also examines how PVA-starch-based films can help raise crop yields, retain soil moisture, and suppress weed growth, all of which support more ecologically friendly farming practices. The main obstacles to scaling up these materials are also covered, including stability, production costs, and long-term environmental impacts. This information will help guide future research and legislative initiatives that will promote sustainable agricultural solutions.

2. Overview of Mulching Films in Agriculture

Mulching has attracted popularity in agriculture because of its shown ability to enhance soil quality and increase crop yields. In addition to controlling soil temperature and moisture, which are essential for nutritious plant growth, it suppresses weeds and improves the physical, chemical, and biological qualities of the soil [1, 26]. Conventional plastics derived from fossil fuels, particularly LDPE, are the most widely used mulching material because of their superior mechanical flexibility, water permeability, and puncture resistance [27]. Notwithstanding these benefits, LDPE mulch films pose serious environmental problems. After harvest, they are difficult to recycle, and many end up as non-biodegradable waste in the soil. The main cause of its durability is LDPE's hydrophobicity and chemical inertness, which render it extremely resistant to chemical and microbiological degradation [28, 29].

Biodegradable mulch films (BDMs), which offer comparable agricultural advantages to traditional LDPE films while contributing in the reduction of long-term plastic pollution, have surfaced as a sustainable solution to these problems [30–32]. However, environmental factors such as moisture, temperature, and microbial activity significantly affect how BDMs break down. Degradation may occur slowly or not at all under unfavorable circumstances, leaving behind film fragments in the soil [33–36]. Mulching nonetheless increases crop yields, suppresses weed growth, and improves the soil microclimate despite these

drawbacks. Therefore, switching to biodegradable materials is crucial to attaining farming methods that are both environmentally friendly and productive [1].

3. Biodegradable Mulching Films (BDMFs): General Concepts

Biodegradable mulch films have become a more environmentally friendly option than traditional polyethylene mulches. They can be applied in accordance with the specific requirements of crop growth or cultivation cycles, and soil microorganisms will gradually decompose them after harvest. This natural biodegradation enhances soil fertility and aids in the restoration of the natural ecosystem in addition to preventing the buildup of plastic residues [37]. Therefore, biodegradable films provide a viable substitute for the extensively utilised LDPE films in agriculture.

Table 1. Classification of the field degradation stage and effective life of biodegradable plastic films

Field Degradation Stage Division of Degradable Plastic Film		Effective Life Grading of Biodegradable Plastic Films	
Grade	Effective Service Life (d)	Degradation Stage	Field Performance
I	≤ 60	I	The phase starting from mulch application and continuing until visible cracks begin to appear
II	$>60 - \leq 90$	II	The phase during which approximately 25% of the plastic film exhibits minor cracking
III	$>90 - \leq 120$	III	The phase characterized by the formation of 2–2.5 cm cracks in the film
IV	>120	IV	The stage at which uniform network-like cracks develop in the mulch film
		V	The stage at which no large fragments of mulch remains in the field
		VI	The stage at which plastic film fragments are no longer visible on the surface.

The classification of biodegradable plastic films according to their field breakdown phases is shown in Table 1, which connects the mulch's visible alterations to its useful life [39]. The biodegradability of different partially renewable mulch materials in soil is compiled in Table 2, which also reports the degradation period and overall biodegradation efficiency of each material [40]. Biodegradable liquid mulch films have gained popularity recently as a cutting-edge substitute for conventional solid mulches. These liquid formulations aid in binding soil particles together when sprayed on the soil, improving important physical characteristics as water retention and thermal insulation [38]. Furthermore, liquid mulch films have the same protective advantages as traditional plastic mulches, preserving soil moisture and heat, with the added benefit of being simple to apply on complicated or uneven terrain where sheet mulches are challenging to utilize [38].

Table 2. Degradability of Partially Renewable Degradable Mulch in Soil

Type of mulch	Biodegradable time(day)	Biodegradation capacity (%)	References
Cellulose	20	50	41
Durian-rind cellulose	28	>99	42
Cellulose/myristic acid	102	>99	43
Cellulose-based bioplastic	180	>99	44
PVA/SA/MAL	50	55	45
Lignin biopolymeric	28	78.7	46
PVA/lignin	35	25.46	47
PVA/CS	30	60	48
CS and copper-doped carbondots	56	63.61	49
Starch-SA-montmorillonite-star anise oil	22	>99	50
SA and corn starch	25	>99	51
PLA/SS-g-PLA	43	80	52
PLA and sisal fibers	98	60	53
PHA	80	75	54
Starch acetates/PVA	50	50	55
PBAT/zein blends	30	53	56
Gelatin	42	>99	57

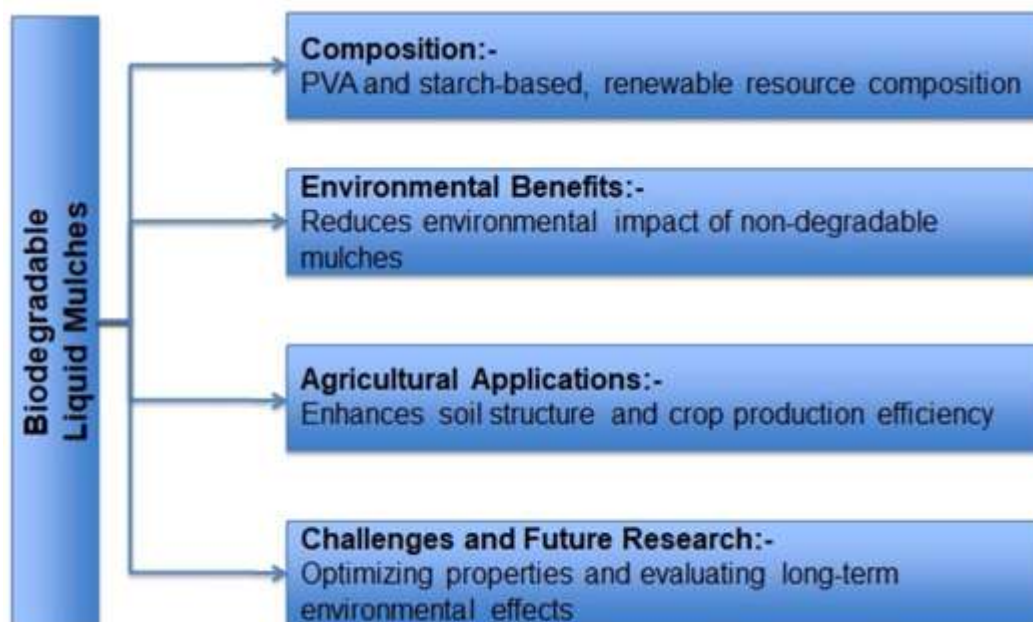


Figure 1. Conceptual Overview of Biodegradable Liquid Mulches in Agriculture

Figure 1 suggests using biodegradable liquid mulches as an environmentally responsible alternative to conventional plastic mulches in farming. These mulches are sustainable and renewable, composed primarily of natural components derived from starch and polyvinyl alcohol (PVA). They promote more environmentally friendly farming methods and lessen the damage that non-biodegradable plastics contribute to the environment by decomposing organically. Furthermore, biodegradable liquid mulches provide a more sustainable method of modern agriculture by enhancing crop yields and soil health

4. Polyvinyl Alcohol (PVA) - Based Mulching Films

4.1. Properties of PVA

The material properties of PVA, including mechanical and thermal properties such as elongation at break, tensile strength, and melting temperature, are shown in Table 3 [58]. It also highlights PVA's drawbacks, particularly its sensitivity to high temperatures and wet environments, which may limit its usefulness.

Table 3. Material properties and limitations of PVA

Type	Material Properties	Limitations
PVA $[\text{CH}_2\text{CH}(\text{OH})]_n$	PVA is a water-soluble synthetic polymer with a melting temperature of 180-230 °C, tensile strength ranging from 28-46 MPa, and elongation at break between 4-40%. It exhibits high tensile strength but limited temperature resistance.	Its properties may degrade at elevated temperatures, limiting its application in high-humidity or aqueous environments.

Utilizing biodegradable polymers offers a sustainable substitute for traditional petroleum-based plastics since soil microbes can convert them into safe, eco-friendly products. Biological safety is ensured, ecological contamination is reduced, and the strain on natural resources is reduced [59, 60]. Among these materials, PVA has attracted significant attention due to its superior physicochemical properties, strong film-forming capabilities, and inherent biodegradability, making it a promising option for creating environmentally friendly plastics [61, 62].

Pure PVA has several drawbacks though, such as a comparatively slow rate of breakdown, restricted usefulness, high water solubility, and increased production costs. These elements may weaken its mechanical properties and limit its usefulness [68]. PVA is frequently combined with biodegradable, renewable biopolymers such as sodium alginate, lignin, starch, gelatin, chitin or chitosan to overcome these issues. In addition to increasing biodegradability, this type of blending reduces production costs and improves the final product's overall performance [62–67, 69–72].

4.2. Enhancing PVA Performance through Blending

By combining PVA with natural polymers, hydroxyl, carboxyl, and other functional groups can interact chemically and physically to generate a stable three-dimensional cross-linked network [73, 74]. This network structure significantly enhances mechanical strength, barrier properties, and UV protection. For example, Kochkina and Lukin [75] used solution casting to produce maize starch/chitosan/PVA composite films that showed improved mechanical strength and UV protection. In a similar vein, Su et al. [76] improved the UV resistance, mechanical durability, water retention, and production costs of PVA-based mulch films by adding sodium alginate and quaternary lignin. Additionally, PVA/chitosan/lignin and PVA/chitin/lignin films were created by Worku et al. [77] and shown robust mechanical qualities, antibacterial activity, antioxidant effects, and efficient UV protection.

There are still certain difficulties despite these advancements. Carboxymethyl cellulose's (CMC) high water solubility limits water resistance [78], while starch's strong crystallinity limits thermoplasticity and makes film formation more difficult [79]. Despite its low cost, water resistance, and UV protection, lignin's poor dispersion due to strong hydrogen bonding and π - π stacking can degrade film performance. Cyanoethylation is one chemical alteration that enhances lignin dispersion in PVA-based films while maintaining its UV-resistant and antioxidant qualities [80–85].

4.3. Preparation and Application of PVA-Based Liquid Mulch Films

Common methods for creating PVA-based liquid mulch films include solution casting, hot-film forming, and spraying. PVA is usually dissolved in water while being constantly stirred; occasionally, acids or other substances are added to enhance solubility and promote crosslinking. To produce a homogenous mixture, biopolymers such as starch are gelatinized and progressively mixed into the PVA solution while being constantly stirred. The solution can be cast or applied directly to create composite films once it has been well combined and allowed to cool [86].

The liquid mulch was prepared in the laboratory. Figure 2 shows two parts: (A) represents the image without any mulch liquid, while (B) shows a liquid mulch layer made from PVA (5 g) with oxalic acid (40% of PVA). Subfigures (a), (b), (c), and (d) illustrate the condition of the mulching layer on the 1st, 2nd, 5th, and 10th days, respectively.

The evolution of the PVA-based liquid mulch is depicted in Figure 2. A distinct, consistent mulch layer made with PVA (5 g) and oxalic acid (40% PVA) is shown in part (B), in contrast to part (A), which shows empty soil. On the first day, the layer appears intact and smooth, which helps retain soil moisture. It begins to lose its shine somewhat on the second day due to drying. Little cracks start to show on the fifth day, and by the tenth day, the layer is considerably more degraded. Overall, the images show that the mulch creates a strong protective layer at first but then breaks down over time, highlighting its biodegradable, temporary protective qualities for agricultural use.

By spraying these films onto soil, biodegradable mulch can be produced that offers the same advantages as conventional plastic mulches, such as crop protection, temperature control, and soil moisture retention [87,88]. Materials such as starch, cellulose, chitosan, alginate, glucomannan, hydroxyethyl cellulose, and lignocellulose waste are commonly used in current biodegradable mulch formulations. These materials can be chemically processed or applied in the field to produce efficient films [89, 90].

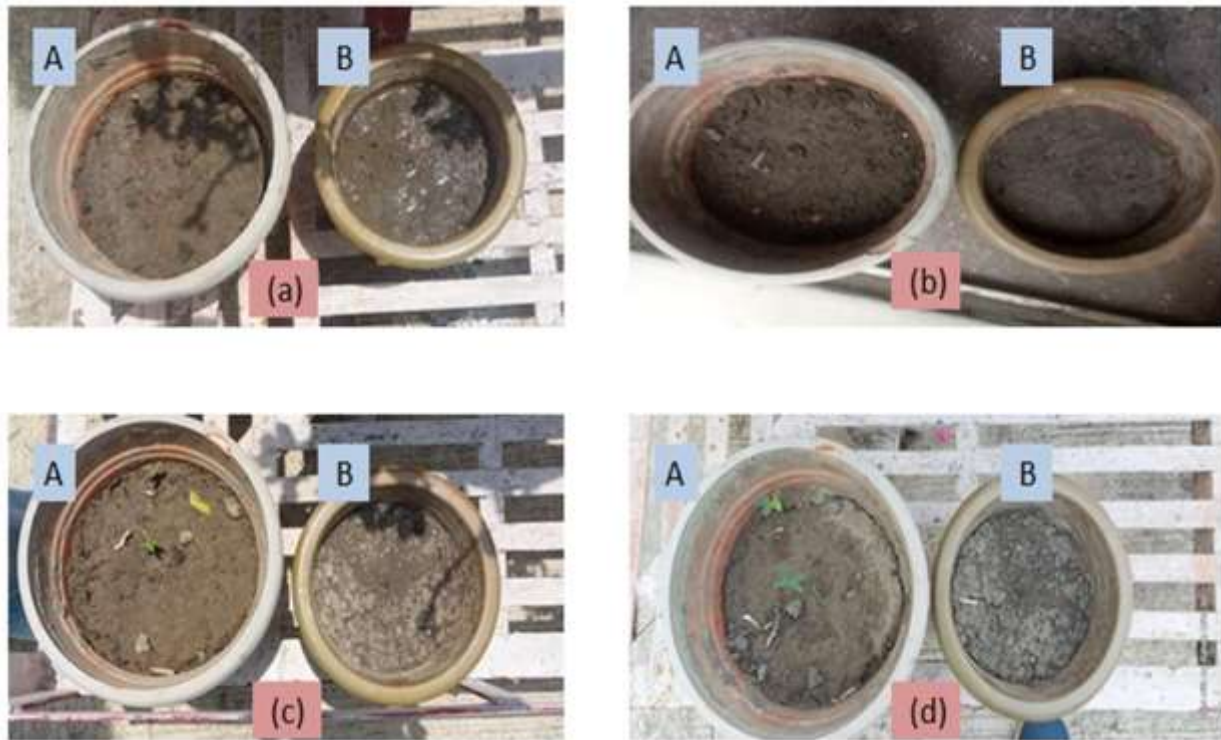


Figure 2. (a). Condition of the mulching layer on the 1st day. (b). Condition of the mulching layer on the 2nd day. (c) Condition of the mulching layer on the 5th day. (d) Condition of the mulching layer on the 10th day.

4.4. Key Properties of PVA for Biodegradable Films

PVA is a good choice for biodegradable liquid mulch films due to several of its characteristics. Strong hydrophilicity, intrinsic antioxidant activity, biocompatibility, good biodegradability, and exceptional film-forming ability are among its many qualities [91–94]. High tensile strength and flexibility are enabled by PVA's many hydroxyl groups, which also allow chemical interactions with substances such as anhydrides, isocyanates, and aldehydes [95]. Additionally, PVA has strong adhesive properties that enhance bond strength in resin systems such as urea-formaldehyde resins with lower formaldehyde content [96].

Although these benefits, PVA-based films have many drawbacks, such as low moisture retention, poor water resistance, and comparatively expensive production costs. Blending PVA with natural polymers or plasticizers can help with these problems [68, 69]. PVA-based films can be made to have better mechanical, barrier, and functional qualities by carefully choosing and modifying complimentary biopolymers. This makes them ideal for sustainable agricultural applications.

5. Starch-Based Mulching Films

One of the most common natural polysaccharides, starch has drawn a lot of interest as a sustainable and environmentally beneficial substance. Its broad availability in nature and quick regeneration cycle make it appealing. In terms of function, starch serves as a significant energy store in plants and is found in components such as stems, roots, tubers, and seeds [97]. Agricultural products like corn, wheat, rice, and barley; tubers like potatoes, cassava, and yam; legumes like peas and lentils; and other plants like bananas,

arrowroot, and sago are among the many botanical sources from which it can be produced [98–100]. The chemical composition of starch (including glucans, proteins, lipids, and moisture), the structural arrangement of amylose and amylopectin, and genetic and environmental factors all affect its physicochemical properties, which vary depending on the source [101,102]. The size and form of starch granules varies greatly, ranging from 2 to 150 μm . The amylose concentration is usually between 15% and 30%, however it can be as low as 0% or as high as 78%. Starch can be broadly divided into two categories based on amylose content: high-amylose starch (>50% amylose) and waxy starch (< 50% amylose) [99,103].

5.1. Modification and Applications of Starch Films

Starch-based materials are becoming increasingly popular as environmentally acceptable substitutes for traditional plastics, offering a sustainable choice for applications such as agricultural mulch films and packaging [104]. Excellent stretchability, superb transparency, resistance to folding, and low permeability to both water and gases are only a few of the advantageous properties of starch films [105].

Researchers have recently concentrated on using chemical and enzymatic changes to enhance the performance of starch films. For example, Guo et al. prepared enzyme-treated waxy maize starch (EWMS) by treating WMS with α -amylase and transglucosidase, yielding microencapsulated starch films with self-healing properties. The films' overall quality and endurance were improved by the efficient reduction of pore size and water vapor transmission caused by the introduction of microcapsules [106].

To improve its functional performance and mechanical strength, starch is frequently combined with other polymers. For instance, combined thermoplastic starch (TPS), maize starch (CS), poly lactic acid (PLA), and poly (ϵ -caprolactone) (PCL) to create biodegradable agricultural mulch films. The blends showed enhanced qualities such greater crop insulation, increased moisture retention, and increased chlorophyll content in tomato plants. They were made with Brabender-type intermittent mixers. Interestingly, in agricultural settings, these starch-based mixtures outperformed traditional plastic mulches [107].

5.2. Biodegradability and Nanocomposites

The development of sustainable polymers heavily relies on biodegradability. According to ASTM guidelines, a biodegradable substance decomposes under particular circumstances via microbial enzymatic activity into carbon dioxide, methane, water, inorganic chemicals, or biomass [108]. Under composting conditions, a polymer must break down by 90% or more within 90 days to be certified as biodegradable [110].

Environmental parameters such as temperature, humidity, pH, and microbial activity, as well as the presence of nano fillers and chemical changes, all affect the rate and degree of starch-based film degradation [109,111,112]. Small additions of montmorillonite (MMT), for example, can increase hydrophilicity and quicken decomposition. The antioxidant properties of nano fillers, such as Graphene oxide or TiO_2 , and specific chemical changes, on the other hand, can slow down biodegradation [111,113,114]. Additionally, crosslinking helps to slow down the rate of degradation. In contrast to unmodified thermoplastic starch, which lost 80% of its weight after 30 days, thermoplastic maize starch cross-linked with oxidised sucrose and reinforced with cellulose nanofibrils only lost 30% [115].

It's interesting to note that nano fillers can have different effects. For instance, under composting circumstances, cationic starch films containing MMT and nano crystalline cellulose broke down more quickly than films including antimicrobial compounds such as silver nanoparticles [114,116]. Because of their affordability and environmental friendliness, natural polymer-based liquid mulches derived from cellulose, sodium alginate, xylan, or starch is frequently used in agriculture. These materials' weak barrier qualities and quick biodegradation, however, can hinder their long-term effectiveness in the field [117–122].

6. Comparative Analysis: PVA vs Starch-Based Films

PVA-based and starch-based biodegradable films differ significantly in their mechanical performance, cost, biodegradability, and practicality, according to comparative research. Since starch is a naturally occurring polysaccharide that soil microbes may readily break down, starch-based films often have high biodegradability. Organic carbon is released into the soil as these films decompose, enhancing microbial activity and soil fertility. Starch-based films are a desirable and sustainable alternative for agricultural mulching, as they not only promote plant growth but also improve soil health in the long term. Low manufacturing costs are another significant benefit of starch-based films. Starch provides an affordable substitute for petroleum-based and even some synthetic biodegradable polymers due to its abundance, renewable nature, and ease of processing. Furthermore, more research has been conducted on starch-based films in actual agricultural environments, with several field tests demonstrating their biodegradability, use, and beneficial effects on soil quality and crop yields. These results have made starch one of the most useful and environmentally responsible ingredients for creating biodegradable mulch films. On the other hand, PVA films are prized for their superior structural stability and mechanical strength. They typically retain their integrity for longer periods of time during the crop cultivation cycle and are more resilient in field settings. In areas where longer-lasting soil covers is necessary to suppress weeds, hold onto moisture, or shield crops from temperature changes, this feature is especially helpful. But compared to starch-based films, PVA films are less biodegradable. Under natural composting conditions, their decomposition is delayed and often incomplete, potentially limiting their environmental benefits.

7. Challenges and Future Perspectives

This analysis highlights several persistent issues with the production and application of biodegradable mulching films. High moisture sensitivity, mechanical fragility, and challenges in managing degradation rates are some of the most notable problems. The effectiveness of the films during the cropping stage is frequently determined by these difficulties. Specifically, starch-based films have poor barrier properties and degrade quickly, even though they are highly biodegradable and environmentally beneficial. Their capacity to retain soil moisture and control weeds may be diminished as their structural stability deteriorates before the end of the growing season. Researchers have investigated using nanofillers, which can significantly alter film properties, to address these problems.

The use of nanoparticles has two sides: although they can increase mechanical strength, moisture resistance, and thermal stability, they have differing effects on biodegradation. Nanofillers can either accelerate or slow microbial decomposition, depending on their type and concentration. To strike the ideal balance between film durability and biodegradability, nanofillers must be carefully selected, optimised, and surface-modified. Combining natural polymers, such as starch, with other biodegradable substances, such as chitosan or PVA, is another interesting tactic. These combinations can improve overall functioning, tensile strength, and flexibility. Achieving uniform component dispersion, developing economical processing techniques, and increasing production to an industrial level without sacrificing sustainability or performance are among the practical obstacles that still need to be overcome. The assessment emphasises the need for ongoing research and innovation to address these issues and provide high-performance, reasonably priced, environmentally friendly materials that can withstand actual agricultural conditions. To ensure long-term stability and reliable performance, future research could focus on advanced cross-linking methods, bio-inspired material designs, and extensive field testing across a range of environmental conditions. Finally, material science is not the only factor in the successful use of biodegradable mulching films. Strong policy backing, industry participation, and cooperation between researchers, farmers, and manufacturers are all equally important.

8. Conclusion

In conclusion, biodegradable mulching films derived from PVA and starch exhibit significant promise as environmentally friendly substitutes for traditional polymers in the agricultural sector. Although starch-based films are inexpensive and extremely biodegradable, they have drawbacks, such as poor barrier properties and rapid disintegration. In contrast, PVA-based films have moderate biodegradability and higher prices, but they are stronger and more durable. The performance of hybrid films can be greatly enhanced by combining these materials with natural polymers or nanofillers. More research is required to improve field durability, lower prices, and ensure environmental safety to fully reap their benefits. Promoting their broad acceptance and attaining sustainable, environmentally friendly agriculture methods would require strong policy backing, interdisciplinary cooperation, and field validation.

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