



Biodegradable Smart Mulches for Sustainable Modern Agriculture

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INTRODUCTION

Agriculture has always depended on efficient management of water, soil and crop health. Among that many agronomic practices helps to improve crop production, mulching has become one of the important technique, because it helps to create a favorable conditions for good growth of a plant. Mulch is placed on the soil surface which acts like a protective layer to conserve moisture, suppress weeds, regulate temperature, and helps to improve overall crop performance. Farmers have used natural mulching materials for centuries, while plastic mulch has become widely adopted in modern farming due to its effectiveness. Although plastic mulch has improved the agricultural crop productivity, it also created major environmental concerns. After harvesting the crop, large quantities of plastic was remain in the field. Removing and disposing of these materials requires additional labors and cost, while small amount of tiny plastic particles left in the soil it gradually accumulates as micro plastic. These residues reduce the soil quality and threaten long-term agricultural sustainability. The search for eco-friendly alternative has led to the development of biodegradable smart mulches. These innovative materials provide the same agronomic benefits as conventional plastic mulch while naturally decomposing after use. Few types of mulch are advanced biodegradable and also designed to respond to environmental conditions, making them more efficient and sustainable. This concept discusses the biodegradable smart mulches, their types, agricultural applications and their advantages, limitations and future prospects in sustainable agriculture.

Importance of Mulching in Agriculture:

Mulching plays as essential role in improving crop production by creating a favorable soil environment. It reduces direct evaporation from the soil surface, allowing crops to utilize available moisture more efficiently. The mulch layer also prevents rapid fluctuations in soil temperature, protecting plant root from extreme heat and cold.

Another major benefit of mulching is weed suppression. By blocking sunlight from reaching weed seeds, mulch limits weed germination and reduces competition for nutrient and water. It also reduces the soil erosion caused by rainfall and wind while preventing nutrient loss through surface runoff. In addition, mulching helps to produce cleaner fruits and vegetables, reduces soil compaction, improves water-use efficiency and contributes to higher crop productivity. These benefits make mulching an important practice to the sustainable agriculture.

Limitations of Conventional Plastic Mulches:

Plastic mulches made from polyethylene have become more popular because they are very durable, long-lasting and inexpensive. However, their widespread use has created environmental and economic challenges. After crop harvest,

plastic mulch must be collected and transport for recycling or disposal. For this process requires more labors and also increases cost of production. In many cases damaged plastic mulches cannot be recycled because it contains plant residues and soil particles.

Another major concern is the accumulation of plastic fragments in agricultural soils. Continues use of plastic mulch results in micro plastic pollution, which affects soil organisms and alters soil structure. These tiny micro plastic particles may remain in the environment for many years without breaking down naturally. Open burning of used plastic mulch is still practiced in some areas, where it can releases very harmful gases into the atmosphere and also it leads to air pollution. These issues have encouraged researches to develop environmentally safer alternatives.



After harvest, plastic mulch must be collected and transported for disposal or recycling, increasing labor and costs.

Plastic fragments break down into microplastics that accumulate in soil and harm soil health and beneficial organisms.

Open burning of used plastic mulch releases toxic gases, causing air pollution and health hazards.

● Plastic mulch waste left in the field after harvest.

● Microplastic fragments accumulate in soil, affecting soil health.

● Burning plastic mulch pollutes air and harms the environment.

Significance of Biodegradable Smart Mulches:

Modern agriculture requires a technology that increases productivity while protecting natural resources. Biodegradable smart mulches meet these needs by crop production benefits with environmental sustainability.

Unlike Conventional plastics, biodegradable mulches gradually decompose into naturally occurring compounds through the action of soil microorganisms. This eliminates the need for costly removal after harvest and reduces plastic waste. Advanced smart mulches may also possess improved properties such as controlled degradation, enhanced moisture conservation and better compatibility with different cropping systems. These features support sustainable agriculture while reducing environmental impact.

Definition of Biodegradable Smart Mulches:

Biodegradable smart mulches are eco-friendly soil covering materials it performs the function of conventional mulch while naturally decomposing after completing their purpose. Smart biodegradable mulches protect the soil during crop growth and gradually break down through microbial activity without leaving harmful residues.

The term “smart” refers to their improved performance, including controlled degradation, better moisture management and compatibility with eco-friendly farming systems.

Composition and Materials in Biodegradable Smart Mulches:

Biodegradable smart mulches are prepared with using renewable biological resource and biodegradable polymers, common materials include starch, cellulose, polylactic acid (PLA), polyhydroxyalkanoates (PHA) and other plant derived compounds.

Natural fibers and natural materials obtained from agricultural residues such as banana fiber, jute, rice straw, coconut coir, and sugarcane bagasse and also incorporated into biodegradable mulch products to improve strength and decomposing characteristics.

Comparison of Both Conventional plastic Mulch and Biodegradable Smart Mulch:

Conventional plastic mulch remains in the field after harvest unless removed manually and contributes to long-term plastic pollution in soil. In contrast, Biodegradable smart mulch gradually decomposes naturally into harmless substances under suitable soil conditions.

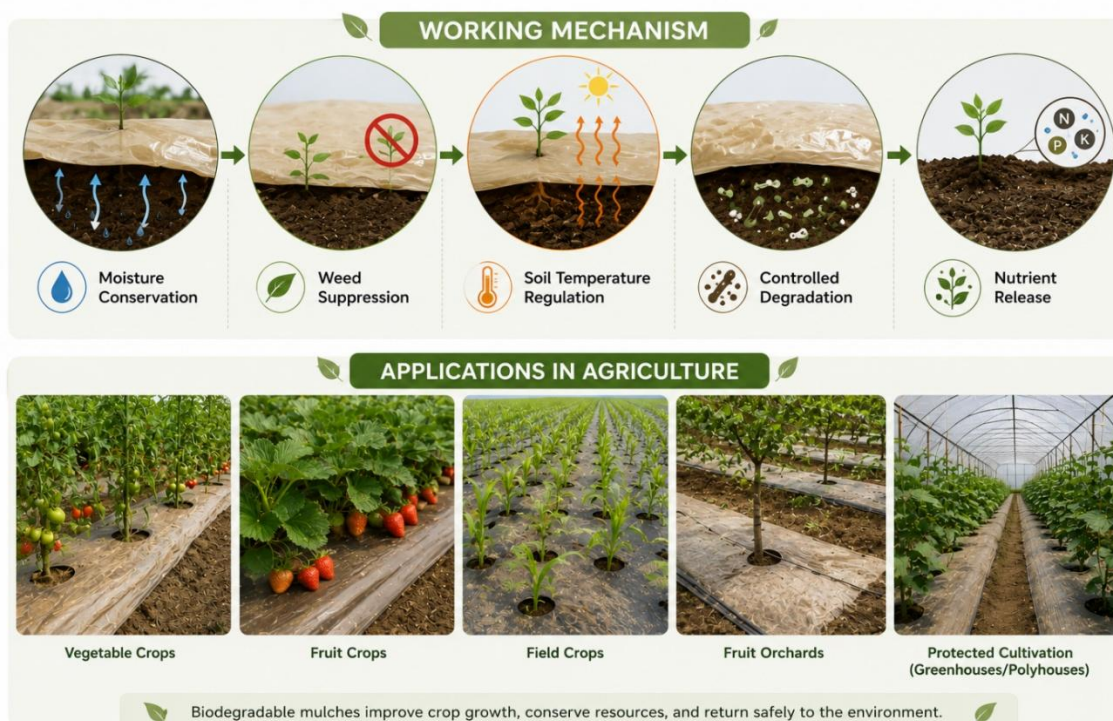
After harvest, conventional plastic mulch requires removal, collection and also creates disposal problems, which increase labor requirements, handling cost and waste management challenges. Biodegradable smart mulch eliminates the need of these additional operations by decomposing in soil, reducing overall cost while promoting cleaner fields and supporting long-term soil health by preventing plastic accumulation.



Types of Biodegradable Smart Mulches:

- **Starch-Based Mulches:** Starch based mulches are produced from renewable source such as maize, potato, wheat starch. They are biodegradable, environmentally friendly and suitable for vegetable and horticulture crops. Their degradation rate can be modified by blending starch with biodegradable polymers.
- **Cellulose-Based Mulches:** Cellulose is the most abundant polymer found in plants. Cellulose-based mulches provide effective weed control and moisture conservation while decomposing naturally through microbial action. Their renewable origin makes them highly suitable for sustainable agriculture.
- **Poly(lactic Acid (PLA)-Based Mulches:** PLA is produced from fermented plant sugars obtained from crops such as corn and sugarcane. PLA-based mulches possess good mechanical strength and provide crop protection comparable to conventional plastics while remaining biodegradable under suitable environmental conditions.
- **Poly(hydroxyalkanoates (PHA)-Based Mulches:** PHA is a biodegradable polymer synthesized naturally by certain microorganisms. These mulches exhibit excellent biodegradable and environmental compatibility. Their ability to decompose completely makes them promising solution for future agriculture applications.
- **Other Bio-Based Mulches:** Several other biodegradable materials are being investigated, including protein-based polymers, natural fibers composites and agricultural residues. Researchers are also combining multiple biodegradable materials to improve strength, durability and degradation behavior.

Working of Biodegradable Smart Mulches:



- **Moisture Conservation:** Biodegradable smart mulches reduce evaporation from the soil surface, allowing moisture to remain

available for longer periods. This improves irrigation efficiency and helps crops withstand short periods of water stress.

- **Weed Suppression:** The mulch layer blocks sunlight from reaching weed seeds, reducing their germination and growth. Lower weed pressure decreases competition for nutrients, water and light resulting in healthier crop development.
- **Soil Temperature Regulations:** Biodegradable mulches maintain a more stable soil temperature by reducing rapid heating during the day and minimizing heat loss at night. Stable temperature encourages better root growth and improve nutrient uptake.
- **Controlled Degradation:** Unlike conventional plastics, biodegradable smart mulches are designed to remain functional throughout the cropping period before gradually decomposing. Soil microorganisms convert these materials into CO₂, water and biomass under suitable environmental conditions.
- **Nutrient Release:** Some biodegradable mulches contain natural compounds that release small amount of nutrients during decomposition. It can support soil microbial activity and improve soil fertility.

Applications in Agriculture:

- **Vegetable crops:** Biodegradable mulches are widely used in tomato, chilli, cucumber, brinjal, watermelon, and other vegetable crops. They improve moisture retention, reduce weed growth and enhance fruit quality while eliminating plastic waste.
- **Fruit Crops:** Fruit orchards benefit from biodegradable mulching through improved soil moisture conservation, better root development and reduced weed competition. Crops such as strawberry, grape, banana, and citrus have shown positive responses.
- **Field Crops:** Field crop including maize, cotton, groundnut and sunflower can also benefit from biodegradable mulching, particularly in water-limited regions where moisture conservation is essential.
- **Organic Farming:** Organic farming systems emphasize environmentally friendly production practices. Biodegradable smart mulches fit well within these systems by reducing synthetic plastic use and supporting ecological sustainability.
- **Protected Cultivation:** Greenhouses and polyhouses often rely on mulching to improve crop performance. Biodegradable materials provide the required benefits while reducing disposal problems associated with plastic films.

Advantages of Biodegradable Smart Mulches:

1. **Reduced Plastic Pollution:** The greatest advantage of Biodegradable smart mulches is the significant reduction of plastic waste in agriculture. Their natural decomposition reduces long-term environmental contamination.
2. **Improved Soil Health:** Unlike conventional plastic residues, biodegradable materials support soil biological activity and reduce the risk of micro plastic accumulation, contributing to healthier ecosystems.
3. **Better Water-Use Efficiency:** Moisture conservation reduces irrigation frequency and improves water-use efficiency an important advantage in drought-prone regions.
4. **Enhanced Crop Growth and Yield:** Improved soil conditions promote stronger root development, better nutrient uptake and healthier crop growth often resulting in increased yield and improved product quality.
5. **Lower Labor Cost for Mulch Removal:** Since biodegradable mulches naturally decompose after use, farmers save both time and labor that would otherwise be required for collecting and disposing of plastic mulch.
6. **Supports Sustainable Farming:** The use of renewable raw materials and environmentally safe decomposition makes biodegradable smart mulches an important component of sustainable agricultural systems.

Limitations and Challenges:

1. **Higher Initial Cost:** Biodegradable smart mulches are generally more expensive than conventional plastic films, limiting their adoption among small-scale farmers.
2. **Performance Under Different Climatic Conditions:** Very dry, cold or extremely wet environments may influence the durability and decomposition behavior of biodegradable mulch materials.
3. **Limited Farmer Awareness:** Many farmers remain unfamiliar with biodegradable mulch technology its benefits and proper field management practices. Extension activities are necessary to increase adoption.
4. **Availability and Commercialization:** Large-scale production and distribution are still limited in many regions. Improving manufacturing capacity and reducing production costs will be essential for wider adoption.

Future Prospects

The future of biodegradable smart mulches is highly promising, with researchers developing nanotechnology-based mulches that improve durability, moisture regulations and disease management while maintaining environmental safety. These mulches are expected to become an important component of climate-smart agriculture by conserving water, reducing plastic waste and improving crop resilience under changing climatic conditions. Future farming may also integrate biodegradable mulch technology with artificial intelligence and precision agriculture, where smart monitoring systems can recommend the most suitable mulch type based on crop requirements, weather conditions, and soil characteristics. In addition, government incentives, awareness programs and research support can encourage wider adoption, while policies promoting sustainable agricultural practices will accelerate commercialization. Future research should focus on improving mechanical strength, reducing production costs, optimizing degradation rates and developing multifunctional mulch materials suitable for

diverse cropping systems through collaborations among scientists, industries and policymakers.

CONCLUSION

Biodegradable smart mulches represent an important advancement in sustainable agriculture by providing the agronomic benefits of conventional mulching without creating long-term plastic pollution. Their ability to conserve soil moisture, suppress weeds, regulate soil temperature and decompose naturally makes them an environmentally responsible alternative for modern farming.

Although challenges such as higher production cost and variable degradation rates remain continuous research and technological innovations are improving their performance and affordability. Greater farmer awareness supportive government policies and increased commercial availability will further encourage their adoption.

As agriculture moves towards environmentally sustainable production systems, biodegradable smart mulches are expected to play an increasingly important role. Their integration into modern farming practices offers a practical pathway to enhance crop productivity while protecting soil health and reducing environmental pollution for future generations.

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