Indian Farming 76 (07): 73-76; July 2026

Innovative mulches: Redefining soil stewardship in rainfed agriculture

S. Susmitha[1]*, K.S.V.P. Chandrika[1], G. Suresh[1] and Anupama Singh[2]

[1]*ICAR-Indian Institute of Oilseeds Research, Rajendranagar, Hyderabad, Telangana 500 030*
[2]*ICAR-Indian Agricultural Research Institute, New Delhi 110 012*

Rainfed agriculture in India remains highly vulnerable to erratic rainfall, moisture stress and soil degradation, necessitating sustainable agronomic interventions. Mulching is a vital moisture conservation practice that improves soil health and stabilises crop yields under climate variability. Conventional plastic mulches such as high-density polyethylene, low density polyethylene, polypropylene and polyurethane revolutionised production systems but resulted in persistent plastic residues and soil contamination. Synthetic biodegradable mulches attempted to overcome disposal concerns, yet incomplete degradation and microplastic persistence remain challenges. Organic mulches like paddy and maize straw, though biodegradable, are often bulky, labour-intensive and inconsistent in performance. Recognising national priorities of soil health restoration, plastic reduction and climate-resilient agriculture, ICAR-Indian Institute of Oilseeds Research is focusing on developing innovative mulch technologies tailored for rainfed eco-systems.

Keywords: Conservation agriculture, Germination, Plastic reduction, Soil health, Weed control

RAINFED agriculture occupies about 51% of country's net sown area and accounts for nearly 40% of the total food production. In view of the growing demand for food grains under climate change scenario and urbanisation in the country, there is a need to develop and enhance the productivity of rainfed areas. Rainfed agriculture is complex, highly diverse and risk prone. Rainfed agriculture is characterised by irregular monsoons, prolonged dry spells, high evapotranspiration and fragile soils which limit productivity and income stability for millions of smallholders.

Soil organic carbon depletion, erosion and poor nutrient use efficiency further intensify vulnerability. Under such conditions, conserving soil moisture and enhancing soil resilience are not optional strategies but fundamental necessities. Among various agronomic practices, mulching has consistently demonstrated its potential to buffer crops against climatic stress while improving soil functionality. However, the widespread use of conventional plastic mulches, especially polyethylene films, has created new environmental concerns.

The early days approach: Plastic as a productivity tool

The introduction of synthetic mulches marked a turning point in crop production. Materials such as high-density polyethylene (HDPE), low-density polyethylene (LDPE), polypropylene and polyurethane were widely adopted due to their durability and efficiency. These plastic films effectively suppressed weeds, reduced evaporation, moderated soil temperature and improved crop yields. For many farming systems, particularly horticulture, they were considered revolutionary technologies. However, the long-term implications of their non-biodegradable nature gradually became evident. Residual plastic fragments accumulated in soils, impairing soil structure and porosity. Over time,

larger sheets fragmented into microplastics, which interfered with soil microbial activity and potentially entered the food chain. Disposal posed additional challenges, as burning released harmful emissions and improper burial led to persistent contamination. While productivity gains were undeniable, ecological sustainability was compromised.

Emergence of synthetic biodegradable mulches

In response to environmental concerns, synthetic biodegradable mulches were developed with the promise of controlled degradation under field conditions. These materials were engineered to break down through chemical and microbial processes, reducing the need for post-harvest removal. Although they represented technological progress, field experiences revealed limitations. Degradation rates varied widely depending on climate and soil conditions. In many cases, partial degradation resulted in residual polymer fragments remaining in the soil. Even when labelled biodegradable, certain formulations contained plastic-based components that did not fully mineralise, leading to microplastic persistence. Thus, while synthetic biodegradable mulches reduced visible plastic waste, concerns regarding long-term soil health remained.

Organic mulches and their constraints

Organic mulches such as paddy straw, maize stover, sugarcane trash and other crop residues have been traditionally used in Indian agriculture. Being naturally biodegradable, they enhance soil organic matter, improve aggregation and stimulate microbial activity. In rainfed areas, they help conserve moisture and reduce erosion. Despite these advantages, practical constraints limit their widespread adoption. Organic mulches are bulky and require substantial labour for transport and uniform application. Their thickness is often inconsistent, leading to uneven weed suppression and variable moisture conservation. Rapid decomposition under warm conditions necessitates repeated application. Additionally, crop residues frequently have competing uses as fodder or fuel, reducing their availability for mulching. Consequently, while environmentally benign, organic mulches are often cumbersome and operationally less efficient, particularly in large-scale farming systems

Transition to innovative mulch technology

The limitations of both plastic and conventional organic mulches have driven the search for integrated solutions that combine performance with sustainability. Unlike earlier plastic-based systems, advanced bio-based mulches decompose into benign components, contributing to soil organic carbon and supporting microbial communities. In pursuit of the national mandate to advance sustainable and climate-resilient agriculture, central to the mission of ICAR and in recognition of the pressing need to reduce plastic dependency while restoring soil health, ICAR-Indian Institute of Oilseeds Research (ICAR-IIOR), Hyderabad, has initiated focused research on the development of innovative mulch technology aimed at transforming mulching practices in rainfed ecosystems. As part of this effort, a bench-scale protocol has been initiated utilising natural functionalities to formulate innovative mulch systems. The innovative eco-mulch technology is rooted in the principles of circular economy, transforming bio-based materials derived from agriculture and allied sectors into value-added soil management solutions. Developed using natural functionalities and renewable resources, the technology emphasises resource efficiency, waste minimisation and ecological regeneration. Instead of relying on petroleum-based plastics that accumulate in soils, this approach utilises biodegradable inputs that reintegrate into the soil system after fulfilling their functional role. By converting agricultural by-products and bio-resources into sustainable mulch formulations, the technology creates a closed-loop system where materials are reused, recycled and returned to the soil as beneficial organic constituents. This not only reduces environmental pollution and plastic dependency but also enhances soil organic carbon and microbial activity. In essence, the innovative mulch represents a convergence of sustainability, soil health restoration and climate-smart agriculture, demonstrating how natural resource-based innovations can drive resilient and environmentally responsible farming systems.

The optimised mulch systems were strategically evaluated under controlled conditions to assess their influence on seedling emergence and weed suppression efficiency. Subsequently, the developed innovative mulch systems were characterised for their quality and functional properties to determine structural integrity, stability and overall performance suitability for field application.

Next-generation mulch: A breakthrough in germination

The developed eco-friendly mulch technology was subsequently subjected to systematic evaluation through a series of experiments under laboratory,

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green house and open field conditions to assess its practical performance. These studies were designed to compare seedling emergence, early vigour and overall establishment under mulch-treated conditions with appropriate control treatments, including checks.

The experimental results demonstrated highly promising outcomes. The developed innovative mulch exhibited 100% germination, comparable to or exceeding the germination observed in both check treatments and market-available mulch controls. The uniformity and rate of seedling emergence indicated that the innovative mulch technology did not impose any inhibitory effects on seed germination or early growth processes. Instead, the optimised innovative mulch technology created a favourable microenvironment by conserving soil moisture, moderating temperature fluctuations and reducing surface crust formation, thereby facilitating enhanced seed-soil contact and rapid sprouting. This innovative mulch technology acted as a protective interface between the soil and the atmosphere, reducing direct exposure of the seed zone to harsh environmental fluctuations. This is particularly important under rainfed conditions and in light-textured soils where moisture loss is rapid. These encouraging findings from different evaluations provide strong evidence of the functional efficacy, crop safety and agronomic potential of the developed innovative mulch technology, thereby supporting its progression toward advanced field-level validation.

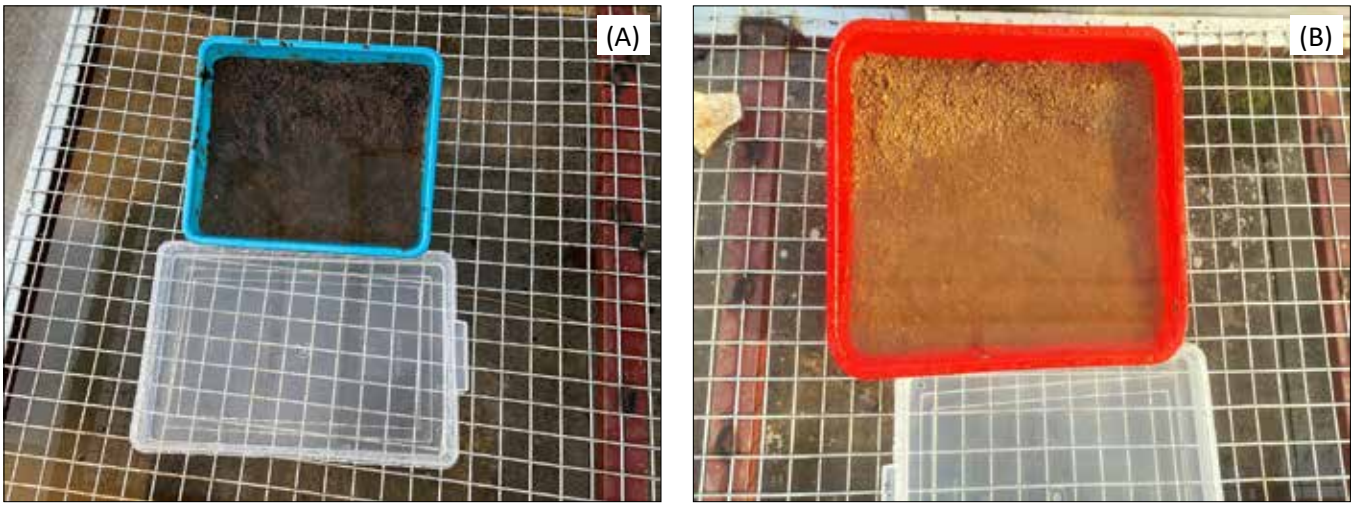
Smart weed control through innovative mulch

Weed infestation is one of the most persistent challenges in Indian agriculture, particularly in oilseed, vegetable and horticultural crops. The developed eco-friendly mulch technology was systematically evaluated for its weed control potential through various open field and laboratory experiments designed to simulate early crop growth conditions. The primary objective was to assess the mulch's ability to inhibit the emergence and establishment of dominant weed species commonly observed in rainfed ecosystems. The results revealed a remarkable reduction in weed incidence under mulch-treated conditions. Trays treated with the developed innovative mulch technology exhibited a markedly lower weed emergence, restricted to only 1–5% of the prevailing weed population. In contrast, untreated control trays recorded substantially higher weed incidence, ranging between 10–15%. These findings clearly demonstrate that the innovative mulch technology effectively suppressed weed growth to a far greater extent than the control treatment, highlighting its strong potential as a sustainable weed management intervention.

The effective weed suppression observed can be attributed to the mulch system acting as a physical barrier that limits light penetration and interferes with germination stimuli required by weed seeds. By creating an unfavourable microenvironment for weed emergence while maintaining conducive soil conditions for crop

Germination in treated (innovative mulch) vs untreated pots

Weeds in (A) treated vs (B) untreated trays



Effect of simulated rainfall conditions on soil (A) with and (B) without innovative mulch

growth, the developed mulch technology demonstrated strong potential as a sustainable alternative to manual and chemical weed control methods in rainfed agriculture. Effective weed suppression reduces the need for manual weeding and chemical herbicides. This not only lowers the cost of cultivation but also minimises the environmental and health risks associated with excessive herbicide use. Reduced herbicide dependency contributes to safer food production and protects beneficial organisms in the agro-ecosystem.

Effect of rain on the innovative mulch

To validate its robustness under real-world stress conditions, the innovative mulch technology was systematically exposed to simulated rainfall under controlled experimental conditions. This evaluation was specifically designed to assess its resistance to washout, surface runoff impact and soil erosivity-critical challenges in rainfed and dryland agriculture. In regions dependent solely on monsoon precipitation, intense and sporadic rainfall events often lead to severe topsoil loss, nutrient depletion and structural degradation, significantly reducing land productivity. Therefore, ensuring mulch stability under such dynamic conditions is essential for its practical adoption.

The simulated rainfall trials replicated high-intensity precipitation events to examine the mulch systems adhesion to the soil surface, structural integrity and ability to remain uniformly spread without displacement. Observations revealed that the developed innovative mulch technology maintained strong soil contact and resisted fragmentation or wash-off even under continuous water impact. Importantly, the mulch acted as a protective barrier that absorbed raindrop impact, reduced splash erosion and minimised crust formation on the soil surface. By buffering the kinetic energy of falling water droplets, it significantly curtailed soil particle detachment and prevented nutrient-rich topsoil from being carried away by runoff. The conserved soil structure further promoted better infiltration, reduced surface sealing and supported sustained moisture retention after rainfall events.

The combined ability to conserve moisture during dry spells and protect soil during heavy rains offers a dual advantage that is particularly valuable in fragile rainfed ecosystems. Soil erosion remains one of the most pressing constraints in dryland agriculture, directly affecting crop establishment, nutrient availability and long-term soil fertility. By addressing both moisture stress and erosive damage simultaneously, the developed mulch technology provides an integrated solution aligned with climate-resilient farming strategies.

SUMMARY

The evolution of mulching technologies from durable plastics to biodegradable synthetics and traditional organic residues clearly demonstrates agriculture's continuous effort to reconcile productivity with environmental sustainability. To advance this technology on a broader and more impactful scale, systematic economic evaluation and region-specific validation are essential. In this direction, ICAR-Indian Institute of Oilseeds Research, Hyderabad proposes to undertake comprehensive economic analysis to assess cost-benefit ratios, long-term soil fertility improvements, input-use efficiency gains and potential labour savings associated with eco-friendly mulch adoption. Further, multi-location trials across diverse agro-climatic zones and soil types will be conducted to evaluate performance stability and adaptability under varied rainfed conditions. Farmer participatory research and integration with conservation agriculture practices will also be emphasised to enhance scalability and field-level acceptance. Through these structured efforts, the institute aims to ensure that innovative mulching technology evolves into a scientifically validated, economically viable and regionally adaptable solution for resilient and climate-smart rainfed agriculture in India.

*Corresponding author email: susmithasomisetty2000@gmail.com