Mulching Influence on Agricultural Productivity and Climate Change Mitigation

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Abstract

Mulching is a major agronomic practice that improves agricultural productivity and mitigates the effects of climate change. It is also an effective soil and water conservation method, as it minimizes evaporation, regulates soil temperature, and enhances water retention, particularly in dry and semi-arid areas that constitute approximately 40% of the world's land mass. There are differences in the contribution of organic and inorganic mulching materials, where organic mulches are more beneficial in enhancing the soil fertility by cycling of nutrients, enhancement of microorganisms, but inorganic mulches, such as plastic films, are more beneficial in terms of immediate moisture retention but have adverse environmental effects, such as plastic pollution. Biodegradable mulches and hydrogel-based materials are examples of new products and solutions that offer eco-friendly substitutes that lower the level of ecological hazard. Mulching has been reported to enhance crop production and water-use efficiency through precision irrigation methods such as drip irrigation. In addition, mulching lowers the emissions of greenhouse gases through regulation of microbial activity of the soil and increasing organic carbon sequestration in soil, especially when used in tandem with other amendments such as biochar. Although mulching has been shown to improve resistance to climate variability among peasant farmers, particularly in middle Africa and Asia, socioeconomic and technological challenges remain. Climate-smart agriculture can be implemented by incorporating mulching within climate-sensitive agricultural systems with the assistance of digital technologies and policy-makers to promote sustainable intensification and food security across the world. The importance of mulching towards climate resiliency, sustainable production and environmental stewardship has been seen in this review in a multifaceted way.

Keywords

Mulching; soil moisture conservation; climate change mitigation; agricultural productivity; biodegradable mulches; smallholder farmers.

1. Introduction

Climate change in the world is a significant and rising risk to the agricultural systems, which can no longer maintain production or guarantee food security. In most farming systems, water scarcity has increased, soil degradation has risen, and yield stability has declined due to temperature regime changes, irregular rainfall distribution, and an increase in extreme weather events (1). These effects are greatest in arid and semi-arid areas, which occupy a large land mass and rely heavily on rain-fed agriculture. In these areas, evaporation is very high, soil is of low structure, and organic matter is on the decline; this greatly limits the availability of soil moisture and crop performance. Consequently, the millions of smallholder farmers have been exposed to greater vulnerability, and there is a pressing necessity to develop viable soil and water management techniques that can be used to improve the resilience of these farmers in the face of the altered climatic conditions (2,3). Mulching has been discovered to be one of the ways to deal with productivity as well as environmental issues among the light variety of climate-smart agronomic practices (4). Mulching helps reduce evaporation losses from the bare surface of soil through the covering with organic residues or synthetic materials, regulating the temperature of the soil and enhancing moisture retention in the root zone (5). Organic mulches also improve the health of soils and contribute to the level of organic matter, improve the aggregation process, and microbial activity (6), which helps to keep the cycle of nutrients and maintain stable crop growth (6–8). Besides yield enhancement, mulching contributes to climate change mitigation efforts through its effects of preventing soil erosion (9), limiting irrigation demands, which requires a lot of energy, and increasing soil carbon sequestration (10,11). The review aims to summarize the existing understanding of mulching, present the critical gaps in the literature and make a practical recommendation on how mulching can be incorporated into the wider climate change adaptation and mitigation strategies. In this respect, the manuscript has been arranged in systematic form to discuss mulching technologies, their influence on soil as well as water conservation, influence on crop productivity, and their roles in reducing climate change, as well as their interrelationship with other farming practices. In this way, the concept of mulching can be evaluated as an eco-friendly and scalable management tool, and its agronomic effects, environmental outcomes, and future developments can be reinforced, which will contribute to climate-resilient farming. Types and Materials of Mulching Technologies The technologies of mulching are usually divided into categories depending on what the material is to cover the surface of the soil; most categories are organic, inorganic and living mulches (12). All the categories vary in source, purpose, durability, and environment and act on their appropriateness to particular crops, climates, and production systems. Organic mulches Organic mulches from plant or animal remains are commonly used in smallholder and commercial farming systems of farming. Waste products of crops like straw, maize stover, rice husk, grass clippings, leaves, wood chips, sawdust and compost are common materials.

These substances are valued as a result of their capacity to retain soil moisture, control weeds, and maintain optimum soil temperature (13). Decomposition of organic mulch release organic matter and nutrients into the soil, thereby enhancing soil structure, improve microbial activity for long-term fertility (14). Their use, however, varies depending on availability, the rate of application and decomposition, which can fluctuate under different climates and different quality of residue used (15,16). Inorganic mulches Most inorganic mulches are synthetic in nature, with plastic films being the most commonly used. Polyethene mulch is used in horticultural and vegetable production because it has a high weed control and moisture retention capacity, as well as soil warming capacity, which promotes early crop development (17–19). Different types are black, transparent, and reflective films to produce certain agronomic results. Although plastic mulches are effective, they harm the environment in terms of disposal, soil contamination, and microplastic formation, which leads to the need to seek more environmentally friendly options (20–22). Other notable inorganic mulches include gravel, concrete, and tephra mulch. Evidence from Tiwari and Sistla (21) demonstrates that microplastic concentrations exceeding 1,000 mg kg^{-1} soil significantly suppress urease, dehydrogenase, and phosphatase activities, and reduce microbial biomass carbon by up to 22%. Li et al. (23) further showed disruption of bacterial functional guilds involved in nitrification and cellulose decomposition. Biodegradable mulches Biodegradable mulches have become a better alternative that offers to be safer to the environment and at the same time more beneficial to the agronomic value of the plastic mulches (24–26). These mulches are made of starchbased polymers, cellulose or other bio-based products which are to decompose in the soil after use. On its part, they are promising; however, their performance, degradation rate, and cost are under active research, especially their performance and degradation rate in different climatic and soil conditions (27,28). The carbon dynamics of biodegradable mulches are inherently non-linear: rapid mineralisation may generate transient CO_2 pulses, but where degradation rates are tuned to soil conditions, residual organic fragments contribute incrementally to stable humic fractions, yielding a net positive SOC trajectory over multiple seasons (24),(26),(29). Living mulches Cover crops, which are also referred to as living mulches, are the practice of planting low competition crops among or between primary crops. By covering the soil surface, these mulches help prevent soil erosion, enhance soil organic carbon and increase biodiversity. Nonetheless, this should be handled well to avoid water and nutrient competition (30). Based on available evidence, the critical threshold at which water competition exceeds conservation benefits appears to occur when cumulative evapotranspiration of the cover crop exceeds 30–40% of total soil water storage capacity within the effective rooting depth (0–60 cm), typically under precipitation below 400 mm yr^{-1} combined with coarse-textured soils (31),(32). The threshold is modulated by rooting depth complementarity: shallow-rooted legume covers competing with deep-rooted cereals generate less competition per unit biomass than same-depth competitors. Mulch Film Colour and Climate Change Mitigation The choice of mulch film colour is no longer just about weed control, it has evolved into a strategic tool for microclimate management and climate change mitigation (33,34). By manipulating the solar radiation spectrum (reflecting, absorbing, or transmitting specific wavelengths), different coloured films directly influence soil temperature, water retention, and crop resilience against extreme weather (20,35). Black Mulch Films Black mulch is the traditional standard, functioning as a broad-spectrum absorber of solar radiation (33). It absorbs most visible and ultraviolet light, transferring heat directly to the underlying soil when physical contact is maintained. (35,36). In regions facing increasingly unpredictable or cooler spring conditions attributable to climate variability, black mulch promotes early soil warming (35). This ensures stable seed germination and root development even under suboptimal ambient temperatures. By completely blocking photosynthetically active radiation (PAR) from reaching the soil surface, black film eliminates weed establishment without recourse to chemical herbicides. (34,37). This directly reduces the carbon footprint associated with the synthesis, transport, and application of synthetic weed-control compounds. Improved early-stage plant growth facilitated by warmer soils translates to higher overall above-ground and below-ground biomass (38). Greater plant biomass temporarily increases the localized fixation of atmospheric carbon dioxide, contributing modestly to carbon sequestration. Silver/Black Co-Extruded Films These films feature a metallised silver layer facing upward and a light-absorbing black layer facing downward (39). They are among the most effective available tools for climate-adaptive crop production. The silver surface reflects a high proportion of incoming shortwave solar radiation back into the atmosphere (39). On a macro-scale, widespread adoption of highly reflective mulches increases the effective albedo of agricultural land, contributing to localised offsetting of surface warming trends. As mean global temperatures rise, excess soil heat can damage root systems and suppress populations of beneficial soil microorganisms (20,38). Silver mulch maintains substantially lower soil temperatures compared to black mulch, thereby preserving the soil microbiome, a critical component for maintaining soil organic carbon (SOC) stocks. Reflected light disorients and deters phytophagous insects, particularly aphids and thrips (39). Reduced pest pressure directly decreases reliance on petroleum-derived synthetic insecticides, lowering associated greenhouse gas emissions from production and application. Clear/Transparent Films Clear films transmit nearly all incident solar radiation to the soil surface while trapping outgoing long-wave infrared radiation, replicating the greenhouse effect on a micro-scale (33,34). Rising temperatures are progressively expanding the geographic distribution of soil-borne pathogens, increasing their relative abundance in soils across regions previously unaffected (40). Concurrently, climate-driven change in temperature and precipitation are modifying weed seed viability and facilitating the spread of weed species into new agroecological zones (41). Clear polyethylene mulch facilitates soil solarization by trapping solar radiation to heat the topsoil to temperatures lethal to pathogens, nematodes, and dormant weed seeds prior to planting (42,43). This form of thermal soil disinfestation represents a viable non-chemical alternative to fumigation with methyl bromide, a compound regulated under the Montreal Protocol as both an ozone-depleting substance and a contributor to global warming (44). Replacing fumigant use with physical solarization eliminates this source of atmospheric pollution. Red and Blue Photoselective Films Photoselective films are engineered to alter the spectral quality specifically the ratio of blue, green, red, and far-red wavelengths reaching both the soil surface and the plant canopy (45,46). Red mulch, for example, reflects far-red wavelengths upward, activating phytochrome photoreceptors in crops such as tomatoes to preferentially allocate photosynthate to fruit production and above-ground growth(45,47). This targeted manipulation of plant morphogenesis results in improved harvest index without additional inputs. By optimising the spectral environment, photoselective films increase the efficiency with which crops convert available soil moisture and solar energy into biomass (34). Plants produce higher yields per unit of water consumed, a critical advantage under projected increases in drought frequency and severity. Enhanced growth efficiency translates to lower synthetic fertilizer requirements per kilogram of produce (38). Since nitrous oxide (N_2O), a gas approximately 265 times more potent than CO_2 over a 100-year horizon is released during the manufacture and soil application of nitrogen fertilizers, reducing NUE-driven fertilizer demand directly curtails agricultural N_2O emissions. The overall impacts of different mulching practices on soil and water conservation, crop productivity, and climate change mitigation are summarized in **Table 1 (52-68)**.

Table 1: The Impact of Mulching Practices on Soil and Water Conservation, Crop Productivity, and Climate Change Mitigation in Agricultural Systems

Type of Mulching	Results Obtained	Type of Agricultural Operation	References
Straw mulch	Increases soil moisture and water holding, reduces evaporation, moderates (often lowers or buffers) soil temperature, improves WUE and yield, enhances soil organic matter and fertility, can reduce erosion	Widely used in maize, wheat, rice, potatoes, vegetables, fruit trees, orchards, rain-fed and irrigated systems, especially in arid/semi-arid regions	(52–57)
Crop residue mulch (surface residues in conservation agriculture)	Reduces evaporation and runoff, controls erosion and soil loss, increases water	Cereal-based and conservation agriculture systems under	(56–59)

	infiltration, raises soil organic carbon, improves soil water storage, helps weed control and can increase SOC gains	minimum/no-till with permanent residue cover	
Plastic film mulch (PE films)	Raises soil temperature and moisture, reduces evaporation, improves early growth, substantially increases yield and water use efficiency; long-term residue accumulation can reduce yield and harm soil properties	Widely used in maize, wheat, potato, cotton, rice, soybean and other cash/vegetable crops, especially in dryland and semi-arid regions	(2,41,60–63)
Biodegradable plastic mulch (BDM)	Provides similar short-term benefits to plastic (weed control, moisture conservation, improved soil physical/biological properties, good for vegetable yield), intended to reduce PE pollution; long-term effects on soil health and microplastics remain uncertain	For vegetable and horticultural crops as a more sustainable alternative; evaluated in field trials in specialty crops	(64–67)
Living mulch / cover crops	Improve soil cover, can reduce erosion, enhance soil biology and organic inputs; as part of permanent soil cover / conservation	Cover crops and living mulches within conservation agriculture	(2,58,65)
Organic compost / organic mulches (including straw-based)	Increase soil organic matter and nutrients, improve moisture retention and infiltration, raise soil moisture and often water productivity and yield	Used in vegetables, beans, tree crops, smallholder and dryland systems; such as composted yard waste and organic mulches in green beans	(2,5,68)

Gravel / stone mulch	Boosts soil water content, reduces evaporation and erosion, contributes to moisture conservation in drylands	Applied in semi-arid and arid farming, sometimes in ridge-furrow/gravel systems	(2,5,55)

2. **Mulching as a Strategy for Mitigating Climate Change** Mulching is necessary to enhance agricultural output despite climate change by keeping soil moisture high and improving the efficiency of water use. Although the temperature is increasing and rainy seasons are becoming erratic, mulching ensures that the root zone maintains constant moisture levels through reduced evaporation levels, improved water penetration, and an increase in water-holding capacity of the soil (69). The benefits are aimed at promoting stability in crop growth and stability in production and reducing the requirement to irrigate, reducing energy use, and indirectly reducing the emission of greenhouse gases. Mulching enhances the robustness of rain-fed and irrigated farming systems via increased utilization of limited water resources, rendering it a beneficial and inexpensive method that connects agricultural product goals with mitigating climate change (Table 2). (70-79)

Table 2 shows the impact of mulching on soil moisture conservation and water use efficiency under various agricultural conditions

Agro-ecological situation	**Mulching type**	**Crop system (examples)**	**Results obtained**	**Impact on water use efficiency**	References
Semi-arid rainfed agriculture	Straw mulch	Wheat and maize	Reduces soil evaporation and improves soil water storage, especially in the upper profile; increases yield in dry climates	Meta-analysis: mulching (straw or plastic) increased WUE of wheat and maize by up to ~60% compared to no mulch; effects larger for maize and in dry conditions	(70–72)
Dryland cereal production	Crop residue / straw mulch	Maize- and wheat-based dryland or	Improves infiltration, reduces runoff	Higher grain water productivity	(70,71,73)

		conservation systems	and erosion, changes spatial/temporal soil-moisture distribution, increases stored soil water	and yield per unit water/rainfall compared with no mulch or conventional practice	
Irrigated vegetable production	Plastic film mulch	Vegetables under drip or furrow irrigation	Strongly reduces soil evaporation, increases soil moisture and stabilizes soil temperature; often allows fewer irrigations with higher yield	Meta-analysis under drip: film-mulched drip irrigation increased CY ≈20% and WUE ≈30% vs. non-mulched drip; other studies report WUE increases of 20–60% vs. no mulch	(2,5,62,74,75)
Horticultural / vegetable systems	Biodegradable mulch films	Vegetable/specialty crops	Biodegradable films generally provide similar soil moisture conservation and yield benefits as plastic, while avoiding long-term PE residues	Systematic review: biodegradable mulches almost always outperform no mulch agronomically, but rarely exceed conventional plastic; WUE benefits context-specific	(5,67,76–78)
Smallholder rainfed farms	Organic residue / compost mulch	Dryland crops, vegetables	Organic mulches increase soil organic	Improved WUE and yield stability in dryland	(5,71,73)

			matter, improve water retention, maintain moisture in root zone during dry spells	agriculture through reduced evaporation, higher soil moisture and better nutrient status	
Orchard systems	Mulch (straw/plastic) and living covers	Jujube orchards, fruit crops; living clover or high-residue covers	Mulching methods in orchards reduce water consumption and increase water-saving potential; living/clover mulches can maintain yields comparable to plastic in arid maize and enhance soil structure and N input	Straw and clover mulches increased maize water productivity by ~30% and ~14% vs. no mulch in an arid irrigated system; orchard mulches reduce ET and improve water productivity	(5,73,77,79)
Arid and semi-arid regions	Gravel/stone mulch	Dryland systems (ridge–furrow, traditional)	Gravel/stone mulches boost soil water content and reduce evaporation and erosion in drylands	Improve effective use of limited rainfall, supporting higher WUE than bare soil (qualitative evidence from reviews)	(5,73)
Conservation horticulture / organic systems	Compost and organic mulches	Organic vegetables and horticultural crops	Enrich soil organic matter and nutrients, improve water retention and soil fertility	Mulched systems (organic +/− plastic) show higher WUE and reduced irrigation requirement	(5,71,73,74)

				compared with no mulch; in some cases irrigation WUE increased by ~20–40%	

3. Mulching's Impact on Soil Fertility, Physical Properties, and Water Dynamics

3.1 Mulching Effects on Soil Fertility, Nutrient Retention, and Cycling

Mulching significantly enhances soil fertility by conserving and recycling essential nutrients. Organic mulches break down slowly, and nutrients like nitrogen, phosphorus and potassium are made available to the soil matrix, which enhances nutrient levels during the crop growing season (74,75). A mulched soil environment minimizes nutrient leaching by keeping the soil moist and active, which is vital for nutrient mineralization and cycling. Notably, the existence of mulch will also facilitate the creation and activity of biofertilizers that synergistically amplify uptake and expansion of nutrients by plants (76). Such a combination enhances the use of natural and applied sources of nutrients, the use of synthetic fertilizers becomes less important, and environmental losses are minimized (77). Maize cropping systems have been found to promote the growth of the soil organic carbon and the various nutrient levels in the soil at different depths, which also shows that it promotes sustainable soil fertility management (78,79).

3.2 Mulching Effects on Soil Water Conservation and Water Use Efficiency

The direct and measurable impact of mulching on water use efficacy and preservation of soil moisture is the fact that it is a vital technology in water-limited and climate-stressed agricultural systems. The mulch is a physical barrier, which will inhibit direct evaporation through the solar radiation and wind because it will cover the soil surface. This protection helps in maintaining moisture in the rhizosphere, which is typically greater during the dry season and the variability in soil water content, which would normally be a stressor to crops. The mulched soils are likely to undergo increased infiltration and reduced surface runoffs when compared to bare soils. The organic mulches minimize the impacts of rainfalls; therefore, water is absorbed but not destroyed by erosion and runoffs. The organic mulch decomposition enhances soil organic matter content, improves the soil structure, porosity and water retention (80). These additions make the soils more effective when it comes to storing moisture, which is then used to produce the crops in abnormal rainfall patterns. In water use efficiency, mulching helps the crops to produce more yields with fewer water inputs. Reduced evaporative loss means that the proportion of applied or stored water consumed in transpiration increases, which directly translates into the production of biomass (81). Through irrigated systems, the frequency of irrigation and the total water demand would be decreased through mulching, which would save energy and reduce pressure on limited water resources. In rain-fed agriculture, it helps crops overcome transient drought stress, which further boosts yield stability (82).

3.3 Increasing the soil physical properties

In addition to nutrient benefits, mulching significantly influences the physical characteristics of the soil that are important to agricultural productivity. It has been linked to the application of mulch, which has been attributed to a decrease in the bulk density of the soil, a rise in porosity and aggregated stability, which have been attributed to improved soil structure and aeration (83,84). Mulching reduces surface runoff and soil erosion by shielding the surface of the soil against the effects of raindrops and wind erosion, thereby improving topsoil conservation for land management. Moreover, the multiplication of microorganisms in the soil microbial community is affected by the process of mulching, which promotes the increase of microbial biomass and activity related to soil aggregation mechanisms and organic matter decomposition (76,85). Conservation tillage study stresses that, when employed simultaneously with mulching, the consequent low degree of soil disturbance is a further driver of these advantageous physical alterations in soil, strengthening the good influence of conservation tillage on crop development and environmental well-being. Those are the changes that are crucial in the management of functioning and resilient soils under climate change pressure (86,87). Figure 1 shows the impact of mulching on the soil for growth and water retention in the soil.

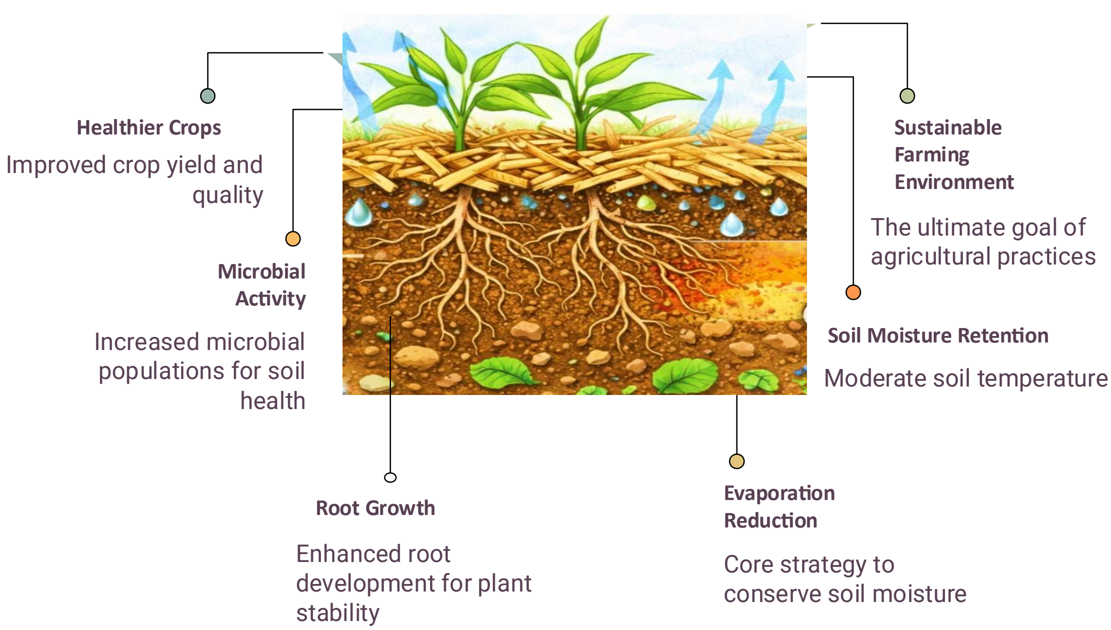

Figure 1: Schematic representation of mulching effects on soil and microclimate, showing moisture conservation, moderated temperature, enhanced root growth, and increased microbial activity.

3.4 The Effect of Mulching on Soil Moisture Conservation and Water Use Efficiency

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3.5 Effects of Mulching on Crop Growth, Yield, and Agricultural Productivity

Physiological Advantages of Mulching to Plants

The direct physiological advantage of mulching on the plants is the provision of favourable micro-environmental conditions for the plants in the most critical growth phases. The mulches with thermal insulation help in the moderation of soil and root zone temperatures to ensure the best germination and early seedling vigour (88,89). This temperature control minimizes the stress associated with temperature extremes, which is very important during the reproductive and grain filling of most crops. Moreover, mulching inhibits the growth of weeds by shading and mechanical interference with the growth of the weed, which reduces competition for water, nutrients, and light, which indirectly improves crop growth (90,91). Moreover, mulches also help in better control of pests and diseases since it changes the soil humidity and temperature conditions that are not conducive to some pathogens and pests (92). All these physiological and protective effects are in favour of plant establishment, health and productivity.

3.6 Mulching Practices Lead to Improved Quantitative Yield

Numerous empirical studies of different types of cropping systems have recorded a considerable improvement in yield as a result of mulching. In field experiments, improvement has been shown in yields of between 10% and more than 60% in staple crops like maize, rice, wheat, and horticultural crops, in the case of proper application of mulching (93). These enhancements are strongly evident when the conditions are highly stressful, like drought, where mulching stabilizes harvests by providing moisture to the harvests and counteracting heat stress. As a long-term use of different mulch materials, the alteration of some soil properties could also take place, and they are largely unobserved. Therefore, the effects of mulching on Haplic Fluvisol properties have been extensively investigated. For example, a long-term field study conducted on 27 perennial plots demonstrated that the effects of different mulch materials (bark and wood chips, wheat straw, cardboard, foil paper, biodegradable matting, unwoven fabric covered with bark chips, crushed basalt, and an unmulched control) on Haplic Fluvisol properties over a four-year period (80,94). The divergence reflects the creation of a bimodal pore size distribution under bark/wood chip mulch: coarse inter-aggregate macropores (>50 μm) generated by fungal hyphal networks and earthworm bioturbation provide high total storage capacity at low matric potentials, while intra-aggregate micropores (<0.2 μm) are relatively fewer than in fine-textured treatments, reducing the steepness of the van Genuchten retention curve near the inflection point (80,95). In practical terms, bark/wood chip soils hold more water at low tensions benefiting shallow-rooted crops but release it less steeply during drying, which can limit plant-available water under rapid drought onset.

Control patches with no mulch had low values, as temperatures were below those of foil mulches, and organic mulches had the highest temperature ranges per day. Mulches were also useful in water storage within the soil, mainly in the spring, before initiating the growth of vegetation and post-cutting perennial plants. There were no significant time changes in organic carbon content (Cox), aggregate stability, and pH, except between patches containing bark or wood chips and wheat straw between patches (96,97). In such cases, the role of decomposed organic matter in increasing the two properties was significant. In contrast, soil hydraulic properties varied significantly across all patches, as a result of no-tillage practices. This management method has resulted in the increase of saturation and residual water content, higher saturated hydraulic conductivity, and greater air-entry pressure, which consequently lead resulted in bulk density reduction. Soil water retention curves for the patches amended with bark or wood chips decreased gradually compared to those of the other patches., and this implies that the patches possessed more water retention capacity at the low-pressure heads. The physical features of the soils overlaid with organic mulches with respect to the slope of the inflexion point of the retention curve were, however, poorer as compared to other scenarios (95,98,99). The readily available water was observed lower when compared with other setups in organic mulch. This confirmed the organic soils as the most effect on the soil conditions, which may be positive or negative effects (80,100). Comparative studies indicate that plastic mulches tend to perform better than organic mulches in the short-term yield production because they are better in terms of moisture retention and control of weeds; nevertheless, organic mulches have long-term soil fertility advantages, which are long-term in terms of yield production. The resulting stability of yield realized by means of mulching, therefore, presents a strategic benefit to farmers who face uncertainties in climatic conditions as well as scarcity of resources (101–107) **(Table: 3).**

Table 3 Influence of Mulching on Plant Development, Crop Yield, and Agricultural Output across Diverse Species

Crop type	**Mulching practice**	**Results on growth and yield**	**Implications for agricultural productivity**	**References**
Cereal crops (maize, wheat)	Straw / crop residue returns or mulch	In wheat–maize systems, straw return increases yield on averages about 5.5% with stronger effects under irrigation and fertilization; 82% wheat and 72% maize gain are from high biochar + fertilizer vs unfertilized control. No straw, no biochar control	Improved long term yield and stability through better soil organic carbon, nutrients and structure, especially under irrigated and well managed systems	(108,109)
Maize	Wheat straw mulch	In irrigated summer maize, 5 t ha^{-1} wheat straw mulch increased grain yield by 18% and total biomass by 20% compared to no mulch; associated with higher leaf area, growth rate and kernels per	Enhanced water productivity and more healthy growth in water limited or heat stress environments	(110)

		ear, plus higher soil moisture and lower daytime soil temperature		
Vegetables (tomato, pepper and other vegetables)	Plastic film mulch (PE, PP)	In tomato, colored plastic films increased total yield by ~33–34% in some seasons compared with no mulch; across vegetables (broccoli, chili pepper, garlic), plastic and biodegradable films increased yields by ~18–30% compared to bare soil	Faster growth and higher marketable yield, improved resource use in intensive vegetable systems	(111–113)
Vegetables (leafy crops, lettuce; various vegetables)	Biodegradable mulches (films, nonwovens, paper)	In tomato and other vegetables, biodegradable films gave yield increases similar to PE films (e.g., broccoli, chili, garlic yields +18–30% compared to bare soil, with no significant difference between BDM and PE); in lettuce, jute/hemp/viscose nonwoven mulches often produced equal or higher yields than agro foil and much higher than bare soil	Maintain and increase yield while improving soil moisture and quality and reducing long term plastic residue problems	(112,114–117)

Legumes (cowpea; cereal–legume systems)	Organic / woody residue mulches and organic nutrient sources	Woody residue amendments in sorghum–cowpea increased cowpea nodule number (+35%), nodule biomass (+64%), and grain yields of cowpea (+41%) and sorghum (+25%), with WUE +40% and +26%; organic nutrient sources in cowpea raised grain yield, nodulation and nutrient uptake; surface mulches improved cowpea physiological traits	Enhanced soil fertility, biological N fixation and legume–cereal productivity in dryland systems	(118–121)
Fruit crops (orchards)	Organic mulch and legume living mulch	Cowpea living mulch in maize-based systems improved soil quality index by 50–100% and increased maize grain yield by 34–84% compared to no living mulch, showing potential for tree/fruit systems with legume covers	Improved long term soil health and productivity where legume covers are incorporated	(122)
Smallholder mixed crops	Organic / residue mulch and living mulch	In Sahelian sorghum–cowpea, woody residue mulch increased cereal and legume yield by 25–41% and WUE by 26–	High resilience, yield under variable rainfall, and food security for smallholders through residue and living mulch use	(118,122)

		40%; in smallholder maize systems in Ghana, cowpea living mulch raised maize yield by 34–84% while improving soil quality		

4. Economic and Social Implications to Farmers

Mulching activities have a significant economic and social implication, particularly to the smallholder farmers who work within constrained resource settings. The figure of costs and benefits shows that mulching leads to an efficient use of resources (116), which means that less irrigation, fertilizers, and labour to weed, and increased profitability. Additional income from increased and more reliable yields can play a key role in the livelihood and food security, especially in those regions which are susceptible. However, the initial expense of materials, labor-intensive application, technical illiteracy, and the availability of appropriate mulch kinds are some barriers to large-scale implementation (117). Adoption trends are also influenced by societal factors, such as gender roles and community labor dynamics, which necessitate the use of participatory extension techniques to ensure that the advantages are shared by all (118,119). These issues should be addressed so as to ensure that we can realize the greatest socioeconomic potential of mulching and its benefits to sustainable agricultural growth. Figure 2 shows the role of mulching in climate change mitigation.

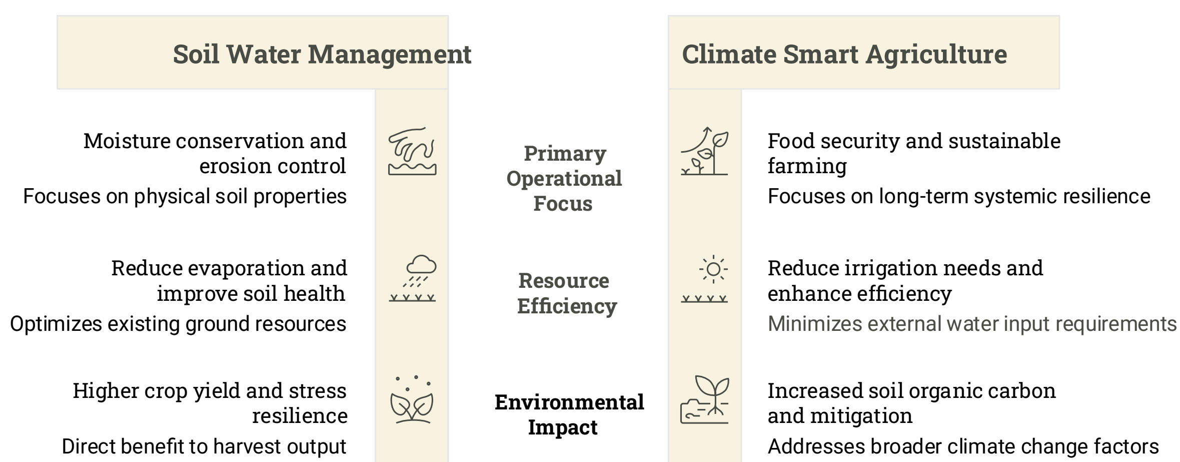

Figure 2. Conceptual framework highlighting the importance of mulching in agricultural production and contributing to climate change resilience and mitigation.

5. Mulching as a Strategy for Mitigating Climate Change

5.1 Agricultural Soils: Decreasing Greenhouse Gas

Mulching also affects greenhouse gas (GHG) emissions caused by agricultural soils in a variety of ways. Mulching has an effect on microbial activities, notably nitrification and denitrification, which govern the emission of nitrous oxide (N_2O) and methane (CH_4) (100). Field research is used to explain that the combined application of mulching and biochar techniques would lead to a reduction in total CO_2 and N_2O emissions, which overall results in a net reduction of the carbon footprint in the cropping system (29). Nevertheless, the measurement of these emission reductions is difficult because of site-specific variability and also through interactions with the soil properties and the practices being undertaken. The environmental trade-offs, including the possible anaerobic zones of thick layers of mulch that might emit methane gases, have to be considered in order to optimize the mulching strategies. However, the evidence highlights how mulching can help to play a significant role in the GHG mitigation of agriculture when it is incorporated into the broad-based soil management systems (120) The proposal of the primary mechanism involves biochar-mediated pH buffering (raising soil pH to ~6.5–7.0), which suppresses incomplete denitrification by nosZ-lacking bacteria, thereby reducing N_2O-to-N_2 ratios. Simultaneously, mulch-derived organic substrates increase the C:N ratio available to denitrifiers, favouring complete reduction of N_2O to N_2 (29), (120). To elucidate these pathways, we recommend amplicon sequencing targeting nirS, nirK, and nosZ functional genes combined with C-labelled mulch tracers and stable isotope probing (SIP) of the coupled C-N cycle (120).

5.2 Mulch-Integrated Systems Carbon sequestration potential

Extensive mulching in the long term increases the stocks of organic carbon in the soil through the addition of organic matter, as well as reducing the loss of carbon through erosion and mineralisation. Mulching, together with conservation tillage and management of agricultural leftovers, will boost the stability and build soil carbon, a critical ingredient in reducing global climate change (121). Local research demonstrates that the soils coated with mulch are more aggregated and contain more organic matter, which helps to stabilize carbon and prevent decomposition losses. Furthermore, mulching systems have synergistic effects on soil carbon sequestration when combined with low tillage and diversified crop rotation, underscoring the relevance of these techniques in large-scale, sustainable low-carbon agriculture (122). These results are consistent with worldwide objectives of soil-based climate solutions to attain high carbon sequestration in the croplands.

5.3 Technological Advancement in Mulching

The technology in the agricultural sector has greatly enhanced the efficiency, precision and sustainability of the mulching practice. The contemporary technologies of mulching do not just operate within the scope of covering the soil but encompass the system that allows maximum utilization of the materials, their distribution, and their functioning under the changing conditions of fields (5,68,85). Mulch applicators, such as mechanized ones, allow the application of the organic residues or films at the same rate, which demands little labour and provides a uniform coverage of the soil over a large area (5). These applicators are commonly linked by planting equipment in conservation and precision agriculture systems, where the applicators are used to seed and mulch around the same time, which increases the efficiency of operations and crop establishment. The study proposes a three-tier fusion architecture: (1) ground-truth point sensors (TDR, thermocouple arrays) at 0.5 m resolution deployed at the mulch-soil interface; (2) UAV-mounted thermal and multispectral imaging at 5–10 cm resolution to capture mesoscale spatial heterogeneity; and (3) satellite time-series (Sentinel-2 SWIR bands) to regionalize patterns. A physics-informed neural network (PINN) embedding the Richards equation as a constraint layer can then invert multi-source observations into continuous soil moisture and temperature fields, as demonstrated for general soil monitoring by (123),(124).

Material innovation. The production of biodegradable and bio-based mulches addresses environmental issues associated with traditional plastic films (125). These are made such that they do not need to be removed and disposed of, but will decompose in the growing season through microbial activities (126). The ongoing trends are geared towards controlling the rate of degradation, tensile strength, and thermal characteristics to suit different crops and climatic conditions.

Digital and data-driven technologies are also dictating the modern mulching systems. This is more monitored through the use of sensors and remote sensing equipment in tracking the dynamics of soil moisture, temperature, and evaporation in mulched soils (123). These data give the opportunity to make effective decisions concerning the sort of mulch, its depth, and the time when it can be applied. Precision agriculture platforms and decision support models in other systems would integrate weather forecasting with soil information to optimize the water-saving mulching pattern to maintain stability of the yield (124).

6. Conclusions

Mulching has several other environmental advantages in addition to the short-term agronomic advantages. By acting as a protective barrier against wind and heavy rain, mulch prevent soil erosion, as well as maintaining the fertile topsoil at the top of the soil and minimizing the transport of sediments to the water bodies around the site. This also aids in avoiding the seepage and flow away of the nutrients and ensures that the crops receive the nutrients and other organic amendments, and not contaminate water and therefore result in greenhouse emissions and loss in nutrient content. Specifically, organic mulches are found to enhance carbon sequestration because organic matter is put into the soil during the decomposition process, and it adds to the stocks of organic carbon in soil, counteracting the stocks of carbon dioxide in the atmosphere. Mulching also helps to reduce resource efficiency as it reduces the level of water and energy in irrigated systems. It also saves soil moisture, which conserves the frequency of irrigation required and the amount of water required, which saves the amount of energy used in pumping and delivering the water. This is an indirect energy consumption decrease that is converted to greenhouse gas emissions of fossil fuel-intensive irrigation systems. Moreover, moderate temperature of the soil and better availability of moisture improve crop growth and yield even in peaky and inconsistent climatic conditions, which makes smallholder and commercial farming systems more resilient due to mulching. Mulching can be used as an economical, scalable, and environmentally friendly option when used together with other agronomic strategies like crop rotation, cover cropping, and integrated nutrient management. It not only enhances agricultural production, but it also carries the ideals of climate-smart agriculture, which helps ensure a sustainable use of resources, minimizes environmental effects, and enhances food security in the future in the wake of varying climate patterns.

List of abbreviations

Abbreviation **Full Form**

- GHG Greenhouse gases
- WUE Water Use Efficiency
- CH_4 Methane
- CO_2 Carbon dioxide
- N_2O Nitrous oxide
- SOC Soil Organic Carbon
- NUE Nutrient Use Efficiency
- SIP Stable Isotope Probing
- CY Crop Yield
- BDM Biodegradable Plastic Mulch
- TDR Time Domain Reflectometry
- UAV Unmanned Aerial Vehicle
- PINN Physics Informed Neural Network
- SWIR Short Wavelength Infrared
- PAR Photosynthetically Active Radiation

Author Contributions

Conceptualization, Investigation, Data curation, Writing – original draft preparation, and Visualization: O.M.; Methodology: K.O.; Writing – review & editing: O.M. and K.O.; Supervision: M.F. All authors have read and agreed to the published version of the manuscript.

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Availability of Data and Materials

The data supporting this review are drawn from published studies and are available in the public domain. All sources are properly cited in the reference list of this article.

AI Disclosure

AI-based tools were used solely for language editing and formatting. No AI tool was used to generate or paraphrase the scientific content of the manuscript.

Figures generated by the authors using Python, with coding assistance from ChatGPT OpenAI.

The authors take full responsibility for the accuracy, originality, and integrity of the work.

Consent for Publication

Not applicable, as this study does not involve human participants, personal data, or identifiable materials.

Conflicts of Interest

The authors declare no conflicts of interest related to this work.

Funding

No external funding was received for this research.

Acknowledgments

The authors greatly acknowledge the management of Landmark University for providing the necessary facilities for this review article. Moreover, we would like to express our appreciation to the Agricultural and Biosystems Engineering Staff for their kind cooperation for this review study.

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