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Review Article

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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, which constitute approximately 40% of the world's land area. Organic and inorganic mulching materials differ in their contributions: organic mulches are more beneficial for enhancing soil fertility through nutrient cycling and enhanced microbial activity, whereas inorganic mulches, such as plastic films, are more effective for immediate moisture retention but have adverse environmental effects, such as plastic pollution. Biodegradable mulches materials is one of the newest product solution that offer eco-friendly alternatives, reducing ecological hazard. Mulching has been reported to enhance crop production and water-use efficiency when combined with precision irrigation methods such as drip irrigation. In addition, mulching lowers greenhouse gas emissions by regulating soil microbial activity and increasing organic carbon sequestration in the soil, especially when used in tandem with other amendments such as biochar. Although mulching has been shown to improve resilience to climate variability among smallholder farmers, particularly in sub-Saharan Africa and Asia, socioeconomic and technological challenges remain. Climate-smart agriculture can be advanced by incorporating mulching into climate-sensitive agricultural systems, supported by digital technologies and policymakers, to promote sustainable intensification and food security worldwide. This review demonstrates, in a multifaceted way, the importance of mulching for climate resilience, sustainable production, and environmental stewardship.

Keywords:
mulching; soil moisture conservation; climate change mitigation; agricultural productivity; biodegradable mulches; smallholder farmers

1. Introduction

Climate change poses a significant and growing risk to agricultural systems worldwide, which can no longer reliably sustain production or guarantee food security. In most farming systems, water scarcity has increased, soil degradation has intensified, and yield stability has declined, driven by shifting temperature regimes, irregular rainfall distribution, and increasing extreme weather events [1]. These effects are most severe in arid and semi-arid areas, which occupy a large land area [2] and depend heavily on rain-fed agriculture. In these regions, evaporation rates are very high, soils have poor structure, and organic matter continues to decline, severely limiting soil moisture availability and crop performance. Consequently, millions of smallholder farmers face heightened vulnerability, creating a pressing need to develop viable soil and water management techniques capable of improving their resilience to changing climatic conditions [3,4]. Mulching has emerged as one of the most effective ways to address both productivity and environmental concerns among the range of climate-smart agronomic practices available [5,6].

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Mulching reduces evaporation losses from bare soil surfaces by covering them with organic residues or synthetic materials, regulating soil temperature and enhancing moisture retention in the root zone [5,7]. Organic mulches also improve soil health and increase organic matter levels, improving aggregation and microbial activity [8,9], which helps sustain nutrient cycling and stable crop growth [9,10]. Beyond yield enhancement, mulching contributes to climate change mitigation by preventing soil erosion [11], reducing energy-intensive irrigation demands [12], and increasing soil carbon sequestration [13, 14]. This review aims to summarize the existing understanding of mulching, identify critical gaps in the literature, and offer practical recommendations on incorporating mulching into broader climate change adaptation and mitigation strategies. Accordingly, the manuscript is organized systematically to discuss mulching technologies, their influence on soil and water conservation, their effects on crop productivity, their role in mitigating climate change, and their interrelationship with other farming practices. In this way, mulching can be evaluated as an eco-friendly and scalable management tool, and its agronomic effects, environmental outcomes, and future developments can be evaluated to support climate-resilient farming.

1.1. Types and Materials of Mulching Technologies

Mulching technologies are generally divided into categories based on the material used to cover the soil surface, with organic, inorganic, and living mulches representing the primary categories [15]. These categories vary in source, purpose, durability, and environmental impact, and their appropriateness depends on the specific crop, climate, and production system. Organic Mulches. Organic mulches derived from plant or animal remains are commonly used in both smallholder and commercial farming systems. Common materials include crop residues such as straw, maize stover, rice husk, grass clippings, leaves, wood chips, sawdust, and compost. These materials are valued for their capacity to retain soil moisture, control weeds, and maintain optimal soil temperature [6]. Decomposition of organic mulch releases organic matter and nutrients into the soil, thereby enhancing soil structure and improving microbial activity for long-term fertility [16]. Their use, however, varies depending on availability, application rate, and decomposition rate, which can fluctuate under different climates and with residue quality [17,18]. Inorganic Mulches. Most inorganic mulches are synthetic, with plastic films being the most commonly used. Polyethylene mulch is widely used in horticultural and vegetable production because of its high weed control and moisture retention capacity, as well as its soil-warming effect, which promotes early crop development [19–21]. Black, transparent, and reflective films are used to achieve specific agronomic outcomes. Although plastic mulches are effective, they harm the environment because of disposal issues, soil contamination, and microplastic formation, creating a need for more environmentally friendly alternatives [20,22,23]. Other inorganic mulches include gravel, sand, and crushed stone, which are used mainly in dryland ridge furrow systems [5,24]. High concentrations of microplastics suppress enzyme activities, such as urease, dehydrogenase, and phosphatase, disrupting biogeochemical cycles in terrestrial ecosystems [25]. Huang et al. [26] further showed disruption of bacterial functional guilds involved in nitrification and cellulose decomposition.

1.1.1. Biodegradable Mulches

Biodegradable mulches have emerged as a safer alternative to plastic mulches, offering comparable agronomic value with reduced environmental impact [27–30]. These mulches are made from starch-based polymers, cellulose, or other bio-based products designed to decompose in the soil after use [31,32]. While promising, their performance, degradation rate, and cost remain under active investigation, particularly under different climatic and soil conditions [33–35]. Incomplete degradation can also release micro- and nanoparticles into the soil [36]. The carbon dynamics of biodegradable mulches are inherently nonlinear: rapid mineralization may generate transient CO_2 pulses, but when degradation rates are matched to soil conditions, residual organic fragments contribute incrementally to stable humic fractions, yielding a net positive SOC trajectory over multiple seasons [37,38].

1.1.2. Living Mulches

Cover crops, also referred to as living mulches, involve planting low-competitive crops among or between primary crops. By covering the soil surface, these mulches help prevent soil erosion, enhance soil organic carbon, and increase biodiversity [39–41]. Nonetheless, they must be managed carefully to avoid water and nutrient competition with the main crop [42,43]. In water-limited environments, the transpiration of a living cover can deplete stored soil water before the following crop is established, so that the water-conservation benefit of ground cover is offset by a water-use penalty, particularly in coarse-textured soils and in low-rainfall seasons [42,44]. This risk can be reduced through the choice of cover species, planting density, and the timing of planting and termi-

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nation relative to the peak water demand of the cash crop [44,45].

1.2. Mulch Film Color and Climate Change Mitigation

The choice of mulch film color is no longer solely about weed control; it has evolved into a strategic tool for microclimate management and climate change mitigation [21,46]. By manipulating the solar radiation spectrum (reflecting, absorbing, or transmitting specific wavelengths), differently colored films directly influence soil temperature, water retention, and crop resilience to extreme weather [46,47].

1.2.1. Black Mulch Films

Black mulch is the traditional standard, functioning as a broad-spectrum absorber of solar radiation [47]. It absorbs most visible and ultraviolet light, transferring heat directly to the underlying soil when physical contact is maintained [47,48]. In regions facing increasingly unpredictable or cooler spring conditions attributable to climate variability, black mulch promotes early soil warming [47], ensuring 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 [49, 50], directly reducing 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 into higher overall above-ground and below-ground biomass [51]. Greater plant biomass temporarily increases the localized fixation of atmospheric CO_2, contributing modestly to carbon sequestration. These benefits are not guaranteed, however: black plastic film mulching has been reported to increase soil nitrous oxide (N_2O) emissions in arid potato fields [52], which illustrates the need to evaluate the net climate effect of each film type.

1.2.2. Silver/Black Co-Extruded Films

These films feature a metalized silver layer facing upward and a light-absorbing black layer facing downward [47, 53]. The silver surface reflects a high proportion of incoming shortwave solar radiation back into the atmosphere [53,54], and silver mulch maintains lower soil temperatures than black mulch [47,53]. As mean global temperatures rise, excess soil heat can damage root systems and suppress populations of beneficial soil microorganisms [46,47]; keeping the root zone cooler therefore helps preserve the soil microbiome that underpins SOC stocks. On a larger scale, widespread adoption of highly reflective mulches could marginally raise the effective albedo of agricultural land, although the contribution of this effect to offsetting surface warming has not been quantified [54]. Reflected light also disorients and deters phytophagous insects, particularly aphids and thrips [53]. Reduced pest pressure can decrease reliance on petroleum-derived synthetic insecticides, lowering the associated greenhouse gas emissions from production and application [48,53].

1.2.3. 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 [15,47]. Rising temperatures are progressively expanding the geographic distribution of soil-borne pathogens, increasing their relative abundance in regions previously unaffected [55]. Concurrently, climate-driven changes in temperature and precipitation are modifying weed seed viability and facilitating the spread of weed species into new agroecological zones [56,57]. 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 [58–60]. 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 [61,62]. Replacing fumigant use with physical solarization eliminates this source of atmospheric pollution.

1.2.4. Red and Blue Photoselective Films

Photoselective films are engineered to alter the spectral quality of light reaching the soil surface and plant canopy, specifically the ratio of blue, green, red, and far-red wavelengths [63,64]. Red mulch, for example, reflects far-red wavelengths upward, activating phytochrome photoreceptors in crops such as tomatoes and promoting the preferential allocation of photosynthate to fruit production and above-ground growth [64,65]. This targeted manipulation of plant morphogenesis improves harvest index without additional inputs. By optimizing the spectral environment, photoselective films increase the efficiency with which crops convert available soil moisture and solar energy into biomass [63], producing higher yields per unit of water consumed (water-use efficiency, WUE) [63,66]—a critical advantage under projected increases in drought frequency and severity [1,67]. Enhanced growth efficiency also translates into lower synthetic fertilizer re-

quirements per kilogram of produce because mulching has been shown to improve nutrient use efficiency (NUE) [66,68,69]. Since nitrous oxide (N_2O), a gas approximately 265 times more potent than CO_2 over a 100-year horizon [70], is released during the manufacture and soil application of nitrogen fertilizers, reducing fertilizer demand through improved nutrient-use efficiency 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 [3,5,24,28,32,39,41,44,66,68,69,71–86].

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 capacity, reduces evaporation, moderates (often lowers or buffers) soil temperature, improves WUE and yield, enhances soil organic matter and fertility, and reduces erosion	Widely used in maize, wheat, rice, potatoes, vegetables, fruit trees, orchards, rain-fed and irrigated systems, especially in arid/semi-arid regions	[68,71–73]
Crop residue mulch (surface residues in conservation agriculture)	Reduces evaporation and runoff, controls erosion and soil loss, increases water infiltration, raises soil organic carbon, improves soil water storage, helps control weeds and can increase SOC gains	Cereal-based and conservation agriculture systems under minimum/no-till with permanent residue cover	[74–76]
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	[66,67,69,77,78]
Biodegradable plastic mulch (BDM)	Provides similar short-term benefits to plastic (weed control, moisture conservation, improved soil physical/biological properties, improved vegetable yield), and is intended to reduce PE pollution; long-term effects on soil health and microplastics remain uncertain	Used for vegetable and horticultural crops as a more sustainable alternative; evaluated in field trials involving specialty crops	[28,32,79,80]
Living mulch/cover crops	Protect the soil with plant cover, reduce erosion, enhance boost beneficial soil life and build up natural organic matter for sustainable farming	Cover crops and living mulches within conservation agriculture	[39,41,44,81]
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, and smallholder and dryland systems; including the use of composted yard waste and organic mulches in green beans	[82–86]
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	[3,5,24]

2. Mulching as a Strategy for Mitigating Climate Change

Mulching is essential to sustain agricultural output despite climate change by maintaining high soil moisture levels and improving water-use efficiency. As temperatures rise and rainy seasons become increasingly erratic, mulching helps the root zone maintain consistent moisture levels through reduced evaporation, improved water infiltration, and increased soil water-holding capac-

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ity [7,12]. These benefits promote stability in crop growth and production while reducing irrigation requirements, energy use, and, indirectly, greenhouse gas emissions. By enabling more efficient use of limited water resources, mulching strengthens the resilience of both rain-fed and irrigated farming systems, making it a beneficial and inexpensive method that connects agricultural productivity goals with climate change mitigation (Table 2) [3,5,12,24,32,66,71,72,79,80,82,84,86–94].

Table 2: 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 with no mulch; effects were larger for maize and under dry conditions	[12,66,86]
Dryland cereal production	Crop residue/ straw mulch	Maize- and wheat-based dryland or conservation systems	Improves infiltration, reduces runoff and erosion, changes spatial/temporal soil-moisture distribution, increases stored soil water	Higher grain water productivity and yield per unit of water or rainfall compared with no mulch or conventional practice	[12,66,72]
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	[5,87–89]
Horticultural/ vegetable systems	Biodegradable mulch films	Vegetable/ specialty crops	Biodegradable films generally provide soil moisture conservation and yield benefits similar to those of plastic, while avoiding long-term PE residues	Meta-analysis under biodegradable mulches almost always outperform no mulch agronomically, but rarely exceed conventional plastic; WUE benefits are context-specific	[32,67,79,80, 90]
Smallholder rainfed farms	Organic residue/compost mulch	Dryland crops, vegetables	Organic mulches increase soil organic matter, improve water retention, maintain moisture in the root zone during dry spells	Improved WUE and yield stability in dryland agriculture through reduced evaporation, higher soil moisture and better nutrient status	[3,12,66,91]

Table 2: *Cont.*

Agro-Ecological Situation	Mulching Type	Crop System (Examples)	Results Obtained	Impact on Water Use Efficiency	References
Orchard systems	Organic 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	Organic mulches improved soil moisture, reduced evapotranspiration (ET), and improved water productivity in orchard and arid irrigated maize systems	[71,84,92–94]
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)	[5,24,91]
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 requirements compared with no mulch; in some cases, irrigation WUE increased by ~20–40%	[5,12,82,88]

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, gradually releasing nutrients such as nitrogen, phosphorus, and potassium into the soil matrix, which enhances nutrient levels throughout the crop growing season [82,83]. A mulched soil environment minimizes nutrient leaching by keeping the soil moist and biologically active, which are vital conditions for nutrient mineralization and cycling [16,82]. Notably, the presence of mulch also facilitates the establishment and activity of biofertilizers, which synergistically enhance nutrient uptake and availability for plants [10,16,41]. This combination increases reliance on natural nutrient sources and improves the use of applied nutrients, reducing dependence on synthetic fertilizers and minimizing environmental losses [68,84]. Mulching in maize cropping systems has been found to increase soil organic carbon and nutrient levels across different soil depths, further demonstrating mulching's contribution to sustainable soil fertility management [95,96].

3.2. Mulching Effects on Soil Water Conservation and Water Use Efficiency

The impact of mulching on water-use efficiency and soil moisture preservation is direct and measurable, making it a vital technology in water-limited and climate-stressed agricultural systems [7,12]. By covering the soil surface, mulch acts as a physical barrier that inhibits direct evaporation caused by solar radiation and wind. This protection helps maintain moisture in the rhizosphere, which typically experiences greater variability in soil water content during the dry season, a condition that would otherwise stress crops. Mulched soils generally exhibit increased infiltration and reduced surface runoff compared with bare soils [97]. Organic mulches also cushion the impact of rainfall, allowing water to be absorbed rather than lost to erosion and runoff. Decomposition of organic

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mulch further enhances soil organic matter content and improves soil structure, porosity, and water retention [82,98]. These additions make soils more effective at storing moisture, which can then support crop production under irregular rainfall patterns. In terms of water-use efficiency, mulching enables crops to produce higher yields with lesser water inputs: reduced evaporative loss increases the proportion of applied or stored water consumed through transpiration, which translates directly into biomass production [99,100]. In irrigated systems, mulching reduces both the frequency of irrigation and total water demand, saving energy and easing pressure on limited water resources [87,88]. In rain-fed agriculture, it helps crops withstand transient drought stress, further improving yield stability [101,102].

3.3. Improving Soil Physical Properties

In addition to its nutritional benefits, mulching significantly influences the physical characteristics of soil relevant to agricultural productivity. Mulch application has been linked to decreased soil bulk density and increased porosity and aggregate stability, both of which contribute to improved soil structure and aeration [97,98]. Mulching also reduces surface runoff and soil erosion by shielding the soil surface from the impact of raindrops and wind, thereby improving topsoil conservation [11,97]. Moreover, mulching promotes the proliferation of microorganisms in the soil, increasing microbial biomass and activity associated with soil aggregation and organic matter decomposition [10,16]. Conservation tillage research emphasizes that, when combined with mulching, the resulting reduction in soil disturbance further drives these beneficial physical changes, reinforcing the positive influence of conservation tillage on crop development and environmental health [103,104]. These changes are crucial for managing functional and resilient soils under climate-change pressures [96,98]. Figure 1 illustrates the impact of mulching on soil, crop growth, and water retention.

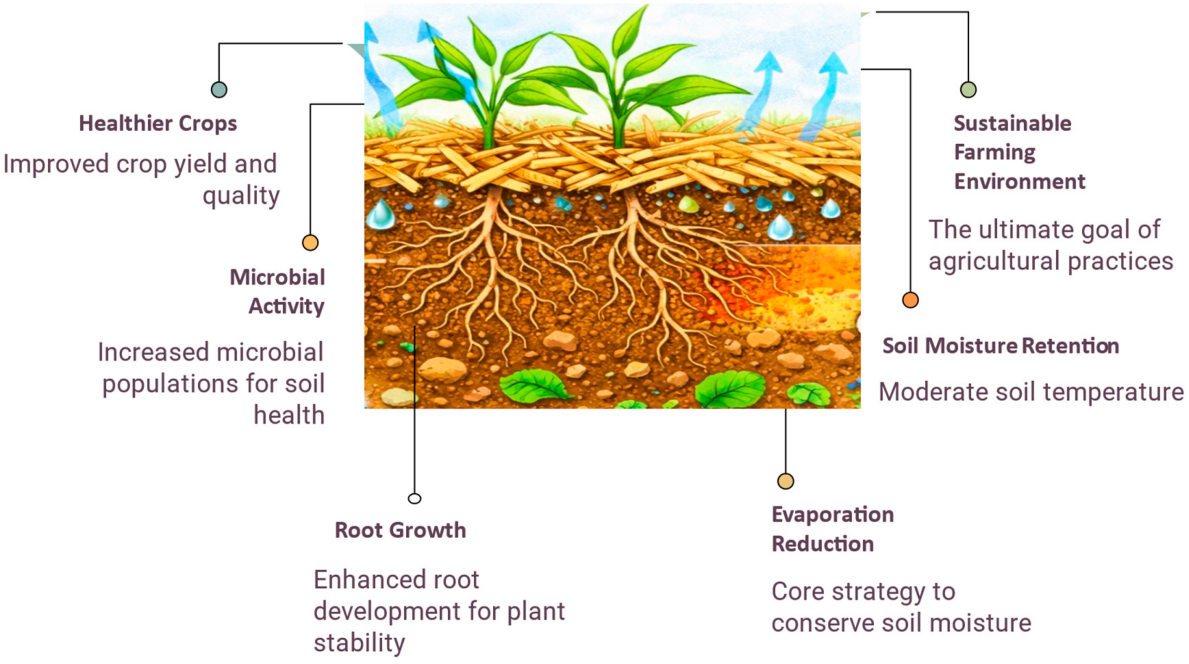


Figure 1: Schematic representation of mulching effects on soil and microclimate, showing moisture conservation, moderated temperature, enhanced root growth, and increased microbial activity.

3.4. Effects of Mulching on Crop Growth, Yield, and Agricultural Productivity

The direct physiological advantage of mulching for plants lies in the favorable micro-environmental conditions it provides during the most critical growth phases. Mulches with thermal insulation properties help moderate soil and root-zone temperatures, ensuring optimal germination and early seedling vigor [105,106]. This temperature control minimizes stress associated with temperature extremes, which is particularly important during the reproductive and grain-filling stages of most crops. Mulching also suppresses weed growth through shading and mechanical interference, reducing competition for water, nutrients, and

light, indirectly enhancing crop growth [21,107]. Additionally, mulches help control pests and diseases by altering soil humidity and temperature conditions in ways that are less conducive to certain pathogens and pests [48,53]. Together, these physiological and protective effects support plant establishment, health, and productivity.

3.5. Mulching Practices Lead to Improved Crop Yield

Numerous empirical studies across different cropping systems have recorded considerable yield improvements as a result of mulching. Field experiments have shown yield increases ranging from 10% to more than 60% in staple crops such as maize, rice, wheat, and various horticultural crops when mulching is applied properly [66,108,109]. These improvements are especially pronounced under highly stressful conditions, such as drought, where mulching stabilizes yields by conserving moisture and counteracting heat stress [101]. With long-term use, different mulch materials can also alter soil properties in ways that warrant investigation; accordingly, the effects of mulching on Haplic Fluvisol properties have been extensively investigated. For example, a long-term field study conducted on 27 perennial plots examined 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 [110]. Bark and wood-chip mulch promote a more bimodal, structure-dominated pore system having a greater storage close to saturation and a more gradual water-retention curve, which reduces the slope near the inflection point relative to other mulch treatments [110]. In practical terms, soils under bark/wood-chip mulch retain more water at low tensions, benefiting shallow-rooted crops, but release it more gradually during drying, which can limit plant-available water under rapid drought onset.

Control patches without mulch recorded lower temperatures than foil-mulched patches, while organic mulches exhibited the highest daily temperature ranges. Mulches also improved soil water storage, particularly in spring, before vegetation growth begins and after perennial plants are cut back. No significant temporal changes were observed in organic carbon content (Cox), aggregate stability, or pH, except between patches containing bark or wood chips and those containing wheat straw, where the role of decomposed organic matter in increasing these two properties was significant [110]. In contrast, soil hydraulic properties varied significantly across all patches as a result of no-tillage practices. This management approach increased saturated and residual water contents, raised saturated hydraulic conductivity, and increased air-entry pressure, consequently reducing bulk density [110]. Soil water retention curves for patches amended with bark or wood chips declined more gradually than those of other patches, indicating greater water retention capacity at low-pressure heads. However, the physical characteristics of soils overlaid with organic mulches, particularly the slope of the inflection point of the retention curve, were less favorable than those of other treatments [110], and readily available water was lower than in other treatments. This confirms that organic mulches have the most pronounced effect on soil conditions, whether positive or negative [82,110,111]. Comparative studies indicate that plastic mulches tend to outperform organic mulches in short-term crop yield production because of their superior moisture retention and weed control; nevertheless, organic mulches offer long-term soil fertility advantages that benefit yield production over time [72,92,112]. The yield stability achieved through mulching therefore presents a strategic advantage for farmers facing climatic uncertainty and resource scarcity [17,21,45,71,80,84,89,90,93,113–121] (Table 3).

Table 3: Influence of mulching on plant development, crop yield, and agricultural output across diverse crops.

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 by an average of about 5.5%, followed by stronger effects under irrigation and fertilization; Yield gains of 82% in wheat and 72% in maize were obtained with high biochar + fertilizer compared with the unfertilized, 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	[113,114]

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Table 3: *Cont.*

Crop Type	Mulching Practice	Results on Growth and Yield	Implications for Agricultural Productivity	References
Maize	Wheat straw mulch	In irrigated summer maize, 5 t ha^{-1} of wheat straw mulch increased grain yield by 18% and total biomass by 20% compared with no mulch; associated with higher leaf area, growth rate and kernels per ear, plus higher soil moisture and lower daytime soil temperature	Enhanced water productivity and healthier growth in water-limited or heat-stress environments	[115]
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 with bare soil	Faster growth and higher marketable yield, improved resource use in intensive vegetable systems	[21,116–118]
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 with 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 or increase yield while improving soil moisture and quality and reducing long-term plastic residue problems	[80,90,117, 119,120]
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	[45,121]
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	[17,71,84,93]
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 26–40%; in smallholder maize systems in Ghana, cowpea living mulch raised maize yield by 34–84% while improving soil quality	Greater resilience, stable yields under variable rainfall, and improved food security for smallholders through residue and living mulch use	[45,89]

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4. Economic and Social Implications for Farmers

Mulching carries significant economic and social implications, particularly for smallholder farmers operating within resource-constrained settings. Cost-benefit analyses show that mulching leads to more efficient use of resources, reducing the need for irrigation, fertilizers, and weeding labor while increasing profitability [66,86,89]. Additional income from higher and more reliable yields can play a key role in supporting livelihoods and food security, particularly in vulnerable regions [45,89]. However, barriers to large-scale implementation remain, including the initial cost of materials and limited access to finance [122], labor-intensive application, limited technical knowledge, and limited availability of appropriate mulch types, partly because crop residues compete with other uses such as livestock feed and fuel [123–125]. Adoption trends are further shaped by societal factors, such as gender roles and community labor dynamics, underscoring the need for participatory extension approaches that ensure the benefits of mulching are shared equitably [89,126,127]. Addressing these issues is essential to realizing the full socioeconomic potential of mulching and its contribution to sustainable agricultural growth. Figure 2 illustrates the role of mulching in climate change mitigation.

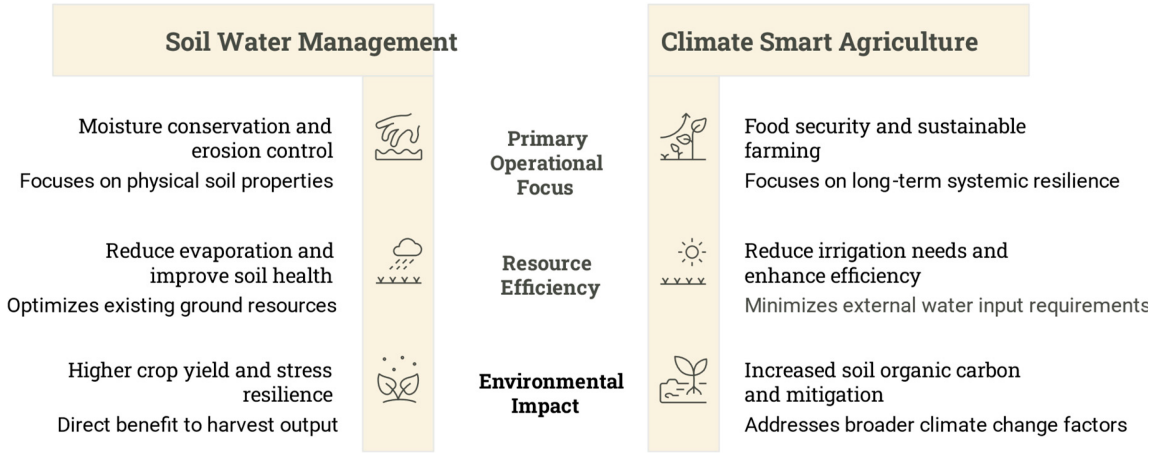


Figure 2: Conceptual framework highlighting the importance of mulching in agricultural production and its contribution to climate change resilience and mitigation.

5. Greenhouse Gas Mitigation and Technological Advances in Mulching

5.1. Agricultural Soils: Reducing Greenhouse Gas Emissions

Mulching also influences greenhouse gas (GHG) emissions from agricultural soils in several ways. It affects microbial activity, notably nitrification and denitrification, which govern the emissions of nitrous oxide (N_2O) and methane (CH_4) [52,108,128]. Field research indicates that combining mulching with biochar application reduces total CO_2 and N_2O emissions, resulting in a net reduction in the carbon footprint of the cropping system [129,130]. Nevertheless, quantifying these emission reductions remains challenging because of site-specific variability and interactions with soil properties and management practices. Environmental trade-offs must also be considered when optimizing mulching strategies: black plastic film has increased soil N_2O emissions in some environments [52], and the decomposition of surface residues can deplete soil oxygen and create anaerobic microsites that promote denitrification-derived N_2O [128,131]. Under thick mulch layers, anaerobic zones could also favor CH4 emissions. Overall, the evidence indicates that mulching can play a significant role in agricultural GHG mitigation when incorporated into broader soil management systems [108,112]. The proposed primary mechanism involves biochar-mediated pH buffering (raising soil pH to approximately 6.5–7.0), which suppresses incomplete denitrification by nosZ-lacking bacteria, thereby reducing N_2O-to-N_2 ratios[132–135]. Simultaneously, mulch-derived organic substrates increase the C: N ratio available to denitrifiers, favoring the complete reduction of N_2O to N_2 [136,137]. To elucidate these pathways, we recom-

mend amplicon sequencing targeting nirS, nirK, and nosZ functional genes, combined with ^{13}C-labelled mulch tracers and stable isotope probing (SIP) of the coupled C-N cycle [135,137].

5.2. Carbon Sequestration Potential of Mulch-Integrated Systems

Extensive long-term mulching increases soil organic carbon stocks through the addition of organic matter while reducing carbon losses through erosion and mineralization [13,75]. Combined with conservation tillage and effective management of agricultural residues, mulching helps stabilize and build soil carbon, a critical factor in mitigating global climate change [75,76,138]. Local research demonstrates that mulch-covered soils have greater aggregate stability and contain more organic matter, which helps stabilize carbon and reduce decomposition losses [76,95]. Furthermore, mulching systems exhibit synergistic effects on soil carbon sequestration when combined with reduced tillage and diversified crop rotation, underscoring their relevance to large-scale, sustainable low-carbon agriculture [95,139]. These findings align with global objectives for soil-based climate solutions aimed at increasing carbon sequestration in croplands [13,138].

5.3. Technological Advances in Mulching

Technological advances in the agricultural sector have greatly enhanced the efficiency, precision, and sustainability of mulching practices. Contemporary mulching technologies extend beyond simply covering the soil, encompassing systems that maximize the utilization, distribution, and functional performance of materials under changing field conditions [5,15,32]. Mechanized mulch applicators enable the application of organic residues or films at a consistent rate, requiring minimal labor while providing uniform soil coverage across large areas [5,15]. These applicators are commonly integrated with planting equipment in conservation and precision agriculture systems, enabling simultaneous seeding and mulching that improves operational efficiency and crop establishment. This study proposes a three-tier fusion architecture: (1) ground-truth point sensors (time-domain reflectometry (TDR), thermocouple arrays) at 0.5 m resolution deployed at the mulch-soil interface; (2) unmanned aerial vehicle (UAV)-mounted thermal and multispectral imaging at 5–10 cm resolution to capture mesoscale spatial heterogeneity [140]; and (3) satellite time-series data (Sentinel-2 short-wavelength infrared (SWIR) bands) to regionalize patterns [141]. A physics-informed neural network (PINN) embedding the Richards equation as a constraint layer can then integrate these multi-source observations into continuous soil moisture and temperature fields, as demonstrated for general soil monitoring applications [142–144].

Material innovation. The development of biodegradable and bio-based mulches addresses environmental concerns associated with traditional plastic films [31,32]. These materials are designed to decompose within the growing season through microbial activity, eliminating the need for removal and disposal [35,145,146]. Ongoing research focuses on controlling the degradation rate, tensile strength, and thermal properties to suit different crops and climatic conditions [33,34,145].

Digital and data-driven technologies are also transforming modern mulching systems. Sensors and remote sensing equipment are increasingly used to monitor the dynamics of soil moisture, temperature, and evaporation in mulched soils [140,141,147], providing data that support more effective decisions regarding mulch type, application depth, and timing. Precision agriculture platforms and decision-support models integrate weather forecasting with soil information to optimize water-saving mulching strategies and maintain yield stability [12,147].

6. Conclusions

Mulching offers several environmental advantages beyond its short-term agronomic benefits. By acting as a protective barrier against wind and heavy rain, mulch prevents soil erosion, helps retain fertile topsoil, and minimizes the transport of sediments into surrounding water bodies. It also helps prevent the leaching and runoff of nutrients, ensuring that crops receive the nutrients and organic amendments intended for them while reducing water contamination and nutrient loss that can, in turn, contribute to greenhouse gas emissions. Organic mulches, in particular, enhance carbon sequestration, as organic matter incorporated into the soil during decomposition adds to soil organic carbon stocks, helping offset atmospheric carbon dioxide. Mulching also improves resource efficiency by reducing water and energy use in irrigated systems: by conserving soil moisture, it reduces both the frequency of irrigation and the volume of water required, thereby lowering the energy needed for pumping and water delivery. This indirect reduction in energy consumption correspondingly lowers greenhouse gas emissions associated with fossil fuel-intensive irrigation systems. Moreover, moderated soil temperatures and improved moisture availability enhance crop growth and yield even under variable and unpredictable climatic conditions, thereby making both smallholder and commercial farming systems more resilient

through mulching. When combined with other agronomic strategies such as crop rotation, cover cropping, and integrated nutrient management, mulching offers an economical, scalable, and environmentally friendly option that not only enhances agricultural production but also advances the goals of climate-smart agriculture, supporting sustainable resource use, minimizing environmental impact, and strengthening food security in the face of changing climate patterns.

List of Abbreviations

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

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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.

Conflicts of Interest

The authors declare no conflicts of interest.

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AI Declaration

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

References

[1] Saleem, A.; Anwar, S.; Nawaz, T.; Fahad, S.; Saud, S.; Ur Rahman, T.; Zahra, N.; Ahmad, N.; Ditta, A.; Hussain, S. Securing a Sustainable Future: The Climate Change Threat to Agriculture, Food Security, and Sustainable Development Goals. *J. Umm Al-Qura Univ. Appl. Sci.* **2024**, *11*, 595–611. [CrossRef]

[2] Prăvălie, R. Drylands Extent and Environmental Issues. A Global Approach. *Earth-Sci. Rev.* **2016**, *161*, 259–278. [CrossRef]

[3] Demo, A.H.; Bogale, G.A. Enhancing Crop Yield and Conserving Soil Moisture through Mulching Practices in Dryland Agriculture. *Front. Agron.* **2024**, *6*, 1361697. [CrossRef]

[4] Kourgialas, N.N. Reconsidering the Soil–Water–Crops–Energy (SWCE) Nexus Under Climate Complexity—A Critical Review. *Agriculture* **2025**, *15*, 1891. [CrossRef]

[5] El-Beltagi, H.S.; Basit, A.; Mohamed, H.I.; Ali, I.; Ullah, S.; Kamel, E.A.R.; Shalaby, T.A.; Bell, S.M.; El-Ramady, H. Mulching as a Sustainable Water and Soil Saving Practice in Agriculture: A Review. *Agronomy* **2022**, *12*, 1881. [CrossRef]

[6] Iqbal, R.; Raza, M.A.S.; Valipour, M.; Saleem, M.F.; Zaheer, M.S.; Ahmad, S.; Toleikiene, M.; Haider, I.; Aslam, M.U.; Naqvi, S.A. Potential Agricultural and Environmental Benefits of Mulches—A Review. *Bull. Natl. Res. Cent.* **2020**, *44*, 75. [CrossRef]

[7] Kader, M.A.; Singha, A.; Begum, M.A.; Jewel, A.; Khan, F.H.; Khan, N.I. Mulching as Water-Saving Technique in Dryland Agriculture: Review Article. *Bull. Natl. Res. Cent.* **2019**, *43*, 147. [CrossRef]

[8] Xing, Y.; Wang, X.; Mustafa, A. Exploring the Link between Soil Health and Crop Productivity. *Ecotoxicol. Environ. Saf.* **2025**, *289*, 117703. [CrossRef] [PubMed]

[9] Liang, M.; Chen, L.; Chen, G.; Zhao, Y.; Liu, G.; Sun, E.; Jia, Z.; Han, Q. Protective Effects of Straw Mulching on Soil Health and Function: A Review. *Environ. Pollut. Bioavailab.* **2025**, *37*, 2533900. [CrossRef]

[10] Zhang, S.; Wang, Y.; Sun, L.; Qiu, C.; Ding, Y.; Gu, H.; Wang, L.; Ge, S.; Li, C.; Zhang, Y.; et al. Organic Mulching Positively Regulates the Soil Microbial Communities and Ecosystem Functions in Tea

Plantation. *BMC Microbiol.* **2020**, *20*, 103. [CrossRef] [PubMed]

[11] Fan, D.; Jia, G.; Wang, Y.; Yu, X. The Effectiveness of Mulching Practices on Water Erosion Control: A Global Meta-Analysis. *Geoderma* **2023**, *438*, 116643. [CrossRef]

[12] Ramos, T.B.; Darouich, H.; Pereira, L.S. Mulching Effects on Soil Evaporation, Crop Evapotranspiration and Crop Coefficients: A Review Aimed at Improved Irrigation Management. *Irrig. Sci.* **2024**, *42*, 525–539. [CrossRef]

[13] Jat, M.L.; Chakraborty, D.; Ladha, J.K.; Parihar, C.M.; Datta, A.; Mandal, B.; Nayak, H.S.; Maity, P.; Rana, D.S.; Chaudhari, S.K.; et al. Carbon Sequestration Potential, Challenges, and Strategies towards Climate Action in Smallholder Agricultural Systems of South Asia. *Crop Environ.* **2022**, *1*, 86–101. [CrossRef]

[14] Xing, Y.; Wang, X. Impact of Agricultural Activities on Climate Change: A Review of Greenhouse Gas Emission Patterns in Field Crop Systems. *Plants* **2024**, *13*, 2285. [CrossRef] [PubMed]

[15] Kader, M.A.; Senge, M.; Mojid, M.A.; Ito, K. Recent Advances in Mulching Materials and Methods for Modifying Soil Environment. *Soil Tillage Res.* **2017**, *168*, 155–166. [CrossRef]

[16] Zhou, W.; Sun, X.; Li, S.; Qu, B.; Zhang, J. How Organic Mulching Influences the Soil Bacterial Community Structure and Function in Urban Forests. *Microorganisms* **2024**, *12*, 520. [CrossRef] [PubMed]

[17] Liu, Y.; Teng, Y.; Zheng, J.; Khan, A.; Li, X.; Cui, J.; Verma, K.K.; Guo, Q.; Zhu, K. The Impact of Long-Term Mulching Cultivation on Soil Quality, Microbial Community Structure, and Fruit Quality in 'Wanzhou Red Mandarin' Citrus Orchard. *Front. Plant Sci.* **2025**, *16*, 1616151. [CrossRef]

[18] Saputra, H.; Arief Soleh, M.; Sauman Hamdani, J.; Saryoko, A. The Potential and Differences between Mulch and Organic Matter in Reducing Drought Stress in Plants—A Review. *Cogent Food Agric.* **2025**, *11*, 2454342. [CrossRef]

[19] Choudhary, M.; Kumari, A.; Choudhary, S. Effect of Mulching on Vegetable Production: A Review. *Agric. Rev.* **2022**, *43*, 296. [CrossRef]

[20] Salama, K.; Geyer, M. Plastic Mulch Films in Agriculture: Their Use, Environmental Problems, Recycling and Alternatives. *Environments* **2023**, *10*, 179. [CrossRef]

[21] Sokombela, A.; Ndhlala, A.R.; Bopape-Mabapa, M.P.; Eiasu, B.K.; Mpai, S.; Nyambo, P. Colored Plastic Mulch Impacts on Soil Properties, Weed Density and Vegetable Crop Productivity: A Meta-Analysis. *Sci. Rep.* **2025**, *15*, 31891. [CrossRef] [PubMed]

[22] Steinmetz, Z.; Wollmann, C.; Schaefer, M.; Buchmann, C.; David, J.; Tröger, J.; Muñoz, K.; Frör, O.; Schaumann, G.E. Plastic Mulching in Agriculture. Trading Short-Term Agronomic Benefits for Long-Term Soil Degradation? *Sci. Total Environ.* **2016**, *550*, 690–705. [CrossRef] [PubMed]

[23] Wang, G.; He, N.; Li, Y.; Huang, W.; Cao, Y.; Wang, J.; Qian, X.; Yin, L.; Zeng, X. The Effects of Different Plastic Film Mulches on the Physicochemical and Microbiological Properties of Soils for Protected Pepper Cultivation. *Horticulturae* **2025**, *11*, 710. [CrossRef]

[24] Gan, Y.; Siddique, K.H.M.; Turner, N.C.; Li, X.-G.; Niu, J.-Y.; Yang, C.; Liu, L.; Chai, Q. Ridge-Furrow Mulching Systems—An Innovative Approach for Boosting Crop Productivity in Semiarid Rain-Fed Environments. *Adv. Agron.* **2013**, *118*, 429–476. [CrossRef]

[25] Su, J.; Zhu, Y.; Chen, X.; Lu, X.; Yan, J.; Yan, L.; Zou, W. Biochar Influences Polyethylene Microplastic-Contaminated Soil Properties and Enzyme Activities. *Agronomy* **2024**, *14*, 2919. [CrossRef]

[26] Huang, S.; Guo, T.; Feng, Z.; Li, B.; Cai, Y.; Ouyang, D.; Gustave, W.; Ying, C.; Zhang, H. Polyethylene and Polyvinyl Chloride Microplastics Promote Soil Nitrification and Alter the Composition of Key Nitrogen Functional Bacterial Groups. *J. Hazard. Mater.* **2023**, *453*, 131391. [CrossRef] [PubMed]

[27] Hofmann, T.; Ghoshal, S.; Tufenkji, N.; Adamowski, J.F.; Bayen, S.; Chen, Q.; Demokritou, P.; Flury, M.; Hüffer, T.; Ivleva, N.P.; et al. Plastics Can Be Used More Sustainably in Agriculture. *Commun. Earth Environ.* **2023**, *4*, 332. [CrossRef]

[28] Dada, O.I.; Habarakada Liyanage, T.U.; Chi, T.; Yu, L.; DeVetter, L.W.; Chen, S. Towards Sustainable Agroecosystems: A Life Cycle Assessment Review of Soil-Biodegradable and Traditional Plastic Mulch Films. *Environ. Sci. Ecotechnol.* **2025**, *24*, 100541. [CrossRef] [PubMed]

[29] Xiong, L.; Li, Z.; Shah, F.; Wang, P.; Yuan, Q.; Wu, W. Biodegradable Mulch Film Enhances the Environmental Sustainability Compared with Traditional Polyethylene Film from Multidimensional Perspectives. *Chem. Eng. J.* **2024**, *492*, 152219. [CrossRef]

[30] Sintim, H.Y.; Flury, M. Is Biodegradable Plastic Mulch the Solution to Agriculture's Plastic Problem? *Environ. Sci. Technol.* **2017**, *51*, 1068–1069. [CrossRef] [PubMed]

[31] Menossi, M.; Cisneros, M.; Álvarez, V.; Casalongué, C. Current and Emerging Biodegradable Mulch Films Based on Polysaccharide Bio-Composites. A Review. *Agron. Sustain. Dev.* **2021**, *41*, 53. [CrossRef]

[32] Abbate, C.; Scavo, A.; Pesce, G.R.; Fontanazza, S.; Restuccia, A.; Mauromicale, G. Soil Bioplastic Mulches for Agroecosystem Sustainability: A Comprehensive Review. *Agriculture* **2023**, *13*, 197. [CrossRef]

[33] Kopitar, D.; Marasovic, P. Degradation of Biodegradable Nonwoven Mulches in the Winter Period. *Polymers* **2024**, *16*, 2279. [CrossRef] [PubMed]

[34] Lorenzo Santiago, M.A.; Rendón Villalobos, J.R.; Contreras Ramos, S.M.; Pacheco Vargas, G.; García Hernández, E. Biodegradation Studies of Biobased

Mulch Films Reinforced with Cellulose from Waste Mango. *Recycling* **2024**, *9*, 96. [CrossRef]

[35] Anunciado, M.B.; Hayes, D.G.; Astner, A.F.; Wadsworth, L.C.; Cowan-Banker, C.D.; Gonzalez, J.E.L.Y.; DeBruyn, J.M. Effect of Environmental Weathering on Biodegradation of Biodegradable Plastic Mulch Films under Ambient Soil and Composting Conditions. *J. Polym. Environ.* **2021**, *29*, 2916–2931. [CrossRef]

[36] Sintim, H.Y.; Bary, A.I.; Hayes, D.G.; English, M.E.; Schaeffer, S.M.; Miles, C.A.; Zelenyuk, A.; Suski, K.; Flury, M. Release of Micro- and Nanoparticles from Biodegradable Plastic during In Situ Composting. *Sci. Total Environ.* **2019**, *675*, 686–693. [CrossRef] [PubMed]

[37] Tao, Z.; Flury, M.; Xu, Y.; Yu, Y.; Bol, R.; Du, H.; Wang, J.; Ding, J.; Jones, D.L.; Chadwick, D.R.; et al. Mineralization and Transfer of Polymer-Derived Carbon from Biodegradable Mulch into the Soil Microbial Biomass and Organic Matter Pool. *Environ. Sci. Technol.* **2025**, *59*, 25830–25841. [CrossRef] [PubMed]

[38] Liu, Z.; Zhao, C.; Zhang, N.; Wang, J.; Li, Z.; Uwiragiye, Y.; Fallah, N.; Crowther, T.W.; Huang, Y.; Huang, Y.; et al. Degradable Film Mulching Increases Soil Carbon Sequestration in Major Chinese Dryland Agroecosystems. *Nat. Commun.* **2025**, *16*, 5029. [CrossRef]

[39] Repullo-Ruibérriz de Torres, M.A.; Carbonell-Bojollo, R.M.; Moreno-García, M.; Ordóñez-Fernández, R.; Rodríguez-Lizana, A. Soil Organic Matter and Nutrient Improvement through Cover Crops in a Mediterranean Olive Orchard. *Soil Tillage Res.* **2021**, *210*, 104977. [CrossRef]

[40] Blanco-Canqui, H.; Mikha, M.M.; Presley, D.R.; Claassen, M.M. Addition of Cover Crops Enhances No-Till Potential for Improving Soil Physical Properties. *Soil Sci. Soc. Am. J.* **2011**, *75*, 1471–1482. [CrossRef]

[41] Li, H.; Hill, N.; Wallace, J.G. A Perennial Living Mulch System Fosters a More Diverse and Balanced Soil Bacterial Community. *PLoS ONE* **2023**, *18*, e0290608. [CrossRef] [PubMed]

[42] Unger, P.W.; Vigil, M.F. Cover Crop Effects on Soil Water Relationships. *J. Soil Water Conserv.* **1998**, *53*, 200–207. [CrossRef]

[43] Mubvumba, P.; DeLaune, P.; Hons, F. Soil Water Dynamics under a Warm-Season Cover Crop Mixture in Continuous Wheat. *Soil Tillage Res.* **2021**, *206*, 104823. [CrossRef]

[44] Garba, I.; Bell, L.; Williams, A. Cover Crop Legacy Impacts on Soil Water and Nitrogen Dynamics, and on Subsequent Crop Yields in Drylands: A Meta-Analysis. *Agron. Sustain. Dev.* **2022**, *42*, 34. [CrossRef]

[45] Abdul Rahman, N.; Larbi, A.; Berdjour, A.; Kizito, F.; Hoeschle-Zeledon, I. Cowpea Living Mulch Effect on Soil Quality and Grain Yield in Smallholder Maize-Based Cropping System of Northern Ghana. *J. Soil Sci. Plant Nutr.* **2022**, *22*, 3925–3940. [CrossRef]

[46] Amare, G.; Desta, B. Coloured Plastic Mulches: Impact on Soil Properties and Crop Productivity. *Chem. Biol. Technol. Agric.* **2021**, *8*, 4. [CrossRef]

[47] Tarara, J.M. Microclimate Modification with Plastic Mulch. *HortScience* **2000**, *35*, 169–180. [CrossRef]

[48] Kasirajan, S.; Ngouajio, M. Polyethylene and Biodegradable Mulches for Agricultural Applications: A Review. *Agron. Sustain. Dev.* **2012**, *32*, 501–529. [CrossRef]

[49] Díaz-Pérez, J.C. Bell Pepper (*Capsicum annuum* L.) Grown on Plastic Film Mulches: Effects on Crop Microenvironment, Physiological Attributes, and Fruit Yield. *HortScience* **2010**, *45*, 1196–1204. [CrossRef]

[50] Rajablariani, H.R.; Hassankhan, F.; Rafezi, R. Effect of Colored Plastic Mulches on Yield of Tomato and Weed Biomass. *Int. J. Environ. Sci. Dev.* **2012**, *3*, 590–593. [CrossRef]

[51] Mahmood, M.; Farooq, K.; Hussain, A.; Sher, R. Effect of Mulching on Growth and Yield of Potato Crop. *Asian J. Plant Sci.* **2002**, *1*, 132–133. [CrossRef]

[52] Meng, C.; Zhao, J.; Wang, N.; Yang, K.; Wang, F. Black Plastic Film Mulching Increases Soil Nitrous Oxide Emissions in Arid Potato Fields. *Int. J. Environ. Res. Public Health* **2022**, *19*, 16030. [CrossRef] [PubMed]

[53] Greer, L.; Dole, J.M. Aluminum Foil, Aluminium-Painted Plastic, and Degradable Mulches Increase Yields and Decrease Insect-Vectored Viral Diseases of Vegetables. *HortTechnology* **2003**, *13*, 276–284. [CrossRef]

[54] Manni, M.; Di Giuseppe, A.; Nicolini, A.; Sciurpi, F.; Cotana, F. Influences of a Highly Reflective Mulching Membrane on Heat Propagation throughout the Soil. *Sustainability* **2021**, *13*, 9737. [CrossRef]

[55] Delgado-Baquerizo, M.; Guerra, C.A.; Cano-Díaz, C.; Egidi, E.; Wang, J.T.; Eisenhauer, N.; Singh, B.K.; Maestre, F.T. The Proportion of Soil-Borne Pathogens Increases with Warming at the Global Scale. *Nat. Clim. Change* **2020**, *10*, 550–554. [CrossRef]

[56] Vilà, M.; Beaury, E.M.; Blumenthal, D.M.; Bradley, B.A.; Early, R.; Laginhas, B.B.; Sorte, C.J.B.; Ibáñez, I. Understanding the Combined Impacts of Weeds and Climate Change on Crops. *Environ. Res. Lett.* **2021**, *16*, 034043. [CrossRef]

[57] Peters, K.; Breitsameter, L.; Gerowitt, B. Impact of Climate Change on Weeds in Agriculture: A Review. *Agron. Sustain. Dev.* **2014**, *34*, 707–721. [CrossRef]

[58] Katan, J.; Greenberger, A.; Alon, H.; Grinstein, A. Solar Heating by Polyethylene Mulching for the Control of Diseases Caused by Soil-Borne Pathogens. *Phytopathology* **1976**, *66*, 683–688. [CrossRef] [PubMed]

[59] Katan, J. Solar Heating (Solarization) of Soil for Control of Soilborne Pests. *Annu. Rev. Phytopathol.* **1981**, *19*, 211–236. [CrossRef]

[60] Stapleton, J.J.; DeVay, J.E. Soil Solarization: A Non-Chemical Approach for Management of Plant Pathogens and Pests. *Crop Prot.* **1986**, *5*, 190–198. [CrossRef]

[61] Ristaino, J.B.; Thomas, W. Agriculture, Methyl Bromide, and the Ozone Hole: Can We Fill the Gap? *Plant Dis.* **1997**, *81*, 964–977. [CrossRef] [PubMed]

[62] Katan, J. Physical and Cultural Methods for the Management of Soil-Borne Pathogens. *Crop Prot.* **2000**, *19*, 725–731. [CrossRef]

[63] Pandey, G.; Parks, S.; Thomas, R.G. Polymer and Photo-Selective Covers on Plant and Fruit Development: A Review. *Agron. J.* **2023**, *115*, 3074–3091. [CrossRef]

[64] Kasperbauer, M.J.; Hunt, P.G. Biological and Photometric Measurement of Light Transmission Through Soils of Various Colors. *Bot. Gaz.* **1988**, *149*, 361–364. [CrossRef]

[65] Decoteau, D.R.; Kasperbauer, M.J.; Hunt, P.G. Mulch Surface Color Affects Yield of Fresh-Market Tomatoes. *J. Am. Soc. Hortic. Sci.* **1989**, *114*, 216–219. [CrossRef]

[66] Qin, W.; Hu, C.; Oenema, O. Soil Mulching Significantly Enhances Yields and Water and Nitrogen Use Efficiencies of Maize and Wheat: A Meta-Analysis. *Sci. Rep.* **2015**, *5*, 16210. [CrossRef] [PubMed]

[67] Gao, H.; Yan, C.; Liu, Q.; Ding, W.; Chen, B.; Li, Z. Effects of Plastic Mulching and Plastic Residue on Agricultural Production: A Meta-Analysis. *Sci. Total Environ.* **2019**, *651*, 484–492. [CrossRef] [PubMed]

[68] Du, C.; Li, L.; Effah, Z. Effects of Straw Mulching and Reduced Tillage on Crop Production and Environment: A Review. *Water* **2022**, *14*, 2471. [CrossRef]

[69] Huang, T.; Wu, Q.; Yuan, Y.; Zhang, X.; Sun, R.; Hao, R.; Ke, X.; Zhao, L.; Zhou, W.; He, G.; et al. Effects of Plastic Film Mulching on Yield, Water Use Efficiency, and Nitrogen Use Efficiency of Different Crops in China: A Meta-Analysis. *Field Crops Res.* **2024**, *312*, 109407. [CrossRef]

[70] Forster, P.; Storelvmo, T.; Armour, K.; Collins, W.; Dufresne, J.-L.; Frame, D.; Lunt, D.J.; Mauritsen, T.; Palmer, M.D.; Watanabe, M.; et al. The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity. In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., et al., Eds.; Cambridge University Press: Cambridge, UK, 2021; pp. 923–1054. [CrossRef]

[71] Yang, Y.; Yin, M.; Guan, H. Responses of Soil Water, Temperature, and Yield of Apple Orchard to Straw Mulching and Supplemental Irrigation on China's Loess Plateau. *Agronomy* **2024**, *14*, 1531. [CrossRef]

[72] Zhao, H.; Liu, J.; Chen, X.; Wang, Z. Straw Mulch as an Alternative to Plastic Film Mulch: Positive Evidence from Dryland Wheat Production on the Loess Plateau. *Sci. Total Environ.* **2019**, *676*, 782–791. [CrossRef] [PubMed]

[73] Biswal, P.; Swain, D.K.; Jha, M.K. Straw Mulch with Limited Drip Irrigation Influenced Soil Microclimate in Improving Tuber Yield and Water Productivity of Potato in Subtropical India. *Soil Tillage Res.* **2022**, *223*, 105484. [CrossRef]

[74] Ranaivoson, L.; Naudin, K.; Ripoche, A.; Affholder, F.; Rabeharisoa, L.; Corbeels, M. Agro-Ecological Functions of Crop Residues under Conservation Agriculture. A Review. *Agron. Sustain. Dev.* **2017**, *37*, 26. [CrossRef]

[75] Francaviglia, R.; Almagro, M.; Vicente-Vicente, J.L. Conservation Agriculture and Soil Organic Carbon: Principles, Processes, Practices and Policy Options. *Soil Syst.* **2023**, *7*, 17. [CrossRef]

[76] Blanco-Canqui, H.; Lal, R. Soil Structure and Organic Carbon Relationships Following 10 Years of Wheat Straw Management in No-Till. *Soil Tillage Res.* **2007**, *95*, 240–254. [CrossRef]

[77] Mari, J.A.; Soothar, R.K.; Thidar, M.; Mangrio, M.A.; Mirjat, M.U.; Katohar, I. Effect of Plastic Film Mulch and Irrigation Water Regimes on Soil Temperature Pattern, Plant Growth and Water Productivity of Maize. *Ecol. Front.* **2024**, *44*, 752–759. [CrossRef]

[78] Zhao, Y.; Mao, X.; Li, S.; Huang, X.; Che, J.; Ma, C. A Review of Plastic Film Mulching on Water, Heat, Nitrogen Balance, and Crop Growth in Farmland in China. *Agronomy* **2023**, *13*, 2515. [CrossRef]

[79] Sintim, H.Y.; Bandopadhyay, S.; English, M.E.; Bary, A.I.; DeBruyn, J.M.; Schaeffer, S.M.; Moore-Kucera, J.; Painter, J.D.; Miles, C.; Flury, M. Impacts of Biodegradable Plastic Mulches on Soil Health. *Agric. Ecosyst. Environ.* **2019**, *273*, 36–49. [CrossRef]

[80] Tofanelli, M.B.; Wortman, S. Benchmarking the Agronomic Performance of Biodegradable Mulches against Polyethylene Mulch Film: A Meta-Analysis. *Agronomy* **2020**, *10*, 1618. [CrossRef]

[81] Agus, F.; Husnain, H.; Yustika, R.D. Improving Agricultural Resilience to Climate Change through Soil Management. *J. Penelit. Pengemb. Pertan.* **2015**, *34*, 147–158. [CrossRef]

[82] Rossi, G.; Beni, C.; Neri, U. Organic Mulching: A Sustainable Technique to Improve Soil Quality. *Sustainability* **2024**, *16*, 10261. [CrossRef]

[83] Nair, P.K.R.; Kumar, B.M.; Nair, V.D. Soil Organic Matter and Nutrient Cycling. In *An Introduction to Agroforestry: Four Decades of Scientific Developments*, 2nd ed.; Springer: Cham, Switzerland, 2022; pp. 383–411. [CrossRef]

[84] Ali, A.; Das, B.; Dhakar, M.K.; Naik, S.K.; Patel, V.B.; Mishra, G.P.; Singh, A.K.; Mehta, S.; Rai, M.; Kumar, A. Enhancing Soil Health and Fruit

Yield through Tephrosia Biomass Mulching in Rainfed Guava (*Psidium guajava* L.) Orchards. *Sci. Rep.* **2024**, *14*, 13913. [CrossRef] [PubMed]

[85] Awad, A.E.; Abuarab, M.E.; Abdelraouf, R.E.; Bakeer, G.A.; El-Shawadfy, M.A.; Ragab, R. Improving Yield and Irrigation Water Productivity of Green Beans under Water Stress with Agricultural Solid Waste-Based Material of Compacted Rice Straw as a Sustainable Organic Soil Mulch. *Irrig. Sci.* **2025**, *43*, 465–490. [CrossRef]

[86] Verma, S.; Pradhan, S.S. Effect of Mulches on Crop, Soil and Water Productivity: A Review. *Agric. Rev.* **2024**, *45*, 335. [CrossRef]

[87] Zhang, W.; Dong, A.; Liu, F.; Niu, W.; Siddique, K.H.M. Effect of Film Mulching on Crop Yield and Water Use Efficiency in Drip Irrigation Systems: A Meta-Analysis. *Soil Tillage Res.* **2022**, *221*, 105392. [CrossRef]

[88] Lei, T.; Luo, C.; Zhang, R.; Hu, C.; Xu, J.; Sadras, V.; Yang, X.; Zhang, S. Partial-Film Mulch Returns the Same Gains in Yield and Water Use Efficiency as Full-Mulch with Reduced Cost and Lower Pollution: A Meta-Analysis. *J. Sci. Food Agric.* **2021**, *101*, 5956–5962. [CrossRef] [PubMed]

[89] Masasi, B.; Aryal, N.; Millogo, V.; Masasi, J.; Srivastava, A.; Kalita, P.K. Assessing the Impacts of Mulching on Vegetable Production under Drip Irrigation in Burkina Faso. *Sustainability* **2025**, *17*, 916. [CrossRef]

[90] Adamczewska-Sowińska, K.; Bykowy, J.; Jaworska, J. Effect of Biodegradable Mulch and Different Synthetic Mulches on Growth and Yield of Field-Grown Small-Fruited Tomato (*Lycopersicon esculentum* Mill.). *Agriculture* **2025**, *15*, 212. [CrossRef]

[91] Mak-Mensah, E.; Yeboah, F.K.; Obour, P.B.; Usman, S.; Essel, E.; Bakpa, E.P.; Zhang, D.; Zhou, X.; Wang, X.; Zhao, X.; et al. Integration of Ridge and Furrow Rainwater Harvesting Systems and Soil Amendments Improve Crop Yield under Semi-Arid Conditions. *Paddy Water Environ.* **2022**, *20*, 287–302. [CrossRef]

[92] Zhao, Z.Y.; Wang, P.Y.; Xiong, X.B.; Zhou, R.; Zhu, Y.; Wang, Y.B.; Noor Mohamed, M.; Jat, M.L.; Jiang, Y.; Zhang, W.F. Can Shallow-Incorporated Organic Mulching Replace Plastic Film Mulching for Irrigated Maize Production Systems in Arid Environments? *Field Crops Res.* **2023**, *297*, 108931. [CrossRef]

[93] Tang, M.; Liu, R.; Li, H.; Gao, X.; Wu, P.; Zhang, C. Optimizing Soil Moisture Conservation and Temperature Regulation in Rainfed Jujube Orchards of China's Loess Hilly Areas Using Straw and Branch Mulching. *Agronomy* **2023**, *13*, 2121. [CrossRef]

[94] Li, L.; Chen, P.; Jing, X.; Lyu, C.; Zhang, R.; Yuan, X.; Zhang, M.; Ding, W.; Zhang, L.; Song, C. Effects of Cover Crops on Water Use Efficiency in Orchard Systems in the Danjiangkou Catchment, Central China. *Plants* **2025**, *14*, 3729. [CrossRef] [PubMed]

[95] Zhou, Z.; Li, Z.; Chen, K.; Chen, Z.; Zeng, X.; Yu, H.; Guo, S.; Shangguan, Y.; Chen, Q.; Fan, H.; et al. Changes in Soil Physicochemical Properties and Bacterial Communities at Different Soil Depths after Long-Term Straw Mulching under a No-Till System. *SOIL* **2021**, *7*, 595–609. [CrossRef]

[96] Kumar, S.S.; Wani, O.A.; Prasad, B.; Banuve, A.; Mua, P.; Sharma, A.C.; Krishnamurthy, S.L.; Dey, P.; Tyagi, V.; Padder, S.A.; et al. Effects of Mulching on Soil Properties and Yam Production in Tropical Region. *Sustainability* **2024**, *16*, 7787. [CrossRef]

[97] Jordán, A.; Zavala, L.M.; Gil, J. Effects of Mulching on Soil Physical Properties and Runoff under Semi-Arid Conditions in Southern Spain. *CATENA* **2010**, *81*, 77–85. [CrossRef]

[98] Mulumba, L.N.; Lal, R. Mulching Effects on Selected Soil Physical Properties. *Soil Tillage Res.* **2008**, *98*, 106–111. [CrossRef]

[99] Hatfield, J.L.; Sauer, T.J.; Prueger, J.H. Managing Soils to Achieve Greater Water Use Efficiency: A Review. *Agron. J.* **2001**, *93*, 271–280. [CrossRef]

[100] Deng, X.-P.; Shan, L.; Zhang, H.; Turner, N.C. Improving Agricultural Water Use Efficiency in Arid and Semiarid Areas of China. *Agric. Water Manag.* **2006**, *80*, 23–40. [CrossRef]

[101] Shah, S.T.; Ullah, I.; Basit, A.; Sajid, M.; Arif, M.; Mohamad, H.I. Mulching Is a Mechanism to Reduce Environmental Stresses in Plants. In *Mulching in Agroecosystems: Plants, Soil & Environment*; Akhtar, K., Arif, M., Riaz, M., Wang, H., Eds.; Springer: Singapore, 2022; pp. 353–376. [CrossRef]

[102] Zhao, L.; Zhang, C.; Liang, M.; Chen, P.; Anwar, S.; Fan, M.; Gu, C.; Ren, H.; Li, J.; Zhang, X.; et al. Exploring the Influence of Planting Densities and Mulching Types on Photosynthetic Activity, Antioxidant Enzymes, and Chlorophyll Content and Their Relationship to Yield of Maize. *Plants* **2024**, *13*, 3423. [CrossRef] [PubMed]

[103] Derpsch, R.; Kassam, A.; Reicosky, D.; Friedrich, T.; Calegari, A.; Basch, G.; Sartori, F.; Ashburner, J.; Dent, D. Nature's Laws of Declining Soil Productivity and Conservation Agriculture. *Soil Secur.* **2024**, *14*, 100127. [CrossRef]

[104] Jug, D.; Jug, I.; Brozović, B.; Šeremešić, S.; Dolijanović, Ž.; Zsembeli, J.; Filipović, V.; Vukadinović, V.; Đurđević, B.; Stipešević, B.; et al. Conservation Soil Tillage: Bridging Science and Farmer Expectations—An Overview from Southern to Northern Europe. *Agriculture* **2025**, *15*, 260. [CrossRef]

[105] Lalljee, B. Mulching as a Mitigation Agricultural Technology against Land Degradation in the Wake of Climate Change. *Int. Soil Water Conserv. Res.* **2013**, *1*, 68–74. [CrossRef]

[106] Lin, C.; Hur, J.; Zhang, M.; Zhang, Y.; Zhang, L.; Huang, Z.; Wang, Y.; Liu, Y.; Li, Y.; Yin, X. Alleviating Heat Stress in Cultivated Plants with a Radiative Cooling and Moisturizing Film. *Energy Convers. Manag.* **2024**, *315*, 118786. [CrossRef]

[107] Khan, B.A.; Nijabat, A.; Khan, M.I.; Khan, I.; Hashim, S.; Nadeem, M.A.; Chattha, M.U.; Ullah, N.; Hassan, M.U.; Zulfiqar, F.; et al. Implications of Mulching on Weed Management in Crops and Vegetable. In *Mulching in Agroecosystems: Plants, Soil & Environment*; Akhtar, K., Arif, M., Riaz, M., Wang, H., Eds.; Springer Nature: Singapore, 2022; pp. 199–213. [CrossRef]

[108] Wei, H.; Zhang, F.; Zhang, K.; Qin, R.; Zhang, W.; Sun, G.; Dai, Q.; Huo, Z.; Xu, K.; Yang, Z. Effects of Soil Mulching on Staple Crop Yield and Greenhouse Gas Emissions in China: A Meta-Analysis. *Field Crops Res.* **2022**, *284*, 108566. [CrossRef]

[109] Bu, L.D.; Liu, J.L.; Zhu, L.; Luo, S.S.; Chen, X.P.; Li, S.Q.; Hill, R.L.; Zhao, Y. The Effects of Mulching on Maize Growth, Yield and Water Use in a Semi-Arid Region. *Agric. Water Manag.* **2013**, *123*, 71–78. [CrossRef]

[110] Pavlů, L.; Kodešová, R.; Fér, M.; Nikodem, A.; Němec, F.; Prokeš, R. The Impact of Various Mulch Types on Soil Properties Controlling Water Regime of the Haplic Fluvisol. *Soil Tillage Res.* **2021**, *205*, 104748. [CrossRef]

[111] Siedt, M.; Schäffer, A.; Smith, K.E.C.; Nabel, M.; Roß-Nickoll, M.; van Dongen, J.T. Comparing Straw, Compost, and Biochar Regarding Their Suitability as Agricultural Soil Amendments to Affect Soil Structure, Nutrient Leaching, Microbial Communities, and the Fate of Pesticides. *Sci. Total Environ.* **2021**, *751*, 141607. [CrossRef] [PubMed]

[112] Wang, L.; Guo, S.; Ge, T.; Mancl, K.M.; Hijri, M.; Iseri, Y.; Lee, S.-J.; Feng, S.; Wang, L.; Ji, H.; et al. Plastic Mulch Productivity-Sustainability Tradeoffs and Pathways toward an Eco-Friendly Framework: Insights from a Global Meta-Analysis. *Nat. Commun.* **2026**, *17*, 1924. [CrossRef] [PubMed]

[113] Islam, M.U.; Guo, Z.; Jiang, F.; Peng, X. Does Straw Return Increase Crop Yield in the Wheat-Maize Cropping System in China? A Meta-Analysis. *Field Crops Res.* **2022**, *279*, 108447. [CrossRef]

[114] Hu, Y.; Sun, B.; Wu, S.; Feng, H.; Gao, M.; Zhang, B.; Wang, X.; Zhang, J. After-Effects of Straw and Straw-Derived Biochar Application on Crop Growth, Yield, and Soil Properties in Wheat (*Triticum aestivum* L.)-Maize (*Zea mays* L.) Rotations: A Four-Year Field Experiment. *Sci. Total Environ.* **2021**, *780*, 146560. [CrossRef] [PubMed]

[115] Noor, M.A.; Nawaz, M.M.; Ma, W.; Zhao, M. Wheat Straw Mulch Improves Summer Maize Productivity and Soil Properties. *Ital. J. Agron.* **2021**, *16*, 1623. [CrossRef]

[116] Mendonça, S.R.; Ávila, M.C.R.; Vital, R.G.; Evangelista, Z.R.; Pontes, N.C.; Nascimento, A.R. The Effect of Different Mulching on Tomato Development and Yield. *Sci. Hortic.* **2021**, *275*, 109657. [CrossRef]

[117] Shan, X.; Zhang, W.; Dai, Z.; Li, J.; Mao, W.; Yu, F.; Sun, Z.; Song, J. Comparative Analysis of the Effects of Plastic Mulch Films on Soil Nutrient, Yields and Soil Microbiome in Three Vegetable Fields. *Agronomy* **2022**, *12*, 506. [CrossRef]

[118] Li, Y.; Zhang, Z.; Wang, J.; Zhang, M. Soil Aeration and Plastic Film Mulching Increase the Yield Potential and Quality of Tomato (*Solanum lycopersicum*). *Agriculture* **2022**, *12*, 269. [CrossRef]

[119] Marasovic, P.; Kopitar, D.; Peremin-Volf, T.; Andreata-Koren, M. Effect of Biodegradable Nonwoven Mulches from Natural and Renewable Sources on Lettuce Cultivation. *Polymers* **2024**, *16*, 1014. [CrossRef] [PubMed]

[120] Di Mola, I.; Cozzolino, E.; Ottaiano, L.; Riccardi, R.; Spigno, P.; Petriccione, M.; Fiorentino, N.; Fagnano, M.; Mori, M. Biodegradable Mulching Film vs. Traditional Polyethylene: Effects on Yield and Quality of San Marzano Tomato Fruits. *Plants* **2023**, *12*, 3203. [CrossRef] [PubMed]

[121] Binacchi, F.; Rusinamhodzi, L.; Cadisch, G. The Potential of Conservation Agriculture to Improve Nitrogen Fixation in Cowpea under the Semi-Arid Conditions of Kenya. *Front. Agron.* **2022**, *4*, 988090. [CrossRef]

[122] Khan, F.U.; Nouman, M.; Negrut, L.; Abban, J.; Cismas, L.M.; Siddiqi, M.F. Constraints to Agricultural Finance in Underdeveloped and Developing Countries: A Systematic Literature Review. *Int. J. Agric. Sustain.* **2024**, *22*, 2329388. [CrossRef]

[123] Valbuena, D.; Erenstein, O.; Homann-Kee Tui, S.; Abdoulaye, T.; Claessens, L.; Duncan, A.J.; Gérard, B.; Rufino, M.C.; Teufel, N.; van Rooyen, A.; et al. Conservation Agriculture in Mixed Crop–Livestock Systems: Scoping Crop Residue Trade-Offs in Sub-Saharan Africa and South Asia. *Field Crops Res.* **2012**, *132*, 175–184. [CrossRef]

[124] Rodriguez, D.; Rufino, M.C.; Odendo, M.; van Wijk, M. To Mulch or to Munch? Big Modelling of Big Data. *Agric. Syst.* **2017**, *153*, 32–42. [CrossRef]

[125] Homann-Kee Tui, S.; Valbuena, D.; Masikati, P.; Descheemaeker, K.; Nyamangara, J.; Claessens, L.; Erenstein, O.; van Rooyen, A.; Nkomboni, D. Economic Trade-Offs of Biomass Use in Crop-Livestock Systems: Exploring More Sustainable Options in Semi-Arid Zimbabwe. *Agric. Syst.* **2015**, *134*, 48–60. [CrossRef]

[126] Perelli, C.; Cacchiarelli, L.; Peveri, V.; Branca, G. Gender Equality and Sustainable Development: A Cross-Country Study on Women's Contribution to the Adoption of the Climate-Smart Agriculture in Sub-Saharan Africa. *Ecol. Econ.* **2024**, *219*, 108145. [CrossRef]

[127] Amghani, M.S.; Sabouri, M.S.; Baghernejad, J.; Norozi, A. Factors Affecting the Livelihood Sustainability of Smallholder Farmers in Iran. *Environ. Sustain. Indic.* **2025**, *26*, 100601. [CrossRef]

[128] Lussich, F.; Dhaliwal, J.K.; Faiia, A.M.; Jagadamma, S.; Schaeffer, S.M.; Saha, D. Cover Crop Residue Decomposition Triggered Soil Oxygen Depletion and Promoted Nitrous Oxide Emissions. *Sci. Rep.* **2024**, *14*, 8437. [CrossRef] [PubMed]

[129] Liu, Z.; Wang, B.; Li, Z.; Huang, F.; Zhao, C.; Zhang, P.; Jia, Z. Plastic Film Mulch Combined with Adding Biochar Improved Soil Carbon Budget, Carbon Footprint, and Maize Yield in a Rainfed Region. *Field Crops Res.* **2022**, *284*, 108574. [CrossRef]

[130] Chen, Y.; Wang, L.; Tong, L.; Hao, X.; Wu, X.; Ding, R.; Kang, S.; Li, S. Effects of Biochar Addition and Deficit Irrigation with Brackish Water on Yield-Scaled N_2O Emissions under Drip Irrigation with Mulching. *Agric. Water Manag.* **2023**, *277*, 108129. [CrossRef]

[131] Saha, D.; Kaye, J.P.; Bhowmik, A.; Bruns, M.A.; Wallace, J.M.; Kemanian, A.R. Organic Fertility Inputs Synergistically Increase Denitrification-Derived Nitrous Oxide Emissions in Agroecosystems. *Ecol. Appl.* **2021**, *31*, e02403. [CrossRef] [PubMed]

[132] Obia, A.; Cornelissen, G.; Mulder, J.; Dörsch, P. Effect of Soil pH Increase by Biochar on NO, N_2O and N_2 Production during Denitrification in Acid Soils. *PLoS ONE* **2015**, *10*, e0138781. [CrossRef] [PubMed]

[133] Cayuela, M.L.; Sánchez-Monedero, M.A.; Roig, A.; Hanley, K.; Enders, A.; Lehmann, J. Biochar and Denitrification in Soils: When, How Much and Why Does Biochar Reduce N_2O Emissions? *Sci. Rep.* **2013**, *3*, 1732. [CrossRef] [PubMed]

[134] Cayuela, M.L.; van Zwieten, L.; Singh, B.P.; Jeffery, S.; Roig, A.; Sánchez-Monedero, M.A. Biochar's Role in Mitigating Soil Nitrous Oxide Emissions: A Review and Meta-Analysis. *Agric. Ecosyst. Environ.* **2014**, *191*, 5–16. [CrossRef]

[135] Harter, J.; Krause, H.-M.; Schuettler, S.; Ruser, R.; Fromme, M.; Scholten, T.; Kappler, A.; Behrens, S. Linking N_2O Emissions from Biochar-Amended Soil to the Structure and Function of the N-Cycling Microbial Community. *ISME J.* **2014**, *8*, 660–674. [CrossRef] [PubMed]

[136] Weier, K.L.; Doran, J.W.; Power, J.F.; Walters, D.T. Denitrification and the Dinitrogen/Nitrous Oxide Ratio as Affected by Soil Water, Available Carbon, and Nitrate. *Soil Sci. Soc. Am. J.* **1993**, *57*, 66–72. [CrossRef]

[137] Hao, D.C.; Wang, Y.; Luan, Y.; Deng, F.; Xie, H.; Lin, Y.; Li, X.; Jia, Z.; Wang, L. Microbial Drivers of N_2O Mitigation in Soils: Role of nosZ II Subclades under Conservation Tillage and Stover Mulching. *Appl. Soil Ecol.* **2026**, *217*, 106655. [CrossRef]

[138] Lal, R. Soil Carbon Management and Climate Change. *Carbon Manag.* **2013**, *4*, 439–462. [CrossRef]

[139] Al-Kaisi, M.M.; Archontoulis, S.V. Influence of Tillage and Crop Rotation Systems on Soil Carbon Sequestration and Soil Quality. *Soil Tillage Res.* **2015**, *148*, 10–21. [CrossRef]

[140] Shi, H.; Liu, Z.; Li, S.; Jin, M.; Tang, Z.; Sun, T.; Liu, X.; Li, Z.; Zhang, F.; Xiang, Y. Monitoring Soybean Soil Moisture Content Based on UAV Multispectral and Thermal-Infrared Remote-Sensing Information Fusion. *Plants* **2024**, *13*, 2417. [CrossRef] [PubMed]

[141] Singh, A.; Gaurav, K. Deep Learning and Data Fusion to Estimate Surface Soil Moisture from Multi-Sensor Satellite Images. *Sci. Rep.* **2023**, *13*, 2251. [CrossRef] [PubMed]

[142] Bandai, T.; Ghezzehei, T.A. Physics-Informed Neural Networks with Monotonicity Constraints for Richardson-Richards Equation: Estimation of Constitutive Relationships and Soil Water Flux Density from Volumetric Water Content Measurements. *Water Resour. Res.* **2021**, *57*, e2020WR027642. [CrossRef]

[143] Wang, Y.; Shi, L.; Hu, X.; Song, W.; Wang, L. Multiphysics-Informed Neural Networks for Coupled Soil Hydrothermal Modeling. *Water Resour. Res.* **2023**, *59*, e2022WR031960. [CrossRef]

[144] Chavoshi, A.; Dashtian, H.; Bakhshian, S.; Young, M.H.; Niyogi, D. PINN-SM: A Physics-Informed Neural Networks Model for Vadose Zone Soil Moisture Profile Prediction. *J. Geophys. Res. Mach. Learn. Comput.* **2025**, *2*, e2024JH000547. [CrossRef]

[145] Song, Z.; Zhao, L.; Bi, J.; Tang, Q.; Wang, G.; Li, Y. Classification of Degradable Mulch Films and Their Promotional Effects and Limitations on Agricultural Production. *Agriculture* **2024**, *14*, 1235. [CrossRef]

[146] Pittarello, M.; Rodinò, M.T.; Sidari, R.; Panuccio, M.R.; Cozzi, F.; Branca, V.; Petrovičová, B.; Gelsomino, A. Employment of Biodegradable, Short-Life Mulching Film on High-Density Cropping Lettuce in a Mediterranean Environment: Potentials and Prospects. *Agriculture* **2025**, *15*, 1219. [CrossRef]

[147] Mojid, M.A.; Mainuddin, M. Water-Saving Agricultural Technologies: Regional Hydrology Outcomes and Knowledge Gaps in the Eastern Gangetic Plains—A Review. *Water* **2021**, *13*, 636. [CrossRef]

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