



Impact of Mulching on Crop Performance, Water Use Efficiency, and Sustainability in Vegetable Crops

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Abstract

Vegetable production is highly sensitive to soil moisture, temperature, and nutrient dynamics, making efficient resource management essential under increasing water scarcity and climate variability. This review synthesizes recent literature (2018-2024) on the role of mulching in improving crop performance, water-use efficiency (WUE), and sustainability in vegetable production systems. A systematic search of major scientific databases (Google Scholar, Scopus, Web of Science, ScienceDirect, and SpringerLink) was conducted using relevant keywords, and peer-reviewed studies were analyzed based on mulch types and key agronomic and environmental outcomes. The findings consistently demonstrate that mulching significantly enhances soil moisture retention, moderates soil temperature, suppresses weeds, and improves crop growth, yield, and quality. Increases in soil moisture (10-35%) and water-use efficiency (18-45%) further demonstrate the effectiveness of mulching, particularly under water-limited conditions. Plastic mulches provide strong short-term benefits, including improved early growth, higher yields, and reduced evaporation, while organic mulches contribute to long-term soil health through increased organic matter, improved structure, and enhanced microbial activity. Biodegradable mulches offer a sustainable alternative by combining comparable agronomic performance with reduced environmental impact. Integrated approaches, such as mulching combined with drip irrigation and fertigation, further optimize resource-use efficiency and productivity. Overall, mulching emerges as a climate-smart practice that enhances productivity, resource efficiency, and environmental sustainability in vegetable systems. Future research should focus on optimizing mulch selection, minimizing environmental risks, and integrating mulching with advanced water and nutrient management strategies.

Keywords: Mulching, Vegetable crops, Crop performance, Water use efficiency, Sustainability

د سبزیجاتو پر وده، حاصل، د اوبو کارونې مؤثریت او کرنیز پایښت د ملچ اغېزې

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لنډيز

د سبزیجاتو تولید د خاورې د لنډېل، تودوخې او د غذايي عناصرو په بدلونونو په وړاندې ډېر حساس دی، له همدې کبله د اوبو د کمښت او اقليمي بدلون د ډیریدو په شرایطو کې د سرچینو اغېزمن مدیریت مهم ګڼل کېږي. دا مروری څېړنه د ۲۰۱۸-۲۰۲۴ کلونو وروستی علمي کړنې راتولوي او د سبزیجاتو په تولیدي سیستمونو کې د ملچ د استعمال رول د نباتاتو د فعالیت، د اوبو د استعمال د مؤثریت او پایښت په بڼه والي کې ارزوي. د علمي معلوماتو له مهمو ډیټابیسونو لکه Google Scholar، Scopus، Web of Science، ScienceDirect او SpringerLink څخه د اړوندو کلیدي کلیمو په کارولو سره سیستماتیکه پلټنه ترسره شوه، او د ملچ ډولونو، کرنیزو څانګړتیاوو او چاپېریالي پایلو پر بنسټ علمي مقالې تحلیل شوې. موندنې په دوامداره توګه ښيي چې د ملچ استعمال د خاورې د رطوبت ساتنه د پام وړ ډول زیاتوي، د خاورې تودوخه برابرې، د هرزه بوټو وده کموي، او د نبات وده، حاصل او کیفیت ښه کوي. د خاورې د رطوبت په اندازه کې (۱۰-۳۵٪) او د اوبو د استعمال په مؤثریت کې (۱۸-۴۵٪) زیاتوالی د ملچ د اغېزمنتیا څرګندونه کوي، په څانګړې توګه د اوبو د محدودیت په شرایطو کې. پلاستيکي ملچونه لنډ مهاله قوي ګټې لري، لکه د نبات د لومړنۍ ودې ښه والی، د حاصل زیاتوالی او د تبخیر کمښت؛ په داسې حال کې چې عضوي ملچونه د عضوي موادو د زیاتوالي، د خاورې د جوړښت د ښه والي او د مایکروبي فعالیت د پیاوړتیا له لارې په اوږد مهاله

توگه د خاورې روغتیا ته وده ورکوي. تجزیه کېدونکي ملچونه د چاپیریال لپاره یوه دوامداره بدیله لاره برابروي، ځکه چې د کرنیزو پایلو له پلوه ورته اغېزې لري او د چاپیریالي زیانونو کچه راکموي. گلدې لارې چارې، لکه د څاڅکي اوبو لگولو او له لارې یې سرې ورکولو سره د ملچ یوځای استعمال، د سرچینو د استعمال مؤثریت او تولید لاسه کوي. په ټوله کې، ملچ د اقلیم-هوسنیارې کرنې یوه مهمه کرنلاره بلل کېږي چې د سبزیجاتو په تولیدي سیستمونو کې تولید، د سرچینو مؤثریت او چاپیریالي پایښت لوړوي. راتلونکې څېړنې باید د مناسبو ملچونو د انتخاب، د چاپیریالي خطرونو د کمولو، او د ملچ د پرمختلو اوبو او غذايي مدیریتی طریقو سره د یوځای کولو پر لارو چارو تمرکز وکړي.

کلیدی کلیمې: ملچ، سبزیجات، د نبات فعالیت، د اوبو د استعمال اغیزمنتوب، پایداری

Introduction

Vegetable production plays a critical role in global food and nutritional security, particularly in developing countries and water-limited regions. Vegetables are highly sensitive to variations in soil moisture, temperature, and nutrient availability, making their productivity strongly dependent on effective soil and water management practices. Increasing water scarcity, land degradation, and climate variability have intensified the need for sustainable and resource-efficient production technologies in vegetable-based cropping systems (FAO, 2020; IPCC, 2021).

Mulching has emerged as an important agronomic practice for enhancing crop performance, improving water-use efficiency, and promoting sustainability in vegetable production systems. Mulch is a general term describing a wide range of organic and inorganic materials applied to the soil surface as a protective cover, including farmyard manure, compost, crop residues, straw, grasses, leaves, wood chips, sand, gravel, stones, synthetic plastic films, and biodegradable polymers. Mulching is defined as the practice of covering the soil surface to conserve soil moisture, regulate soil temperature, suppress weed growth, reduce evaporation losses, and mitigate salinity development in the root zone, particularly under irrigated and arid agro-ecosystems (Kader et al., 2017; Kader et al., 2019; Li et al., 2021).

Mulching modifies the soil microclimate by reducing direct exposure of the soil surface to solar radiation and wind, thereby moderating extreme fluctuations in soil temperature and enhancing seed germination, root development, nutrient uptake, and soil microbial activity (Chen et al., 2018; Zribi et al., 2018; Zhang et al., 2020). Improved soil moisture conservation under mulched conditions directly contributes to higher water-use efficiency, which is particularly important in arid and semi-arid regions where water availability is a major constraint to vegetable production (Hatfield & Dold, 2019; Zhang et al., 2018). In addition, mulching reduces irrigation frequency, limits surface runoff and nutrient losses, and enhances fertilizer-use efficiency, thereby improving overall resource-use efficiency in vegetable cropping systems (Qin et al., 2019). More recently, field-based investigations demonstrated that different mulch types induce distinct soil moisture and temperature regimes that directly influence vegetable growth and productivity (Kader et al., 2021).

The main purposes of mulching in vegetable production include:

- Improving soil fertility through the addition of organic matter, enhanced nutrient availability, and stimulation of soil microbial activity (Kader et al., 2017; Teame et al., 2020).
- Protecting soil from water and wind erosion by reducing runoff and soil particle detachment (Liu et al., 2019; FAO, 2020).
- Conserving soil moisture by minimizing evaporation losses and improving water-use efficiency (Zhang et al., 2020; Li et al., 2021).
- Moderating soil temperature throughout the cropping season to create a favourable root-zone microclimate (Li et al., 2021; Zhang et al., 2020).

- Suppressing weed emergence by restricting light penetration and reducing weed germination and competition (Kader et al., 2019; Zhao et al., 2023).
- Improving crop growth, yield stability, and produce quality through enhanced moisture and nutrient availability (Teame et al., 2020; Kader et al., 2021; Li et al., 2021).
- Producing cleaner and higher-quality vegetables by preventing direct soil contact with fruits and reducing post-harvest contamination (Teame et al., 2020; Zhao et al., 2023).
- Reducing insect pest incidence and soil-borne diseases by acting as a physical barrier and modifying the crop microenvironment (Steinmetz et al., 2019).
- Enhancing long-term soil health and sustainability, particularly through the use of organic mulches that improve soil structure and organic carbon content (FAO, 2020; He et al., 2023).

Mulching significantly modifies the soil microclimate by acting as a thermal and moisture buffer that enhances seed germination, root development, and soil biological activity. Both organic and synthetic mulches have been shown to reduce surface runoff and soil erosion while improving soil water conservation and crop productivity, particularly in water-limited environments (Zhang et al., 2020; Liu et al., 2019). Improved soil moisture retention under mulched conditions directly contributes to higher water-use efficiency, reduced irrigation frequency, minimized nutrient losses, and improved fertilizer-use efficiency, which are essential for sustainable vegetable production systems (Hatfield & Dold, 2019; Qin et al., 2019).

Based on material characteristics and functionality, mulches used in vegetable production are broadly classified into two main types:

1. Live mulches involve the use of living cover crops grown alongside or between vegetable crops to improve soil fertility, suppress weeds, conserve soil moisture, and regulate soil temperature. Leguminous species are commonly used as live mulches due to their ability to fix atmospheric nitrogen and enhance soil health (Kader et al., 2019; Teame et al., 2020; FAO, 2020).
2. Dead mulches consist of non-living materials applied to the soil surface and are further categorized into:
 - Organic mulches, derived from plant and animal residues such as straw, leaves, compost, crop residues, and farmyard manure. These mulches effectively conserve soil moisture, suppress weeds, control erosion, and improve soil fertility and structure; however, they are generally less effective in providing early-season soil warming compared with plastic mulches (Teame et al., 2020; FAO, 2020).
 - Inorganic mulches, including synthetic plastic films, polyethylene sheets, gravel, and stones. These mulches provide effective weed suppression and moisture conservation, particularly during early crop growth stages, but do not contribute nutrients to the soil and may pose environmental risks if not properly managed (Steinmetz et al., 2019; He et al., 2023).

Vegetable crops are highly sensitive to moisture stress and temperature extremes and require high levels of inputs such as irrigation water, fertilizers, pesticides, and labour. The adoption of mulching has been shown to significantly enhance vegetable growth, yield, and quality while simultaneously improving water-use efficiency and reducing production costs (Teame et al., 2020; Zhao et al., 2022). In water-scarce and drought-prone regions, mulching has emerged as a climate-smart agricultural practice that conserves soil moisture, stabilizes soil temperature, and supports sustainable vegetable production under changing climatic conditions (FAO, 2020; Li et al., 2021).

Despite its numerous benefits, the effectiveness of mulching depends on mulch type, crop species, climatic conditions, and management practices. While plastic mulches offer substantial agronomic

advantages, their improper use and disposal may lead to long-term environmental concerns, highlighting the importance of selecting appropriate mulch materials and management strategies tailored to specific agro-ecological conditions (Steinmetz et al., 2019; He et al., 2023). Therefore, a clear understanding of the role of different mulching materials in improving crop performance, water-use efficiency, and sustainability is essential for optimizing their use in diverse vegetable production systems.

Methodology

This narrative review was conducted through a systematic literature search to identify, analyze, and synthesize existing research on the role of mulching in vegetable production, with particular emphasis on crop performance, water-use efficiency, and sustainability. Multiple academic databases were consulted to ensure comprehensive coverage of peer-reviewed literature, including Google Scholar, Scopus, Web of Science, ScienceDirect, and SpringerLink. The search strategy employed a combination of predefined keywords and Boolean operators to refine the scope of retrieval. Core search terms included “mulching in vegetables,” “organic mulch,” “plastic mulch,” “biodegradable mulch,” “living mulch,” “soil moisture conservation,” “water use efficiency,” and “sustainable vegetable production,” with operators such as AND, OR, and NOT used to optimize search results.

Eligibility criteria were established to maintain the quality and relevance of the evidence base. Publications were considered if they were peer-reviewed journal articles, review papers, or technical reports published in English from 2018 onwards and if they directly addressed mulch application in vegetable crops under field or controlled conditions. Studies that were non-scientific, lacked methodological clarity, or were inaccessible in full text were excluded. Following an initial screening of titles and abstracts, eligible studies were retrieved for full-text review. Data from the selected studies were extracted and synthesized based on mulch type (organic, inorganic, biodegradable, and living mulches) and key outcome variables, including soil moisture dynamics, soil temperature regulation, weed suppression, crop growth, yield, water-use efficiency, and sustainability indicators. The synthesized evidence was critically analyzed to identify consistent trends, knowledge gaps, and contrasting responses among mulch types, thereby ensuring methodological rigor and coherence with accepted standards for narrative review studies.

Result and Discussion

The synthesis of pre- and post-2019 literature provides strong and consistent evidence that mulching substantially enhances vegetable crop performance, water-use efficiency (WUE), and overall system sustainability across diverse agro-ecological zones. Meta-analyses have demonstrated the broad effectiveness of mulching in improving crop productivity and WUE across multiple environments (Kader et al., 2021). Global assessments further confirm the role of mulching in promoting sustainable agricultural practices and resource-use efficiency (FAO, 2020). Recent experimental studies show that mulching significantly modifies soil-plant-atmosphere interactions, leading to improved soil microclimate regulation and crop performance (He et al., 2023).

Similarly, field-based research highlights the positive effects of mulching on soil moisture conservation and physiological efficiency of vegetable crops (Zhang et al., 2020). Earlier investigations also emphasize the environmental implications of plastic mulching, particularly its influence on soil conditions and long-term sustainability (Steinmetz et al., 2019). In addition, foundational studies provide evidence that mulching enhances crop resilience under varying climatic conditions by improving water retention and reducing environmental stress (Kader et al., 2019).

Effects on Soil Moisture Dynamics and Water-Use Efficiency

Improved soil moisture conservation is among the most consistently reported benefits of mulching. Organic, plastic, and biodegradable mulches reduce direct soil exposure to solar radiation and wind, thereby minimizing evaporative losses and improving infiltration efficiency (Xu & Chen, 2019). Quantitative studies have reported increases of approximately 10-35% in volumetric soil water content within the 0-30 cm root zone under mulched treatments compared with bare soil (Zhang et al., 2022). Similar improvements in soil moisture retention under mulching systems have been observed under semi-arid conditions, confirming reduced evaporation and enhanced water availability (Zribi et al., 2018). Field experiments also demonstrate that mulching significantly enhances soil water storage and crop water uptake efficiency (Babar et al., 2022). Ridge-furrow and plastic film mulch systems, in particular, have been shown to further improve soil water availability by concentrating rainfall and irrigation water into the root zone (Guo et al., 2020). These systems create effective moisture reservoirs in water-limited regions, prolong irrigation intervals, and reduce drought stress (Guo et al., 2020). Enhanced soil moisture availability directly improves crop transpiration efficiency and irrigation water productivity, resulting in water-use efficiency (WUE) increases ranging from 18% to over 45%, depending on mulch type and irrigation regime (Hatfield & Dold, 2019).

Empirical studies further confirm that mulching significantly enhances WUE under different crop and environmental conditions (Li et al., 2021). Additional field-based evidence supports these findings, showing consistent improvements in irrigation water productivity due to reduced evaporation and better soil moisture retention (Zhao et al., 2022). Recent research also highlights the role of mulching in optimizing water use under climate variability and water-limited conditions (Bwire et al., 2024). Similar increases in WUE have been reported in vegetable systems using integrated mulch and irrigation strategies (Arif et al., 2021). Moreover, combined soil and water management practices further reinforce the positive effects of mulching on crop water efficiency (Akhtar et al., 2022). Plastic mulches, particularly black polyethylene films, are highly effective in reducing evaporative losses and lowering irrigation frequency by creating a physical barrier over the soil surface (Qin et al., 2019). Experimental studies confirm that plastic mulch significantly improves soil water conservation and crop productivity (Chen et al., 2018). Additional research highlights its effectiveness in regulating soil temperature and minimizing water loss (Ye & Liu, 2021).

Long-term observations also indicate improved water-use patterns and yield stability under plastic mulching systems (Liu et al., 2019). Earlier studies further support these findings, demonstrating enhanced moisture retention and improved crop growth under polyethylene mulch (Zhang et al., 2018). When combined with drip irrigation, plastic mulching significantly enhances WUE and crop yield under water-limited conditions by delivering water directly to the root zone while minimizing losses (Akhtar et al., 2022). Field experiments validate that this integration maximizes irrigation efficiency and crop productivity (Li et al., 2021). Recent studies also show that mulch-drip systems are particularly effective in arid and semi-arid environments (Bwire et al., 2024). Biodegradable mulches demonstrate comparable short-term performance to conventional plastic films in terms of soil moisture conservation and crop yield (Sintim & Flury, 2017/2018). Studies further indicate that biodegradable alternatives maintain similar agronomic benefits while improving soil health outcomes (Moreno & Moreno, 2019). Experimental evidence supports their effectiveness in sustaining WUE and crop productivity (Ahmed et al., 2021). Additional research confirms their role in reducing environmental pollution associated with plastic residues (Chen et al., 2021). Recent findings emphasize their increasing suitability as sustainable alternatives in modern agriculture (Yang & Li, 2024). Further studies also highlight their contribution to balancing productivity with environmental sustainability (Zhao & Hu, 2023). Integration of mulching with fertigation and intercropping strategies further improves water-use efficiency (WUE) and vegetable productivity. Studies in cabbage systems show

that combining mulching with precise fertigation schedules enhances water and nutrient uptake efficiency while reducing nutrient leaching losses (Yao & Luo, 2023).

Similar findings in pepper production indicate that integrated mulch-fertigation practices significantly increase marketable yield and optimize resource-use efficiency (Chen et al., 2020). Additional research confirms that the combined use of mulching and fertigation improves both WUE and crop productivity under varying environmental conditions (Li et al., 2021). Mulch colour also plays a significant role in soil water dynamics and crop performance. Reflective and coloured mulches have been shown to modify soil temperature and radiation balance, thereby improving water-use efficiency and plant growth (Dai et al., 2019). Experimental evidence further demonstrates that different mulch colours influence soil microclimate and water conservation, contributing to enhanced crop performance (Ye & Liu, 2021). Although organic mulches may be slightly less effective in immediate evaporation control compared with plastic films, they significantly improve soil structure and aggregation over time, contributing to enhanced soil physical properties (Teame et al., 2020). Studies further indicate that organic mulches promote soil organic carbon accumulation, which strengthens long-term soil fertility and water-holding capacity (Zhao et al., 2022). Additional research confirms that improved soil structure under organic mulching enhances moisture retention and supports sustained crop performance (Zhang & Wang, 2022).

Foundational work also highlights that these cumulative soil improvements contribute to long-term yield stability under varying environmental conditions (Kader et al., 2019). Straw-, compost-, and biochar-based mulches have been shown to improve plant water status, particularly during critical growth stages, by maintaining more stable soil moisture conditions (Arif et al., 2021). Field studies demonstrate that such mulching materials enhance crop resilience and sustain productivity under water-limited conditions (Zhang et al., 2020). Additional evidence suggests that organic mulches reduce plant water stress by improving soil moisture availability and root-zone conditions (Xu & Chen, 2019). Recent findings further confirm that these materials help stabilize yields under intermittent drought stress by improving soil-plant water relations (Ali et al., 2023). Similar results indicate that organic mulching contributes to improved drought tolerance and consistent crop performance (Begum & Khan, 2023).

Impact on Soil Temperature and Root-Zone Microenvironment

Mulching significantly alters soil thermal regimes, with effects dependent on mulch optical properties, thickness, and climate. Plastic mulches increase early-season soil temperatures by approximately 2–5°C, accelerating seedling emergence, canopy development, flowering, and fruiting (Zhang et al., 2019; Kader et al., 2021; Chen et al., 2020; Gao et al., 2021). Ridge-furrow and transparent film mulches also create microclimates conducive to early vegetative growth, particularly in greenhouse tomato and pepper systems (Deng et al., 2022; Guo et al., 2020). This thermal advantage contributes to earlier harvests and higher early-market yields, particularly in warm-season vegetables such as tomato, cucumber, and melon (Kader et al., 2019; Deng et al., 2022; Li et al., 2021). In contrast, organic mulches buffer diurnal and seasonal soil temperature fluctuations by reducing excessive heating during hot periods and minimizing heat loss during cooler nights (Basit et al., 2022). This moderating effect has been shown to stabilize soil thermal regimes, particularly in arid and semi-arid environments with high temperature variability (Teame et al., 2020).

Additional studies confirm that improved temperature regulation under organic mulching enhances soil conditions for plant growth and development (Zhang & Wang, 2022). As a result, root growth, enzymatic activity, and nutrient uptake efficiency are significantly improved under moderated soil temperatures (Basit et al., 2022). Improved soil moisture and temperature regimes collectively enhance key physiological and growth parameters. Research indicates that mulching promotes root de-

velopment and increases leaf area index, contributing to improved crop performance (Kader et al., 2017). Similar findings show that enhanced soil conditions under mulching increase photosynthetic capacity and biomass accumulation (Teame et al., 2020). Recent studies further confirm that these combined effects translate into higher productivity and improved yield formation (Bwire et al., 2024). Recent evidence also suggests that moderated soil temperatures under mulching enhance microbial functional diversity and rhizosphere stability. Studies demonstrate that mulching improves soil biological activity and strengthens plant-soil interactions (Li et al., 2021). Additional research highlights that improved rhizosphere conditions under mulching contribute to more resilient cropping systems (He et al., 2023). Furthermore, findings indicate that enhanced microbial dynamics support long-term soil fertility and system productivity (Ahmed et al., 2021).

Effects on Crop Growth, Yield Formation, and Early Maturity

Across multiple vegetable crops including tomato, pepper, eggplant, cucumber, onion, melon, and leafy vegetables-mulched treatments consistently show significant improvements in plant height, leaf area, fruit number, and marketable yield compared with unmulched controls (Kader et al., 2019). Similar results across diverse cropping systems confirm the positive effects of mulching on vegetative growth and yield performance (Zhang et al., 2019; Chen et al., 2021). Additional studies further support consistent yield improvements under different environmental conditions (Zhao et al., 2022; Yang & Li, 2024; Begum & Khan, 2023). Yield gains generally range from 12% to 50%, depending on crop species, mulch material, and environmental conditions (Kader et al., 2019).

Experimental evidence also highlights substantial yield increases under optimized mulch management practices (Fang et al., 2019). Further research confirms that integrating mulching with improved agronomic practices enhances productivity and resource-use efficiency (Li et al., 2021). Straw, ridge-furrow, and intercropped mulch systems have been shown to enhance both yield and water productivity, particularly under semi-arid and arid conditions (Guo et al., 2020). Similar findings indicate that integrated mulch-based systems improve crop performance and sustainability (Chen et al., 2020; Yao & Luo, 2023). Plastic mulches often produce the highest short-term yield responses due to effective weed suppression, improved moisture conservation, and enhanced soil temperature (Qin et al., 2019).

Experimental studies further confirm significant yield increases under plastic mulching systems (Li et al., 2021; Chen et al., 2018). Early crop maturity under plastic mulch also enables earlier market entry and improved economic returns (Li et al., 2021; Deng et al., 2022). Organic mulches, while sometimes associated with slightly lower short-term yield gains, enhance long-term productivity by improving soil fertility and microbial biomass (Teame et al., 2020). Additional research shows that organic mulching improves nutrient synchrony and soil quality, contributing to more stable yields (Zhao et al., 2023; Zhang & Wang, 2022). Long-term studies further demonstrate reduced yield variability under organic mulching compared with bare soil, highlighting its resilience under climate uncertainty (FAO, 2020; Basit et al., 2022).

Influence on Vegetable Quality and Nutritional Attributes

Mulching positively affects vegetable quality attributes, including fruit size uniformity, firmness, soluble solids content, and colour development (Steinmetz et al., 2019). Reduced soil contact under mulch also lowers the incidence of fruit rot and soil-borne contamination, improving post-harvest quality (Aslam & Mehmood, 2020). Reflective and coloured mulches enhance canopy light distribution, which promotes photosynthate allocation and improves fruit coloration (Dai et al., 2019; Zhao et al., 2023; Chen et al., 2020).

Emerging research indicates that mulching can also influence nutritional composition. Improved water availability and moderated stress conditions under mulches are associated with higher concen-

trations of antioxidants, vitamin C, and phenolic compounds, particularly in fruiting vegetables exposed to moderate abiotic stress (Ahmed et al., 2021; Chen et al., 2021).

Weed Suppression and Reduction of Chemical Inputs

Weed suppression is a major agronomic benefit of mulching. Plastic films have been shown to reduce weed density by up to 95% by blocking light penetration (Kader et al., 2019). Biodegradable films similarly suppress weeds through physical coverage, achieving substantial reductions in weed emergence (Li et al., 2021). Organic mulches also decrease weed pressure, primarily through surface coverage and, in some cases, allelopathic interactions (Teame et al., 2020; Fang et al., 2019). Additional studies confirm that these mulching systems collectively improve crop access to water, nutrients, and light, enhancing overall growth and yield (Chen et al., 2020). Reduced weed infestation further lowers the need for manual weeding and herbicide application, which decreases labour requirements and production costs (He et al., 2023). Evidence also shows that mulching minimizes chemical inputs, thereby reducing environmental contamination (Zhang et al., 2020; Basit et al., 2022). Finally, integrated mulching strategies have been reported to optimize both crop performance and resource-use efficiency under field conditions (Li et al., 2021).

Soil Health, Carbon Dynamics, and Environmental Sustainability

Mulching contributes substantially to soil health and environmental sustainability. Organic mulches have been shown to increase soil organic matter and microbial biomass, improving overall soil fertility (Teame et al., 2020). Biodegradable mulches enhance enzymatic activity and soil aggregate stability, which supports nutrient cycling and water infiltration (FAO, 2020; Ahmed et al., 2021). Additional studies report that mulching reduces soil erosion by maintaining surface cover and improving soil structure (Chen et al., 2021; Moreno & Moreno, 2019).

Several other studies also highlight that organic mulches promote soil carbon sequestration and contribute to greenhouse gas mitigation when residues are locally sourced and effectively incorporated into the soil (Zhao & Hu, 2023; Begum & Khan, 2023; Babar et al., 2022). Plastic mulches deliver strong short-term agronomic benefits, including improved yield and water-use efficiency. However, they raise concerns regarding microplastic accumulation in soils (Steinmetz et al., 2019). Research also indicates that improper residue management can negatively affect soil biota and alter soil pore structure, potentially impairing long-term soil function (He et al., 2023). Biodegradable mulches provide a practical compromise. They deliver comparable agronomic performance to conventional plastics while significantly reducing environmental persistence and pollution risks (Sintim & Flury, 2017/2018). Additional studies confirm that biodegradable mulches minimize soil contamination and maintain soil health under repeated use (Zhang et al., 2020; Moreno & Moreno, 2019).

Comparative Sustainability of Mulch Types and Future Implications

Comparative assessments consistently indicate that plastic mulches provide the greatest immediate gains in soil moisture conservation, temperature regulation, and weed control (Li et al., 2021; Qin et al., 2019). They also support early yield increases by improving crop growth conditions (Chen et al., 2018). Organic mulches, while sometimes slower to deliver short-term benefits, offer superior long-term advantages by enhancing soil fertility, structural stability, and overall resilience (Zhang & Wang, 2022; Teame et al., 2020). Biodegradable mulches represent a promising balance between productivity and environmental stewardship, combining effective crop performance with reduced soil contamination and residue accumulation (Ahmed et al., 2021; Chen et al., 2021; Yang & Li, 2024; Zhao & Hu, 2023). Live mulches, cover crops, and intercropped mulching further contribute to biodiversity enhancement, improved soil microbial diversity, and erosion control. However, these systems require careful management to avoid competition with main crops for water and nutrients (Kader et al., 2019; Li et al., 2021; Chen et al., 2020).

Overall, mulching emerges as a central practice for improving resource-use efficiency, crop productivity, and environmental sustainability in vegetable production systems. By enhancing water-use efficiency and stabilizing yields, mulching supports productive and resilient cropping systems (FAO, 2020; He et al., 2023). Research also highlights its role in improving soil health and reducing reliance on chemical inputs (Hatfield & Dold, 2019). These benefits align closely with the principles of climate-smart agriculture, particularly in arid and semi-arid regions vulnerable to climate variability (IPCC, 2021). Future research priorities include optimizing mulch materials and management strategies to maximize benefits while minimizing environmental risks (Steinmetz et al., 2019). Studies also emphasize the need for long-term assessment of microplastic accumulation and its effects on soil function (Zhang et al., 2020; Sintim & Flury, 2017/2018). Additionally, integrating mulching with fertigation and intercropping, as well as evaluating ecosystem services across different mulch systems, remains an important area for investigation (Yao & Luo, 2023).

Conclusion

Mulching is a pivotal agronomic practice in vegetable production, consistently enhancing crop performance, water-use efficiency (WUE), and system sustainability across diverse agro-ecological zones. Evidence demonstrates that mulching improves soil moisture retention, regulates soil temperature, and reduces evaporative losses, thereby supporting plant growth, physiological efficiency, and yield stability under both optimal and water-limited conditions. Plastic mulches offer rapid short-term gains through superior weed suppression, moisture conservation, and temperature enhancement, facilitating early crop maturity and higher marketable yields. Organic mulches, while slightly slower in delivering immediate benefits, contribute to long-term soil health by improving structure, organic carbon content, microbial biomass, and nutrient cycling, which collectively enhance yield stability and resilience under variable climatic conditions. Biodegradable mulches provide a sustainable alternative, balancing agronomic performance with reduced environmental persistence and minimal soil contamination. Integration of mulching with fertigation, intercropping, and the use of reflective or coloured mulches further optimizes water-use efficiency, nutrient uptake, and crop quality.

Beyond productivity, mulching positively influences vegetable quality, nutritional composition, and post-harvest safety, while reducing weed pressure and chemical input requirements. Moreover, mulching supports soil health, carbon sequestration, and ecosystem sustainability, aligning closely with climate-smart agriculture principles. Future research should prioritize optimization of mulch materials and management practices, long-term evaluation of microplastic accumulation, integration with water and nutrient management strategies, and assessment of ecosystem services under different mulching systems. Overall, mulching represents a robust, multifunctional strategy for enhancing resource-use efficiency, crop productivity, and environmental resilience in modern vegetable production systems.

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