



Mulching Practices for Sustainable Agriculture: Enhancing Yield, Soil Moisture and Environmental Benefits in Field and Fruit Crops

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ABSTRACT

Mulching has become a foundation of sustainable agriculture that is characterized by a variety of benefits in a variety of cropping systems. This review is a synthesis of recent evidence of the agronomic, ecological and economic effects of mulching with particular focus on the mulching in increasing yield, preserving soil moisture, and increasing the environmental resilience in both field and fruit crops. Mulching is the protective cover of soil, which checks temperature, pressure of weeds, and water loss, thus favoring plant growth. Organic mulches, e.g. straw, compost and crop residues are beneficial to long term soil fertility due to their gradual breakdown and release of nutrients and synthetic and biodegradable mulches have immediate effects of water retention and weed suppression. Mulches are also used in controlling erosion, as well as enhancing soil structure, which is very essential in ensuring the long-term sustainability of the soil. The invention of mulching materials, especially biodegradable and hybrid ones, is a potential way to lower the rate of plastic pollution and improve the environmental sustainability. Moreover, effective implementation of the



mulching practice depends on the need to suit the strategy to special crops, soils, and climatic conditions, good policy backing and effective extension services. This review highlights the serious challenge toward the need to conduct interdisciplinary research and implement mulching systems centered on farmers to have a resilient and sustainable future of agriculture.

Keywords: Mulching practices for sustainable agriculture, Soil moisture, Environmental, Ecological and Economic effects.

INTRODUCTION

Global Context: Water Scarcity, Rainfed Agriculture, and the Challenge of Food Security

The problematic issue of 21st century agriculture is unquestionable: to feed the increasing world population with increasing environmental limitations. The central issue of this difficulty is the nexus of water, land, and climate that is critical. Whereas the irrigation has been the foundation of the rising agricultural productivity in the last century, its future growth is highly constrained by the physical water limit, rivalry with urban and industrial industries, and over-exploitation of aquifers¹. It is against this backdrop that rainfed agriculture is not a side system, but rather the much needed system in the world food production. Rainfed systems contribute most to the global agricultural production (around 60-70 percent) and cover majority of the total cropland especially in parts of Asia, sub-Saharan Africa, and Latin America, which produce most of the staple grains (such as wheat, maize, and sorghum) and pulses and livestock fodder. Nevertheless, rainfed agriculture is very weak and becoming even weaker. They are the effects of climate change in these areas in terms of rising temperatures, accelerated evaporative demand and, most importantly, variability and unpredictability of rainfall pattern. The semi-arid and arid areas which host a large number of the poorest and most food insecure populations in the world are overburdened. Unpredictable precipitation results in frequent dry periods, late arrival of the monsoon seasons and more severe and less productive precipitations that result in runoff instead of infiltration. This hydrological uncertainty is directly translated into agricultural risk: the scarcity and unreliability of soil moisture supply are turned out to be the major barrier to crop production and, consequently, the low and unstable productivity. The difference between the yield of the rainfed and irrigated systems is still as dramatic, a witness of the lack of moisture characteristic of dryland agriculture²⁻⁴.

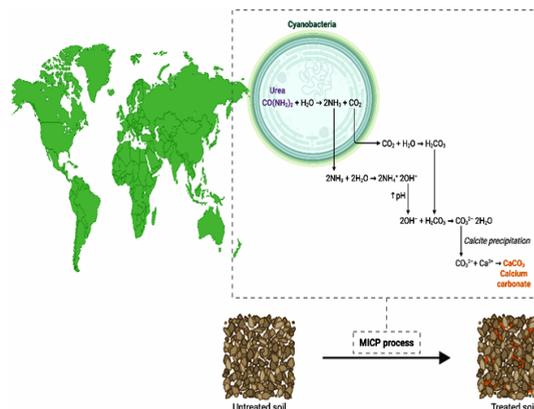


Fig. 1. Global Context Microbial Induced Calcite Precipitation (MICP) Using Cyanobacteria

This situation poses a very formidable triple challenge of food security, water resources of dwindling water resources, and changes in the climate, all these in the existing agricultural land base or even reduced agricultural land base. Even the expansion of the irrigated area by simply increasing the area is not sustainable and in most instances, impossible. Thus, there is need to change the paradigm, as it is necessary to increase productivity of water through maximizing crop per drop of each millimeter of rainfall received, instead of focusing on the increase of water supply⁵. This is the essence of the sustainable dryland agriculture. It requires the shift to agricultural activities that would improve the ability of the soil to absorb, store, and effectively use precipitation. Rainfed system inefficiencies involving significant proportion of the rainfall may go to waste and be lost to surface evaporation, surface runoff, and deep percolation outside the root zone is a problem and opportunity. Through addressing these losses, great yields and stability gains can be attained without further water abstraction. It is in the pursuit of this purpose that a range of soil and water conservation technologies come into the frame with one of the most effective, multi-purpose, and readily available technologies being mulching as a method of radically changing the micro-environment of the soil and enhancing the resilience of the cropping systems to climatic uncertainty⁶.

Table 1: Characteristics and Management Considerations of Common Mulching Materials

Mulch Type	Primary Materials	Key Advantages	Key Disadvantages/Risks	Ideal Use Cases
Straw	Wheat, rice, barley stalks	Excellent insulation, good moisture retention, weed suppression, low cost if local	Can introduce weed seeds; may temporarily immobilize N; fire risk when dry	Vegetable gardens, berry patches, seasonal cover for field crops
Wood Chips/Bark	Shredded tree branches, bark	Long-lasting, excellent weed suppression, improves soil structure over time	High C:N can severely immobilize N; can acidify soil; not for annuals if filled in	Orchards, vineyards, perennial landscapes, pathways
Compost	Decomposed organic matter	Adds nutrients & organic matter directly; improves soil health; no N immobilization	Can be costly; may contain weeds if not fully composted; less effective weed barrier	As a nutritive top-dressing for most crops, especially nutrient-demanding vegetables
Black Plastic Film	Polyethylene (PE)	Superior moisture conservation, excellent weed control, warms soil	Non-biodegradable, removal/disposal problem, soil contamination (microplastics)	Intensive vegetable production (tomatoes, melons), early season cropping in cool climates
Biodegradable Film	PLA, PHA, starch blends	Agronomic benefits of plastic, decomposes in soil post-harvest	Higher cost, degradation rate must match crop cycle, long-term soil impact unclear	Systems where plastic benefits are needed but disposal is problematic (organic, high-value crops)

Mulching as a Key Strategy for Dryland and Sustainable Agriculture

The practice of spreading a protective layer of material over the soil surface known as mulching is an ancient agricultural practice that has been re-contextualized to be a modern, science-based solution to sustainable intensification. Its principle is beautifully simple; to place a barrier between the soil and the atmosphere, and so alter microclimatic conditions at the soil-plant interface⁷. As a means of intervention in the context of dryland agriculture, this basic intervention deals with the most important constraints in a systematically and synergistically manner. Fundamentally, mulching is an *in-situ* rainwater collection technique. The rainfed systems where there is no irrigation can only have the water supplied by the precipitations. Whether a crop is successful or not is whether it is practical to transform this rainfall into soil moisture available to plants (the green water component of the hydrological cycle). Mulching is aimed at the key routes of loss. To begin with, it lowers evaporative loss by a very high percentage. Bare soil particularly when wet and publicly exposed to sun and wind, is lost to water quickly⁸. Physical insulator is a mulch layer that is either organic such as straw or synthetic such as plastic film. It seals the ascent of water to the surface through capillaries and slows the wind velocity at the soil- atmosphere boundary and saves invaluable moisture in the root zone by days or weeks compared with bare soil. Research indicates that mulch is always able to raise the level of soil moisture, by 10-50 percent, essentially extending the length of water supply to plants at those crucial growth phases and even overcome brief dry seasonal periods. Secondly, mulch increases infiltration of rainwater and suppresses runoff. It also helps to reduce sealing and crust formation of the soil surface caused by the impact of raindrops and this is a significant hindrance to the entry of water. This will enable more water to enter into the soil profile and not lost as surface runoff and also the fertile topsoil is washed away, a process called erosion. Besides, mulch reduces the speed of overland flow, thereby extending the duration of water percolation, particularly on slopes. This conservation and protection aspect duality also renders mulching to be a pillar of soil and water conservation (SWC) practices. In addition to moisture, mulch is extremely important in controlling the soil temperature. In dry and semi dry areas, soils may be allowed to get their extreme temperatures which may be harmful to the

growth of roots and the activity of microbes and the germination of seeds⁹. Lighter color and creating air pockets, organic mulches are more likely to keep the soil cool on hot days and warm on cool nights, which is buffering the daily extremes. Clear or black plastic mulches have the advantage of warming the soil and this is facilitated by the fact that the solar radiation can be absorbed and transferred to the soil allowing crops to be planted earlier, especially where the seasons are cooler or are of higher altitude which accelerates the germination and growth of crops. The advantages trickle down to the health and fertility of the soil especially when using organic mulches. When sources of organic matter are made such as straw, compost or wood chips are broken down, they add to the earth¹⁰. This benefits the soil structure and increases porosity and aeration, water-holding capacity, and slow-release of nutrients. This process also activates biological activities in the soil, this leads to a better ecosystem of earthworms and other helpful microbes necessary in the recycling of nutrients and soil building. Moreover, heavy layer of the mulch gives great weed control as it blocks the sunlight, cuts the competition on the water and nutrients- a big benefit in water-starved environment¹¹.

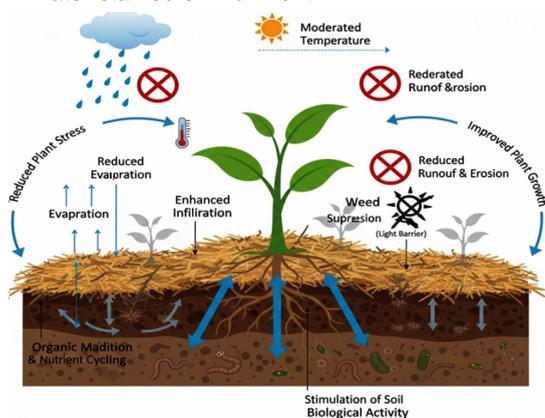


Fig. 2. Mechanism of Mulching to stimulation of Soil in Biological Activity

Thus, mulching is not merely a technique but a systems based strategy that is fully compatible with the provisions of sustainable and climate-wise agriculture. It increases adaptive ability by insulating crops against climatic fluctuations in the form of rainfall and thermal stresses¹². It helps prevent the causes of mitigation such as sequestration of carbon in the soil (organic mulches) and lessening the necessity of fossil-fuel-related inputs such as irrigation and herbicides. It enhances resilience through long-term soil health that forms the basis of

any effective agro-ecosystem. To the dryland farmer, the key to the difference between failure of crop and harvest, between soil depletion and soil regeneration may lie in mulching. The ability to make the most out of every millimeter of rainfall and make it more reliable and productive is where mulching comes in as a major, practical, and potent tool to achieve food production, resource preservation, and maneuvers around the vagaries of shifting climate in the most vulnerable farmlands in the world¹³.

Types and Characteristics of Mulching Materials

The types of materials used as mulch are a wide variety of substances, broadly classified as organic, inorganic and a newer group of special or biodegradable mulches with their physical and chemical properties defining their behaviour with the soil, climate and crop. Organic mulches are composed of natural once living substances and contain wood chips, straw, sawdust, bark, newspaper and compost. These materials are characterized in terms of being biodegradable since they slowly decompose and get assimilated into the soil ecosystem. This is a key advantage as well as an aspect that is taken into account in their management. They decompose and release organic matter as they do and it is the building block of soil health, mediated by soil microbes and fauna¹⁴. The introduction of organic carbon enhances the structure of soil as it increases its aggregation and consequently increases its porosity to enhance aeration and water infiltration. The better structure also enhances the water retaining ability of the soil, which forms a more stable reservoir of plant roots. Moreover, the decomposing process also releases over time a range of macro and micronutrients, which, in fact, is a natural, slow-release fertilizer. Biological activity induced by such materials created a lively soil food web that supports earthworms and useful microorganisms that help in the cycling of nutrients and the suppression of diseases. But the decomposition process also requires a periodical application and also has possible disadvantages. Other materials especially those that contain a high ratio of carbon to Nitrogen contents such as fresh sawdust or wood chips can temporarily bind soil nitrogen as microbes use it to break the carbon-containing substance, which can starve

young plants. Insulating organic mulches are usually spectacular in terms of controlling soil temperature, with roots being cooler during summers and providing mild frost protection during winters, and are also quite exceptional in terms of smothering weeds due to creating physical light barrier¹⁵. They are very effective in conserving moisture, but tend to be somewhat less immediate in effect at the same time as impermeable films, since they do not close off the gaseous exchange and evaporation entirely, but rather significantly lower it. Going into detail, wood chips, which are generally made of shredded branch and bark, provide a stable, long-lasting choice to mulching. They have a rough texture which permits good water permeability and air circulation and forms a good weed-suppressive mat. Since they break down very slowly over an extended period, years, they offer long-term benefits to soil structure and they are especially appreciated in perennial environments such as orchards, vineyards, and landscape ornamentals¹⁶. The slow decomposition contributes to the soil with stable organic matter¹⁷. But being rich in lignin and cellulose content, they contain large proportion of carbon as compared to nitrogen and thus, in the event they are added to the soil without undergoing proper decomposition or where they are applied around heavy-feeding annual crops without the addition of supplemental nitrogen fertilizers, they will cause serious threat of nitrogen drawdown. One of the most common organic mulches in annual cropping systems is the straw mulch which is made up of the dried stalks of cereal grains such as wheat, rice or barley. It is comparatively cheap particularly in farm lands, and offers excellent insulation and waterproofing. A stratum of straw is very effective in reducing fluctuations in the temperature of the soil, guard soil surface against crusting and erosion by heavy rain and against germinating seeds of weeds. It is also quite low-density with hollow stems that offer home to useful predatory insects. As it breaks down during the course of one season or two, it adds small portions of nutrients and organic matter. The important practical consideration is a thorough check of the straw to make sure that it is not contaminated with any remnants of persistent herbicides or survivingweed seeds that will bring in some new issues¹⁸⁻²¹.

Table 2: Impact of Mulching on Soil Properties and Crop Performance

Parameter	Effect of Mulching (Compared to Bare Soil)	Consequence for Crop Production
Soil Moisture	Increases by 10-50% in root zone	Reduces irrigation need, mitigates drought stress, extends water availability
Soil Temperature	Organic: Buffers extremes (cooler by day, warmer by night), Plastic: Can warm (black) or cool (white)	Promotes optimal root growth & microbial activity; can advance or extend season
Weed Biomass	Reduces by 50-95% depending on material and thickness.	Lowers competition for water/nutrients; reduces weeding labor/cost.
Soil Erosion	Dramatically reduces splash and sheet erosion	Preserves fertile topsoil and organic matter; protects downstream water quality.
Soil Organic Matter	Increases with organic mulches (long-term)	Enhances structure, water-holding capacity, CEC, and nutrient cycling
Water Use Efficiency	Significantly increased (more crop per drop)	Higher yields per unit of water applied or rainfall received; crucial for drylands
Yield	Increases typically 20-50% in field crops; improves quality/stability in fruit crops	Direct economic benefit and enhanced food security

It may save soil moisture up to 30-50 percent over bare soil, and is therefore an effective technology in drylands or dry areas with limited and costly irrigation water. Moreover, plastic wrap affects soil significantly in terms of temperature²². Transparent or clear polyethylene permits the entry of solar radiation into the soil and is absorbed by the soil followed by the capture of radiant heat by the film to establish an effective green house effect that can warm dark soil by 5-8degC-an important benefit in planting crops early in the spring, lengthening the growing season and enhancing yield in cooler climates. Black plastic covers also warms the soil, but mainly by absorbing the sun energy itself, and passing the heat to the soil beneath; it is slightly less efficient than clear film in warming the soil but has the important added advantage of being entirely opaque, with the result that it gives full protection to the weed germination below. Other colors, such as white or silver reflective mulches, have the effect of cooling the soil, reflected sunlight, through which sensitive crops such as lettuce can be grown in summer, and have the added advantage of repelling some insect pests such as aphids by causing disorientation²³. The extent and internationalization of plastic mulching since its commercialization in the mid 20th century has been truly revolutionary which has led to what is commonly referred to as plasticulture. Its capability to improve its yields, reduce water usage, manage weeds, and accelerate maturity of crops have seen it become widely deployed mainly in intensive vegetable, fruit and staple grain production. China is the biggest consumer in the world where hundreds of thousands of tons of plastic film are being applied over tens of millions of hectares of land with researchers reporting a proven increase in crop yields of crops such as maize and wheat by more than 30 percent in plastic film mulching. There also exist large systems of plastic mulch in other countries such as the United States, Spain, Japan and South Korea particularly in high value horticulture²⁴. In the Almeria area of Spain, large areas of green houses and open fields are used to produce vegetables using plastic mulch. The amount of plastic film consumed worldwide in a year is estimated at more than one million tons. This scale has addressed its agronomic efficiency, but has brought about a dilemma on the environment, which is truly deep. The traditional polyethylene mulch is not biodegradable. It is removed manually and expensively at the end of the season. In many cases, thin and worn layers

get ripped and broken apart contaminating the soil with microplastics. This unspent plastic can interfere with the growth of roots, movement of water and soil tillage during the next seasons²⁵⁻²⁸.

Moreover, the recycling of used plastic mulch is a problem, burning generates poisonous exhausts, landfill is not sustainable, and recycling is negated by soil contamination, moisture, and vegetation remains. This is the plastic pollution legacy which leaves the soil health of the future generations in poor condition and is the greatest disadvantage of this otherwise very productive technology. It is the high environmental cost of traditional plastic mulch that has led to an intensive research and development effort in a third category; special and biodegradable mulch. This category seeks to combine the established agronomic advantages of plastic, specifically, its excellent method of moisture retention and warming of the soil, with the environmental ethos of organic mulches, that is, their safety in the event of degradation in the soil by the expiry of the cropping cycle. Biodegradable plastic mulches (BDMs) are normally made of renewable biological-based polymers, including polylactic acid (PLA) produced using corn starch, polyhydroxyalkanoates (PHA) produced using bacterial fermentation, or starch-polyester hybrids. The rest can be fossil-fueled though with artificial additives to induce fragmentation and digestion by microorganisms²⁹⁻³².

The ideal BDM acts like ordinary plastic throughout the season of growth giving it the impact of moisture conservation, temperature control and weeding control, but after incorporation, it breaks down to water, carbon dioxide and microbial biomass, with no residual build up. This gets rid of the disposal issue and the soil contamination problem over the long term. There are however problems with the technology. The degradation rate and completeness needed should be fine-tuned to keep pace with the crop cycle; in the case of excess degradation, the advantages are lost and delayed degradation is inconvenient. The end products and their effect on the soil microbial communities need to be extensively researched over a long period³³. Moreover, the price of BDMs is, at present, more expensive than traditional polyethylene but that would be subject to change with more scale and with technological development. Other non-organic

mulches There are geotextile fabrics composed of woven or non-woven polypropylene or polyester, which are porous and thus allow water and air to pass but prevent weeds, and are commonly employed in long-term perennial landscaping to exclude weeds. The other new strategy is sprayable polymer mulches which are liquid versions that are sprayed over the soil field and they will create a thin and stretchable water-retaining film that eventually breaks down. The development of mulching material state is indicative of the continuing quest of agronomic performance and sustainability, the balancing act between the immediate agronomic performance and long-term soil stewardship, a discussion between the synthetic and the organic in the name of assuring the food production in an ever-scarcer world³⁴⁻³⁷.

Mechanisms and multifaceted benefits of mulching

Direct and far-reaching impacts of the stabilization of the soil surface through mulching benefits the soil physical properties and counteracts the degradation and improve the structure. Erosion control is one of the most important activities. The kinetic energy of raindrops is absorbed by the mulch layer, which dispels the destructive displacement of soil particles that disperse on the surface and form a crust³⁸. Mulch also preserves the surface porosity of the soil that is necessary in the infiltration of water by reducing crusting. Moreover, its slowing overland flow velocity decreases the transport capacity of water leading to reduction of sheet and rill erosion and subsequent loss of fertile topsoil, which, as a non-renewable resource in the times of humans, is a loss of both. This coverage is particularly critical on hilly terrain and areas where there are high chances of serious and convective storms. In addition to erosion, mulch affects the structure and the compaction of the soil. As the organic matter decomposing in the form of mulches is always added and earthworms and other soil fauna are encouraged to be active, the soil aggregates are formed and stabilized³⁹. These aggregates form a good, crumb-like structure, which improves pore space, macro-pores that allow the drainage and aeration of the soil and micro-pores that retain water. This enhanced design is a direct contradiction to compaction as it raises the strength and

effectiveness of the soil to the compressive force of heavy rainfall, machinery, or pedestrian traffic. The mulched and well organized soil can withstand compaction, retain its porosity and allow the roots to penetrate more soil space in search of water and food. The mulch layer in itself is also a physical cushion which spreads the weight and further shields the soil surface against direct compressive forces. The end result of these processes is a soil that is more hospitable to roots, has enhanced water infiltration rates, has slower surface runoff, and increased ability to retain water that is available to plants to grow and perform their functions⁴⁰⁻⁴².

Poly(lactic acid) (PLA) is a biodegradable polymer, an aliphatic polyester, the degradation of which occurs mainly by hydrolysis into its ester bonds in soil. Abiotic hydrolysis is the first step and rate-limiting process in PLA biodegradation mobilization whereby water molecules enter the amorphous parts of the polymer framework and assault the ester bonds in the backbone. The end effect of this process is the progressive chain scission, which causes a decrease in the molecular weight and the creation of shorter oligomers and, finally, lactic acid monomers. The rate of hydrolysis is greatly affected by the environment which in turn varies with the soil moisture content, temperature, pH and the crystallinity of the polymer whereby higher moisture content and high temperatures enhance faster degradation of ester bonds. With the further development of the degradation process, water uptake and hydrolytic potential are further improved by further increasing the hydrophilicity and surface area of the resulting polymer fragments. Lactic acid that is produced by the PLA hydrolysis is easily absorbed by the soil microorganisms through the normal biochemical pathway to generate carbon dioxide, water, and biomass of the microorganisms. The successful degradability of PLA in farm soils is based on this two-step process which consists of chemical degradation followed by biological degradation. Therefore, materials made of PLA, e.g. biodegradable mulch films, provide an environmentally-friendly alternative to traditional plastics by allowing them to decompose completely without the formation of any permanent deposits in the ecosystem.

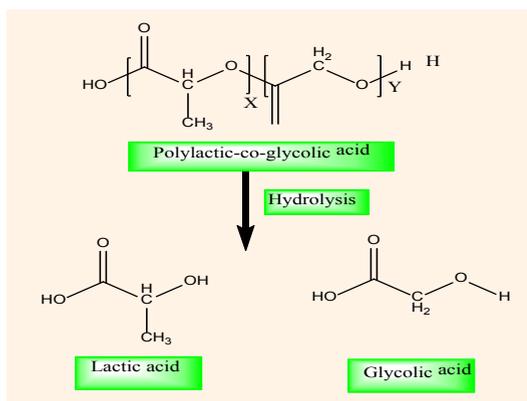


Fig. 3. Hydrolysis of Poly(lactic acid)

These physical changes cannot be done without positive changes in the chemical properties of soils and their fertility processes. Mulching especially using organic materials will start a cycling system of nutrients that is slow and continuous. When the mulch is decomposing, it also produces vital macro and micronutrients, such as nitrogen, phosphorus, potassium, calcium, and magnesium, in mineralized form, which can be absorbed by the plants. This is a process that turns the mulch cover into a fertilizer, which adds nutrients to the soil, saving the use of foreign synthetic inputs⁴³. An example would be legume mulches such as clover or vetch which can remediate nitrogen in the atmosphere to the soil. Nevertheless, the chemical effect is subtle. Sawdust or wood chips which contain a very large percentage of carbon as opposed to nitrogen may also have a temporary effect of nitrogen immobilization where soil microbes consume all available nitrogen to break down the carbon-rich material, possibly causing crops to starve without added nitrogen⁴⁴. This nitrogen is later released in the long duration of time as the process of decomposition goes on. Moreover, the introduction of organic matter through mulch enhances the cation exchange capacity (CEC) of the soil (or the capacity of the soil to retain positively charged nutrient ions such as ammonium, potassium, calcium) and stop their loss to leaching away with percolating water. This generates a more effective nutrient store⁴⁵. Mulch may also affect the pH of soil. When some organic materials, such as pine needles or oak leaves, decay, some weak organic acids may be emitted, which over time reduces the pH and can be useful in soils with high pH or to plants that prefer acid conditions. On the contrary, the chemicals used in some materials degradation or the use of certain

plastic mulches may change pH dynamics subtly by changing the respiration of microorganisms or the solubility of nutrients. Most importantly, due to its ability to make the soil cooler and more moist, mulch may increase the solubility and availability of important micronutrients such as zinc and iron. The general chemical condition of the soil under mulch changes towards higher retention, cycling, and availability of nutrients towards more fertile and self-sustaining system⁴⁶⁻⁵⁰.

This improves physical and chemical conditions that promote a blossom of soil biological activity, the engine of ecosystem functioning. Mulch, and most importantly organic mulch, is a home and food supply of an extensive community of soil organisms. The regulated temperature and a uniform humidity provide the perfect environment of the soil microbes-bacteria, fungi, actinomycetes and protozoa. These are the first to decompose, the microorganisms capable of degrading the mulch and soil organic matter, mineralizing nutrients resulting in symbiotic associations with plant roots (e.g., mycorrhizal fungi). The universal indicator of better soil health under mulching regimes is an increased microbial biomass and activity⁵¹. This soil activity is accompanied by stimulation of fauna. Earthworms particularly are a species that are more successful in mulched areas, the protective cover enables them to exist in the upper area where they feed on organic materials leaving casts that are rich in nutrients and bioturbation of the soil, creating pore holes that enhance aeration, water penetration, etc. There are other positive arthropods like predatory beetles and spiders which seek refuge in the mulch layer and hence help in natural pest control. The life community in the mulch not only is larger but healthier and richer in its functions. This food web of soil has been known to provide important ecosystem services: competition and antagonism of soil-borne pathogens, enhancement of soil structure by their ability to generate binding agents such as fungal hyphae and microbial glues, and the complexity of biochemical processes that are the basis of nutrient cycling. Essentially, mulch transforms the soil out of a physical component, into a booming bioactive living system which actively promotes plant development⁵². An immediate and much prized agronomical reward of this altered environment is a beneficial reduction of weeding and a reconfigured interaction between pests and their predators. Control of weeds occurs

in many mechanisms, which may or may not act together. Primarily, the layer of mulch that is thick enough creates a physical barrier preventing the penetration of the photosynthetically active radiation to the soil surface, which inhibits the germination of the photoblastic weed seeds. The physical impedance of the mulch material can deplete energy stores before any of the weeds through deeper seed banks or the mulch reaches light even of weeds that emerge through deeper seed banks, or due to the mulch⁵³. Moreover, some organic mulches such as cereal straw or walnut hulls may have allelopathic properties and will release natural biochemicals that prevent the germination of weed seeds and the development of seedlings. The microclimate existing under the mulch, which can be cooler and with increased humidity, may also be unfavourable to the germination of certain species of weeds that are accustomed to bare and sun-baked soil⁵⁴. This inhibition decreases or eradicates the necessity of mechanical tilling or herbicides, which decreases the cost of production and environmental degradation. The change in pests and diseases, on the other hand, is more dualistic and complex. On the one hand, the mulch habitat will be able to sustain the population of advantageous predatory insects and spiders which assist to control the pest insects. The reflective mulches (e.g. silver) are specifically employed to ward off aphids, and other insect vectors by disorienting them. Conversely, a cool and damp and shady place with some mulch may occasionally be conducive to the development of slugs, snails, or fungus and requires close, comprehensive control measures and/or integrated pest management. The point is that mulching changes the ecology of the agroecosystem, which usually leads to an increase in the biological regulation and decreases dependence on synthetic interventions so that mulching becomes an ideal practice in the dryland and water-efficient agriculture. The practice performs its duty in the most effective way possible of optimizing the fate of every millimeter of precipitation or irrigation by systematically treating loss pathways⁵⁵.

The most notable water-saving process, which directly increases the percentage of water that can be used by the crop, is the decrease of direct evaporation of the soil surface, which has been described above. At the same time, through the increased supply of soil structure and surface sealing, mulch increases significantly the rate of

infiltration value such that water is absorbed into the soil structure at a rapid rate during rainfall or irrigation periods instead of being carried away as surface runoff⁵⁶. This water thus stored is better stored in the root zone because the water holding capacity of the root zone has been enhanced by the presence of additional organic matter. The mulch layer per se also minimizes the runoff velocity, which further increases the infiltration opportunity time and minimizes the erosive water flow as well. Efficiency is maximized in plastic mulch systems in which water is applied through drip irrigation beneath the film, almost zero evaporation occurs, and water is applied to the root zone in a controlled way. The overall result is a significant enhancement of the water use efficiency (WUE)-the biomass or yield that is generated with each unit of water used. Research on different crops in different climates will always indicate that mulching can cut down crop water by 20-50 percent without reducing or even yielding neglect. This holistic water conservation is not simply an agronomic measure, but a very essential adaptive measure to be taken with the advent of the water scarcity caused by the changes in climate enabling farmers to put more dependable output with less water, protect the soil resources and create resilience into their agricultural systems. In such a way, mulching as an integrated systems intervention, by inter-relating, microclimatic modulation, soil physics, and chemistry, biology, and ecology, creates a more conserve, stable, fertile, and biologically robust rhizosphere which supports the patterning of sustainable agricultural productivity⁵⁷⁻⁶⁰.

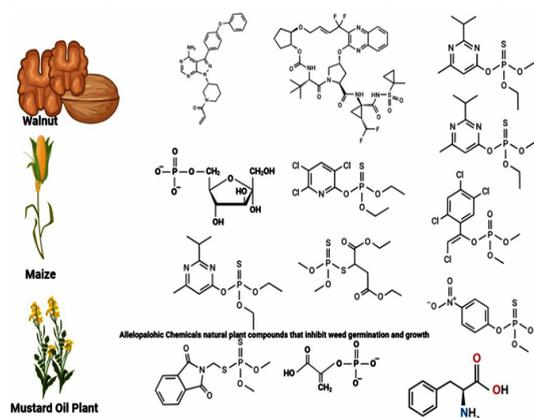


Fig. 4. Natural allelopathic compounds from plants inhibiting weed growth

Impact of mulching on crop production and yield

The influence of mulching on crop production is both extensive and highly documented but manifests itself and differs considerably

between the yearly cycle of the field crops and the long-term systems of the fruit crops depending on a complicated interchange between materials, environment and plant physiology. In field crops like maize, wheat, legumes and vegetables, the main role of mulching is that of a season-long stabilizer of the root zone environment, which directly opposes the climatic vulnerability which limits rainfed yields⁶¹. In semi-arid areas where water is the main limiting factor, responses of cereals, such as maize and wheat, to plastic or straw mulching can be phenomenal and meta-analyses report a 30% to more than 50% increase in average yield. This increase can mostly be explained by increased water use efficiency (WUE). Through the reduction of evaporation, mulching ensures that a larger percentage of the scarce rainfall or little irrigation will be used in productive transpiration by the plants. In the case of maize, which is a crop that is vulnerable to moisture stress during silking and grain fill, the uniform moisture content guaranteed by mulch is directly proportional to the number of kernels on each ear, and the weight of each kernel. In the same case, in wheat cultivation, mulching also holds the effects of terminal heat and drought stress in grain filling so that yield potential is retained. The soil temperature modulation is essential besides moisture. Plastic mulches increase germination and early-season growth in a uniform manner in the seedbed by warming it, thereby enabling crop to develop a strong canopy prior to the onset of stress associated with summertime⁶²⁻⁶⁵. This comes especially in advantage to warm-season vegetables such as tomatoes, peppers, and cucurbits (e.g., melons, squash), in which black plastic mulch is widely used in commercial production to promote maturity, fruit size and overall marketable yield. In the case of cool-season vegetables, such as lettuce or broccoli, organic mulches or reflective films can keep root zones cooler and prevent bolting to keep the quality. Mulching in the legume crop like soybean or pulses preserves the moisture available to the crop to fix nitrogen and enhances the physical soil environment to fix nitrogen by nodulation⁶⁶. Moreover, the process of weed suppression provided by the mulches does away with stiff competition between water and nutrient which is especially useful in the organic vegetable systems where mechanical weeding is too expensive. These improvements in yield of field crops are what are strictly referred to as the direct result of mitigating abiotic stresses,

primarily water scarcity and temperature extremes, and mitigating biotic competition, which enables genetic yield potential to be achieved at a higher level in a single growing season. Contrarily, the benefits of mulching on the fruit crop and orchards are calculated in terms of years and decades, and lack the compulsion to induce seasonal crop production but in practice aim at establishing long term soil health and tree well-being⁶⁷. Orchard crops such as apple, citrus, grapevine or berry plantations need to be on a low-lying stable, healthy soil system that will carry decades of production. In this case, the most common organic mulches are wood chips, compost or straw, because the benefits of soil building of these materials are long-lasting, and the short term temperature altering impacts of plastic may be disregarded as well, or may be inconvenient in a permanent planting. Indirect and cumulative are the key processes that contribute to the better yield and fruit quality in the orchards. To begin with, mulch has a significant beneficial impact on the moisture regime in the root zone, which eliminates the irrigation need and eliminates the vulnerability of trees to drought stress at the crucial stages of their development, such as fruit set and fruit size⁶⁸. Regular humidity is essential to avoid such problems as drop of fruits in citrus or shrivel in berries in grapes. Second, mulch keeps root activity and health active throughout the year by regulating soil temperature extreme heat in summer and extreme cold in winter, which kills the fragile surface-feeding roots. Third, and, possibly, most importantly, the natural decay of organic mulch also contributes a lot of organic material, which helps to create a highly fertile, biologically active soil⁶⁹.

This improves soil structure, recycling of nutrients and gradual release of minerals which results to improved nutrition of the trees being indicated in the nutrient status of leaves and overall vigor of tree. The healthier, less-stressed tree will have more resources in uniform flowering, fruit set and quality formation. It has been demonstrated in apple orchards that mulching can enhance the volume of fruit, quantity of sugar (Brix) and colour formation and in vineyards, mulch can enhance grape composition to make wine⁷⁰. Moreover, the presence of weeds within the tree cover zone suppresses grass competition regarding water, and nutrients which are a major problem in the management of orchard. Physical protection of mulch also prevents soil erosion in slopes that are commonly

used to construct orchards and vineyards as well as curtailing of trunks by mowers or string trimmers. Although the annual growth of the yield may not be as dramatic as the soaring heights of annual crops, the long-term advantages include the increased stability in the yields, better measures of the quality of fruits, less water and weeds input to maintain the orchard ecosystem, and the long-term survival and hardiness of the orchard ecosystem itself⁷¹.

The effect of mulching on yield is not universal however; it is conditioned by many decisive factors which pre-determine its efficacy or not. The most significant variable is the type of mulch which is a fundamental trade-off between the short-term agronomic efficiency of the soil and the long-term soil health. Annual systems typically offer plastic films, particularly black polyethylene, as the most immediate and most effective yield increases because of their better moisture conservation, warming of soil and weed elimination. They are very impermeable resulting in a controlled root environment⁷². Nevertheless, they add no content to soil organic matter, and they are difficult to dispose of. Such organic mulches as straw or compost can provide a beneficial, although less dramatic, aspect of moisture retention, but over time develop soil fertility and structure, the yield of which may improve with the season as the soil becomes healthier. Their selection depends on the major goals: peak one-season production or continuing productivity⁷³. The climatic condition is the overdetermining factor of which mulching benefits have the highest value. The warming of the soil by clear or black plastic is one of the main yield drivers in cool or temperate regions, which increases the duration of the growing season and speeds up the development of the crop. In dry, hot or semi-arid areas the water-retaining characteristic is most important, and mulches which lower the temperature of soil (as straw or white plastic) are desirable to prevent root overheating. In wet areas, the advantages can change to the suppression of weeds and erosion, and there will be a requirement to use mulches (such as well-aerated wood chips) which do not support fungal infections through excessive moisture retention. Lastly, there is the growth stage of the crop that determines the most important time of the mulching. Much influence on yield is usually realized when the mulch is used to relieve the stress at the phenologically sensitive times⁷⁴. With majority of crops, early establishment is crucial; proper establishment entails a mulch in

which the germination and the seedling appears to be healthy. In the case of grain crops, it is essential to preserve moisture in the flowering and grain filling stages. In the case of the fruit trees, it is important to keep the roots of fruit trees moist and cool as fruit grows. Late mulching can miss these important windows, and applying the wrong mulch (e.g. high-carbon mulch immobilizing nitrogen on a young, nitrogen-needing crop) may in fact inhibit early growth and eventually actually lower yield. Thus, to maximize vegetation cover response, a subtle and context-dependent approach that balances the characteristics of the mulch substance with the climatic constraints and physiological requirements of the plant at its most sensitive phases, is required instead of a one-size-fits-all approach to specific agro-ecological management⁷⁵.

Table 3: Economic and Logistical Factors in Mulch Adoption

Factor	Considerations & Challenges	Implications for Farmers
Initial Material Cost	Plastic: Recurring purchase cost. Organic: Purchase or opportunity cost (e.g., residue not used for feed). BDMs: Currently highest cost	Upfront capital requirement can be a barrier, especially for smallholders
Labor Cost	High for application (spreading, laying film) and for removal (plastic)	Increases operational costs; timing can conflict with other critical farm activities
Availability & Logistics	Bulk organic mulches are expensive to transport. Reliance on local by-products subject to market/seasonal variation	Limits scalability; favors use of on-farm or locally available materials
Long-Term Economics	Cost savings from reduced irrigation, weeding, and fertilization. Yield increases and premium for early/quality produce	Positive Return on Investment (ROI) oftenclear, but may be realized over multiple seasons
Disposal/Management Cost	Plastic: High cost for removal, hauling, landfill fees, or environmental fines. Organic: No disposal cost; may need replenishment	Significant hidden cost for plastic mulch, making alternatives economically attractive over time
Risk Management	Stabilizes moisture buffer, reducing risk of crop failure from dry spells	Provides insurance value, crucial for climate resilience and securing loans/insurance

Negative Impacts and Challenges of Mulching

Although the list of agronomic and environmental advantages of mulching is quite convincing, a more critical and comprehensive evaluation should take into consideration the serious negative and disadvantaged implications of mulching, which are not always the same in nature and severity. The greatest issue and the most alarming is the fact that the conventional plastic mulch has left a legacy of environmental and soil contamination. These characteristics that have contributed to the success of polyethylene films as effective especially its durability and impermeability make it an unwanted pollutant⁷⁶. When the growing season ends, the thin degraded films are hard to clear off; they are torn and ripped and leave traces behind them, which build up in the soil in the subsequent seasons. It leads to the extensive pollution by both macro- and microplastics. These pieces of plastics may change the physical characteristics of soils in such a way that they inhibit the infiltration of water and penetration of roots and interfere with the lives of soil organisms. Worse still, microplastics have the capability to adsorb toxic compounds and pathogens, which could potentially find their way into the food web via the soil fauna and create a threat to soil ecological activity. The burning of used plastic mulch is also another crisis: burning on-site emits toxic gases, landfill is not an option, and recycling is not always economically feasible because of the soil, moisture, and organic debris contamination. This is a vicious circle where a technology which was implemented to increase productivity in the short-term risks the long-term soil health and the integrity of the ecosystem, an important ethical and practical contradiction to sustainable agriculture⁷⁷.

In addition to the plastic pollution crisis, there are other perceived negatives, especially with organic mulches, which have to be managed. The humid, microclimate that is under mulch though favorable to crops and soil creatures can accidentally form a perfect habitat to some pests and diseases. The presence of straw or wood chip mulches means that slugs, snails and rodent populations may flourish in the protective cover, and may therefore cause more damage to crops. Equally, the steady humidity may support fungal fungi, e.g. mildew-inducing or fruit-rotting, particularly on compacting or excessive thick mulch in moist climates⁷⁸. Moreover, there are allelopathic properties of certain organic mulches.

Some plant remains, such as walnut hulls or certain cereal straws, contain natural biochemicals (e.g., juglone) capable of suppressing the germination and growth of later crops or easily damaged plants and so mulch materials will have to be carefully selected and rotated. The other important essential chemical factor is nitrogen immobilization. New organic substances are rich in carbon such as sawdust, wood chips and straw, and their carbon-to-nitrogen (C:N) ratio is very high. When integrated into the soil or when they in turn start breaking down in the soil-mulch interface, the microbial community charged with their breakdown will cannibalize available soil nitrogen to develop their own biomass, temporarily locking it out of the reach of the plants. This may cause a lack of nitrogen in the crops which appear in the form of chlorosis and delayed growth unless it is supplemented with a nitrogen fertilizer at the planting stage. All these biological and chemical processes highlight the fact that mulching is not a free ride since it must be done in a manner that uses informed selection of species, at the right time, and integrated pest and nutrient management, as it has some undesirable negative effects that cannot be afforded to small farmers. Initial costs may be enormous in terms of funds to buy materials. Buying plastic film, landscape cloth or even a bulk purchase of organic products such as compost or bark are direct costs which are to be offset with an uncertain payoff in the seasons. In the case of organic mulches, transportation would increase the costs since large and low-density products such as straw are costly to transport over long distances and locally available waste products are the only alternative available to use. Another significant limitation is labor⁷⁹.

In the mulch that can be laid down in a uniform fashion, be it by hand, where plastic sheets are laid down or the laying down of tons of straw, is a very laborious process. The labor burden turns the other way at the end of the season plastic mulch needs to be tediously washed off and removed, the exhausted organic mulch can be replenished. This requirement of work force is at the already busy times in planting and harvesting. A major challenge is related to logistics such as the availability of appropriate mulch material in adequate quantities on a regular basis. Straw dependency on agricultural by-products is exposed to other uses (e.g., livestock feed, bioenergy), as well as to an unpredictable production each year. These economies and logistical

advantages bring about a physical obstacle to entry and growth. To be a sustainable practice, a practice should be economically viable to the farmer. Thus, although the benefits of better soil health and water savings are obvious in the long-term, short-term costs and complexity of administration is posing as an impediment to adoption, in general favoring large-scale or more valuable production systems where the pay-off on investment is more certain and readily realized. Therefore, mulching is an agricultural two-edged sword: an efficient means of creating strength and efficiency, an activity with negative environmental, biological, and practical-economic payables and costs, requiring considerate and situation-specific decisions and continuous innovations⁸⁰.

Economic Implications and Sustainability Considerations

Introduction of mulching into the contemporary agricultural practice is a critical nexus in terms of which immediate economic calculus collides with the long-term ecological imperatives, which requires a subtle analysis that would include the entire gamut of systemic sustainability rather than simplistic profit-and-loss accounting. It is a strategic choice that has an extended impact on the economics of farms, the environmental health of the region, and the stability of the global food system, rather than just a technical agronomic intervention, a practice that consists of applying organic or synthetic substances to the soil surface. The economic consequences are deep and multiple, involving direct cost-benefit relations, whereas the sustainability issues compel a renegotiation of the very trade-off between the short-term productivity and maintenance of the ecological basis on which all agriculture rests on. Finally, it is necessary to consider the role of mulching, not as a separate method, but as a part of the developing system of sustainable agricultural activity, where the value of this practice will be evaluated in its role in the formation of circular economies, adaptation to climate changes, and profitability of the necessary soil capital⁸¹.

Cost-Benefit Analysis and Economic Advantages

A cost-benefit analysis (CBA) of mulching should not be based on naive input-output comparisons but includes elements of the tangible and intangible, direct and indirect benefits, and above all, temporal element, which considers long-term asset development and short-term expenditure. The first cost framework is very fluctuating, depending on

the type of mulch. Organic mulches (e.g., straw, wood chips, compost, crop residues) can require the cost of purchase, transportation, and application but may be obtained on-farm (waste stubble can be turned into a valuable input, e.g., straw, pruned branches), therefore internalizing the benefits, and saving cash expenditure. By comparison, synthetic plastic mulches (observably polyethylene) include recurrent costs of material acquisition, special laying gear, and, most importantly, removal and disposal, which is progressively a large economic and regulatory liability as the restriction of plastic waste becomes stricter⁸².

These early investments are often justified and outpaid back by the economic benefits in a series of yield-increasing and cost-cutting processes. The short-term gain is strong moisture preservation of the soil. Mulching can save a lot of water cost and energy used in pumping, by cutting down on evaporative losses in irrigation by up to 20-40 percent, which in turn saves direct costs of water and energy as well as reduces pumping costs. It is not only a cost-saving measure but a very important risk-reduction measure in drought prone areas either in the face of increasing hydrological uncertainty in response to climate change, insuring against water stress on the profits. Moreover, successful weeding of the weed through preventing the pass of light helps to minimize the application of herbicides and mechanical weeding which saves money on chemicals, fuel, labor, and machinery wear-and-tear. This is more economically appealing in organic production systems where herbicide choices are few and costly and manual work in weeding farming is a significant operational expense⁸³⁻⁸⁵.

Another economic lever is temperature modulation. Black plastic covers in cooler temperatures or the opening seasons will warm the soil, causing quicker crop maturity and seed germination, enabling an earlier entry to the high-quality markets and price. Organic mulches cover the soil in warmer climates avoiding overheating and stress in root-zones, and thus safeguarding yield potential. The most substantial long-term economic benefit is based on the improvement of the soil health. It is also true that organic mulches as they break down provide food to the soil microbial life, enhance soil structure and soil organic matter. This means that in the long-run there is less requirement of artificial fertilizers because the nutrient cycling

will enhance and the natural fertility in the soil will be strengthened. A better soil structure reduces the effect of compaction on root penetration and erosion, which retain the best capital asset of a farm, that is, topsoil. Economic preferences that have generally not been considered in traditional CBA include the prevention of soil erosion, which prevents the irreversible loss of the productive properties of the land, and the externality of waterways siltation. Further, soils of better quality in terms of organic matter can hold water better and this is a virtuous cycle that consequently increases drought resilience. Thus, the economic analysis of mulching in reality is the capital analysis: the short-run investments in mulch material are an investment in the biological, physical, and chemical capital of the soil, the returns in terms of years and decades are to be benefits in the decrease of the cost of inputs, the stabilization and even the growth of the yields, and the stability of the resilience of the farm system to climatic and economic crises⁸⁶.

The Trade-off Between Productivity and Environmental Health

Traditional intensive agriculture has been greatly based on the presumed, and in fact, short-term trade-off between the optimum productivity and environmental health. The paradigm emphasizes short-term profit growth by massive applications of synthetic fertilizers, pesticides and intensive tilling, shifting the costs of soil erosion, water pollution, loss of biodiversity and greenhouse gas emissions on to the environment. The art of mulching, especially in its organic forms, puts this dichotomy to the test by providing a way to balance productivity with environmental stewardship, but not without its own complications and environmental trade-offs⁸⁷.

Mulching has the main environmental advantages. It is an effective soil conservancy tool as has been observed to physically safeguard the soil against the erosive power of wind and rain. This protects aquatic ecosystems directly against sedimentation and other related pollution run off. Atmospheric carbon is sequestered by the enhancement of soil organic matter, which helps reduce climate change- a service that is now widely accepted to have economic importance to society. Organic mulching increases on-farm biodiversity by encouraging the establishment of useful insects and soil organisms and mitigating the effects of herbicide

drift. Less irrigation reduces some of the valuable freshwater, and reduced synthetics (fertilizer) and pesticide demands reduce the possibility of nutrient (eutrophication) leaching into the ground-water and exposure of non-target organisms to toxic chemicals⁸⁸.

But in some situations the trade-off dynamic will arise. Productivity especially of heat-loving crops such as tomatoes, melons and peppers can be maximized by the use of impermeable black plastic mulch which gives excellent weed control and soil warming benefits, yet at a high environmental cost. It is a petroleum based product that has a carbon footprint of its manufacture and transportation. It also produces non-biodegradable waste at the end-of-life, which may spread through the soils and waterways when not carefully extracted in microplastics. Moreover, although it most likely preserves soil moisture below, it can change the patterns of water infiltration, which may augment the water runoff off its surface. Even organic mulches may have trade-offs: when obtained in an unsustainable manner (e.g. clearing forests to obtain wood chips), it may only push environmental harm elsewhere. When crop residues are used as soil mulch, though this is a good practice in keeping the soil healthy, there may arise a trade-off between soil conservation and other highly important livelihood requirements such as livestock fodder or source of domestic fuel.

The important point here is that through a system of mulching, although applied as a unitary system, has the potential to shift the equilibrium towards non-zero-sum trade-off and synergy. Mulching may result in productivity that is both high and long-lasting due to the savings of water, the reduction of weeds and the enhancement of the soil health without the declining returns and degradation of input-intensive systems. The environmental gains (carbon sequestration, biodiversity, water quality) are subsequently co-products of an effective system instead of its seemingly antagonistic alternatives. The trick lies in intelligent design: choice of suitable mulch material (preferably locally-sourced, organic, or new-generation bio-degradable plastics), balancing nutrients with consideration of temporary immobilization of some carbon-rich mulches, and combining mulching with other activities such as crop rotation and conservation tilling. Under this framework, it does not act to reduce the harm of the environment but to restore agro-ecosystems through active regeneration and remain economically viable⁸⁹.

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Role of Mulching in Sustainable Agricultural Systems

Mulching is not a silver bullet, it is a pillar of more extensive sustainable systems of agriculture like conservation agriculture, agroecology, organic farming and permaculture. It has a transformative effect and can be used to apply in practice the main principles that characterize such systems, reducing soil disturbance, preserving soil cover, and promoting functional biodiversity⁹⁵. Mulching is the driver of the second principle in Conservation Agriculture (CA) which is constructed on the three-fold pillars of minimum tillage, permanent soil cover, and crop diversification. Reduced or no-tillage becomes practically and economically viable and effective due to the permanent organic cover offered by mulch or cover crop residues. It manages weeds without the need of tillage, regulates soil temperature and moisture to allow seed germination and maintains a consistent feeding on the soil biology. Such symbiotic interactions save on fuel and labor, establish soil organic matter, and develop robust soil structure, hence CA systems are economically and ecologically sustainable in the long term.

Agroecologically, it is important to manage the farm as an ecosystem and one of the strategies is mulching. It improves cycling of nutrients since it gradually sends nutrients as decomposition takes place, similar to natural nutrient flows in a forest floor. It forms microhabitats to predatory insects and spiders which control the population of pests thus decreasing reliance on insecticides. It reduces its reliance on chemicals that are used to control weeds by physically oppressing them, which is in the principle of agroecology of reducing the use of external inputs. Moreover, water-saving property of mulching is an important climate adaptation measure, which augments the system against droughts and unpredictable rainfall regimes- an element of climate-resilient farming⁹⁶⁻⁹⁸.

In the circular bioeconomy model, mulching is an ideal example of a nutrient and biomass loop closure. Organic wastes that occur on farms such as crop residues, prunings, manure, and even food processing wastes that are treated properly are re-conceptualized as resources to be recycled back to the soil as mulch. This makes costs of waste management turn into value creation, less reliance on purchased fertilizers, and farm autonomy and efficiency of resource use. It represents the waste-is-food principle of the circular systems⁹⁹.

In organic certification requirements, where synthetic herbicides are banned and where soil fertility management mainly relies on organic means the technique of mulching is nearly essential. It offers a non-chemical management technique of the weed, and it is one of the major ways of introducing organic material into the soil. It has a high economic viability in terms of use in organic systems because organic produce is priced high and alternative methods to control weeds are expensive¹⁰⁰.

CONCLUSION

The research synthesis continuously proves that mulching brings substantial, mutually reinforcing advantages in terms of yield, soil moisture, and soil health, especially in susceptible ecosystems. Its important discovery is that these effects are not independent of each other but

rather synergistic: improved soil moisture retention is a direct cause of reducing plant water stress that results in more stable and frequently higher crop yields, and the increase in soil health: by increasing organic matter, microbial activity, and the soil structure, water infiltration and holding capacity increase in a positive feedback loop. Simply put, mulching is a one-stop solution to the process of degradation by conserving water, preserving life in the soil and enhancing productivity, which makes it a fundamental aspect of resilient farming. In the dry and semi-arid areas, the priority of the recommendations should be to maximize the conservation of water and adjust to the limited resources. The most important is the utilization of organic mulches that are locally available (e.g. crop residues, stones, sand), as it lowers the cost and facilitates circularity. *In-situ* residue management can be practiced and combined with infiltration (e.g., contour bundling or micro-catchments) to maximize the use of rainwater and minimize wind erosion. The presence of Farmer training and sharing of knowledge is essential to implementation of such principles into local settings to make sure that the techniques are culturally acceptable and cost effective. There are still research gaps that are critical, namely, the development and functioning of inexpensive and indeed biodegradable mulch films, which break down fully without leaving microplastic traces in dryland soils. Moreover, the future outlook should be based on the integrated management systems and the research on the best combinations of mulching and the use of some other practices such as drip irrigation, drought-resistant types of crops and agroforestry. There is also a need to carry out long term socio-economic studies to gain insight on barriers to adoption and formulate policy structures that encourage the use of sustainable mulching materials to bridge the gap between ecological gain and the livelihood of farmers.

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Conflict of interest

The author declare that we have no conflict of interest.

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