ACCSCIENCE PUBLISHING

Explora: Environment and Resource

REVIEW ARTICLE

Materials used for soil mulching: A comprehensive review of performance, soil impact, and sustainability

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Abstract

Soil mulching is a widely used agronomic practice for improving soil water conservation, temperature regulation, weed suppression, erosion control, and crop performance under variable environmental conditions. Its relevance has increased because modern agriculture faces water scarcity, heat stress, soil degradation, plastic pollution, and the need for resource-efficient production systems. This review synthesizes current knowledge on the main categories of mulch materials, including organic mulches, polyethylene plastic films, biodegradable films, mineral mulches, fiber-based covers, superhydrophobic sand, and biochar-based mulches. The review evaluates how these materials affect soil moisture retention, soil temperature, aggregation, nutrient cycling, microbial activity, water-use efficiency, yield formation, and environmental sustainability. Organic mulches generally provide the strongest long-term benefits for soil health because they add organic matter, stimulate biological activity, and reduce erosion, although their performance depends on biomass quality, decomposition rate, and nutrient management. Plastic films remain highly effective for short-term yield improvement, but their long-term use raises serious concerns related to residue persistence, microplastic accumulation, and soil contamination. Biodegradable films are promising alternatives, yet their degradation rate, durability, cost, and ecological consequences vary considerably under field conditions. Mineral and advanced mulches may be useful in arid and semi-arid agriculture but require broader field validation. The review concludes that no single mulch material is universally optimal. Effective selection should integrate climate, crop system, soil constraints, irrigation regime, tillage practice, material availability, economic feasibility, and environmental priorities.

Keywords: Mulching materials; Soil temperature regulation; Biodegradable mulch; Plastic mulch impact; Sustainable agriculture; Organic mulch

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Citation: Rahman MR, Rofi MRI. Materials used for soil mulching: A comprehensive review of performance, soil impact, and sustainability. *Explora Environ Resour*.
doi: 10.36922/EER026200018

Received: May 13, 2026

Revised: June 18, 2026

Accepted: July 9, 2026

Published online: August 7, 2026

1. Introduction

Soil mulching is one of the oldest and, at the same time, one of the most adaptable soil management practices in agriculture. In its simplest form, mulching involves covering the soil surface with a protective layer of organic, synthetic, mineral, or engineered material. This cover modifies the exchange of water, heat, gases, and energy between the atmosphere and the soil surface. Although the practice is technically simple, its agronomic and environmental consequences are complex. Mulch materials can reduce evaporation, moderate soil temperature, suppress weeds, limit runoff and erosion, improve infiltration, influence nutrient cycling, stimulate or disturb microbial processes, and ultimately affect crop growth and yield formation.[1–4] The importance of mulching has increased sharply in recent years because agricultural systems are increasingly exposed to drought, irregular rainfall, heat waves, declining soil organic matter, erosion, salinity, and rising irrigation costs. Under such conditions, maintaining a stable root-zone environment is critical for crop productivity. Organic mulches, such as straw, crop residues, leaves, grass clippings, compost, bark, and wood chips, function as porous covers that reduce evaporation and erosion while gradually decomposing and contributing organic matter to the soil.[5,6] Meta-analytical evidence also shows that soil mulching can enhance yield and water- and nitrogen-use efficiencies, although the magnitude of the response depends on crop, soil, climate, and management context.[7] In saline and saline–alkaline systems, mulch can additionally reduce evaporation-driven salt accumulation near the soil surface, but the outcome remains strongly dependent on water management and local soil conditions.[8] Plastic mulches, especially polyethylene films, act as continuous physical barriers that strongly reduce evaporation, increase soil temperature, suppress weeds, and often improve early crop growth and marketable yield.[9] However, the growing environmental concern around agricultural plastic use has shifted attention from purely agronomic performance toward long-term sustainability, end-of-life management, residue persistence, and soil contamination.[10,11] Biodegradable films are designed to provide many of the same short-term benefits as polyethylene films while reducing the need for removal and disposal after harvest.[12–15] Mineral and advanced mulches, including gravel, stones, and superhydrophobic sand, are particularly relevant in arid and semi-arid environments because they can reduce capillary water loss and improve water-use efficiency.[16] The increasing evidence on agricultural microplastics further reinforces the need to compare mulch materials not only by yield response but also by their environmental fate.[17] Recent studies on dryland mulching, long-term plastic residue accumulation, and biodegradable film performance confirm that mulch selection should be treated as a sustainability decision rather than only an agronomic input.[18–20] A key limitation in many mulch studies is that mulch materials are evaluated as if they acted independently from the soil system. In practice, mulch performance depends strongly on the condition of the soil beneath the cover. Soil density, surface roughness, seedbed preparation, aggregate stability, infiltration capacity, hydraulic conductivity, compaction, tillage depth, residue distribution, and nutrient status all affect how a mulch layer performs.[21–26] A polyethylene film placed over a well-prepared strip may conserve moisture and improve early crop development, whereas the same film placed over compacted or poorly structured soil may fail to provide favorable root-zone conditions. Similarly, straw mulch can reduce evaporation, but its effect on crop growth depends on nitrogen availability, residue quality, rainfall, and microbial decomposition. This review also draws on recent studies and reviews on synthetic biodegradable mulches and dryland mulching,[27,28] organic mulching and crop-specific water-use efficiency,[29–32] biodegradable film trials and plastic-film hydrothermal effects,[33–36] straw strip mulching and soil-water regulation,[37–39] erosion mitigation and double-mulching systems,[40,41] biodegradable film alternatives and field degradation,[42–45] plastic residues and microplastic accumulation,[46–51] biodegradation mechanisms and life-cycle assessment,[52,53] crop water-use studies and tillage interactions,[54–58] microbial and nutrient-cycling responses,[59–67] and crop-specific meta-analyses or field studies on film and organic mulching.[68–70] This review aims to provide an integrated assessment of mulch material categories, their mechanisms of action, their effects on soil physical, chemical, and biological properties, and their agronomic and environmental trade-offs. The review also proposes a decision-support perspective for selecting mulch materials according to climate, crop system, soil constraints, management goals, and sustainability priorities. The conceptual framework of mulch material categories and their effects on soil processes, crop performance, and environmental sustainability is shown in Figure 1.

2. Methodology

This article was prepared as a structured narrative review rather than a formal systematic review. This correction is important because a true systematic review requires predefined search strings, complete database records, duplicate removal, transparent exclusion criteria, quality assessment, and preferably a Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA)-style flow diagram. The earlier version of the manuscript referred to a systematic literature review, but the available structure did not provide enough methodological detail to support that claim. Therefore, the present version uses a more accurate review design: a structured synthesis of review papers, meta-analyses, field experiments, environmental assessments, and selected mechanistic studies relevant to soil mulching. The literature was organized around 10 analytical themes: general mulch benefits; organic

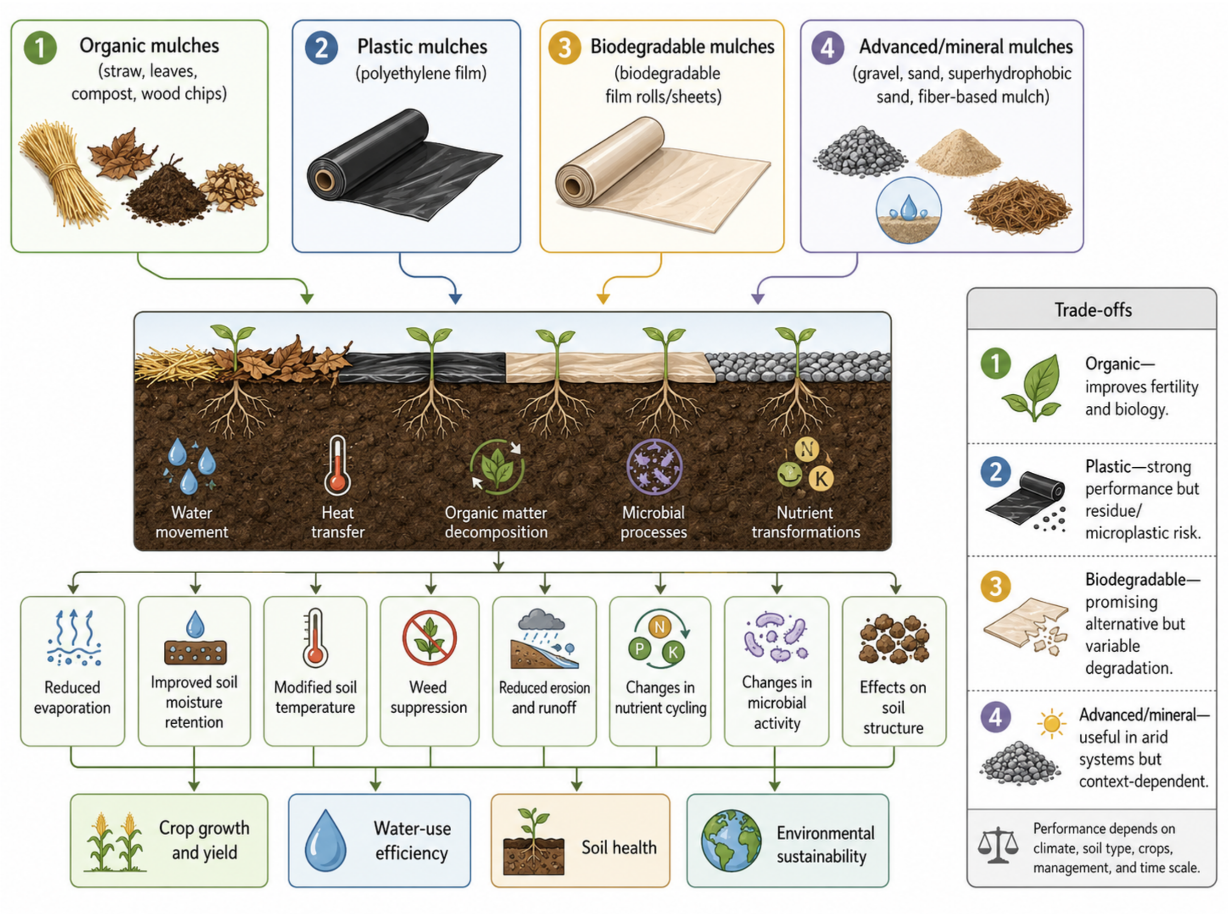

Figure 1. Conceptual framework of mulch material categories and their effects on soil processes, crop performance, and environmental sustainability

mulch and soil health; plastic-film mulch performance; biodegradable mulch films; mineral and advanced mulch materials; soil moisture and temperature regulation; nutrient cycling and microbial activity; plastic residues and microplastics; mulch–tillage interactions; and decision-making for sustainable mulch selection. Broad review papers and meta-analyses were used to establish general patterns, while field experiments were used to illustrate crop-specific and climate-specific responses. Older but foundational references were retained where they remain important for understanding plastic mulch, biodegradable film development, and soil hydrothermal modification. The review does not attempt to rank mulch materials as universally "good" or "bad." Instead, it evaluates each material category according to mechanism, agronomic function, soil impact, environmental risk, and practical suitability. This approach is more appropriate because mulch performance is highly context-dependent. A mulch material that is effective in a cool vegetable production system may be unsuitable in a hot dryland cereal system. Likewise, a biodegradable film that performs well in one soil may degrade too slowly or too rapidly in another.

3. Classification and detailed review of mulch materials

Mulch materials can be classified by origin, structure, durability, mode of action, environmental persistence, and suitability for specific cropping systems. The traditional division into organic and synthetic mulches is useful but incomplete. Current mulch research includes a broader range of materials, including biodegradable polymers, mineral covers, engineered fiber materials, biochar-based covers, and hydrophobic or superhydrophobic materials designed to reduce evaporative water loss. Table 1 summarizes the main mulch categories relevant to agricultural soil management.

Organic mulches are derived from plant residues or other biologically based materials. Their greatest advantage is that they provide both physical soil protection

Table 1. Classification of mulch materials used in agricultural soil management

Mulch category	Typical materials	Main mechanism	Main soil effect	Most suitable use	Key references
Organic mulches	Straw, crop residues, leaves, grass clippings, compost, bark, wood chips	Physical soil cover, gradual decomposition, organic matter input	Improves moisture retention, aggregation, microbial activity, and nutrient cycling	Sustainable farming, orchards, vegetables, erosion-prone soils	1,2,5,6,18,29,31,37,38,41,59–62
Plastic mulches	Polyethylene films, black films, transparent films, colored plastic films	Impermeable barrier, evaporation reduction, heat accumulation	Strong moisture conservation and soil warming, but residue accumulation risk	Intensive vegetable production, early crop establishment, drip-irrigated systems	9–11,19,20,34–36,43,44,46–50
Biodegradable film mulches	Starch-based films, PLA blends, PBAT-based films, cellulose-based films	Temporary film cover followed by biological or physicochemical degradation	Similar short-term function to plastic mulch, with lower disposal burden	Systems requiring plastic-like performance with reduced waste	3,12–15,20,27,33,42–45,52,53,66
Mineral and inorganic mulches	Gravel, stones, sand, superhydrophobic sand	Surface insulation, capillary disruption, evaporation limitation	Reduces evaporative water loss and moderates surface temperature	Arid and semi-arid regions, desert agriculture, orchards	16,32
Fiber-based mulches	Jute, coir, hemp, wool, paper-based materials, engineered natural fibers	Biodegradable cover, thermal insulation, erosion control	Stabilizes soil surface and reduces runoff and erosion	Slopes, horticulture, restoration areas, low-input systems	1,2,27,29
Biochar-based mulches	Biochar, straw–biochar mixtures, compost–biochar mixtures	Surface protection plus carbon-rich amendment	Improves water retention, reduces erosion, and may enhance soil structure	Degraded soils, erosion-prone soils, carbon-oriented soil management	40,58

Abbreviations: PBAT: Polybutylene adipate terephthalate; PLA: Polylactic acid.

and biological contribution. As they decompose, organic mulches can add organic carbon, release nutrients, stimulate microbial activity, and improve aggregate stability. However, their performance depends on material quality. Straw and woody residues usually decompose slowly and may temporarily immobilize nitrogen, whereas grass clippings and fresh leaves decompose rapidly but may provide shorter-lasting soil cover. Compost mulch can improve soil fertility more directly, but its availability, cost, maturity, and transport requirements may limit large-scale use. Plastic mulches remain widely used because they provide reliable and immediate agronomic effects. Polyethylene films can strongly reduce evaporation, warm the soil, suppress weeds, and increase crop earliness and yield. However, polyethylene is highly persistent, and incomplete removal can lead to long-term residue accumulation. The environmental cost of plastic mulch is therefore not limited to visible waste; it also includes microplastic formation, possible chemical leaching, altered soil physical properties, and changes in microbial communities. Biodegradable films are designed to address the disposal problem of conventional plastic mulch. They are usually made from starch-based polymers, polylactic acid blends, polybutylene adipate terephthalate-based materials, cellulose-derived materials, or other degradable polymer combinations. Their value lies in combining film-like agronomic performance with lower removal burden. However, field degradation is influenced by temperature, moisture, microbial activity, film thickness, and polymer composition. Therefore, biodegradable films should be considered promising but not automatically risk-free. Mineral and advanced mulches represent more specialized strategies. Gravel mulch can reduce evaporation and improve water productivity in arid and semi-arid regions. Superhydrophobic sand is an engineered material that reduces capillary water movement toward the soil surface, thereby limiting evaporation under extreme aridity. These materials have potential, but their cost, scalability, and long-term environmental behavior require further evaluation.

4. Main pathways of mulch action

Mulch affects soil and crop performance through several interacting pathways. The first and most widely studied pathway is the reduction of evaporation. By covering the soil surface, mulch reduces direct solar heating, wind exposure, and vapor exchange between the soil and atmosphere. This effect is particularly important in dryland agriculture, where limited rainfall and high evaporative demand often restrict crop development. Organic residues reduce evaporation by forming a porous insulating layer, while plastic and biodegradable films create a more continuous barrier. Mineral mulches and superhydrophobic sand reduce evaporation partly by limiting capillary movement and surface water loss. The second pathway is temperature regulation. Plastic films often increase soil temperature by trapping heat and modifying surface energy balance. This warming effect is useful in cool climates and early-season vegetable production, where faster germination and root growth can improve crop establishment. By contrast, organic mulches usually moderate temperature extremes. They reduce overheating during hot periods and limit heat loss during cooler periods, creating a more buffered root-zone environment. Biodegradable films typically behave more like plastic films during the active crop period, but their thermal function may decline as degradation progresses. The third pathway involves soil structure. Organic mulches protect the surface from raindrop impact, reduce crusting, improve infiltration, and gradually contribute organic matter. Biochar-based mulches may add further benefits by increasing water retention and stabilizing degraded soils, although their effectiveness depends on biochar properties, application rate, and soil texture. Plastic films generally do not improve soil structure directly. Their effect is mainly physical and temporary; when residues accumulate, they may disturb aggregation, porosity, and microbial processes. The fourth pathway concerns nutrient cycling and microbial activity. Organic mulches provide substrates for microbial decomposition and can increase soil enzyme activity, microbial biomass, and nutrient transformations. Plastic films may indirectly affect nutrient availability by maintaining moisture and reducing leaching, but they do not supply nutrients. Biodegradable films may contribute small amounts of carbon during degradation, although their nutrient contribution is minor compared with organic mulches. The comparative effects of the major mulch materials on these soil–plant pathways are shown in Figure 2.

The overall performance of mulch materials differs according to the relative strength of these pathways. Table 2 provides a comparative assessment of the main mulch categories.

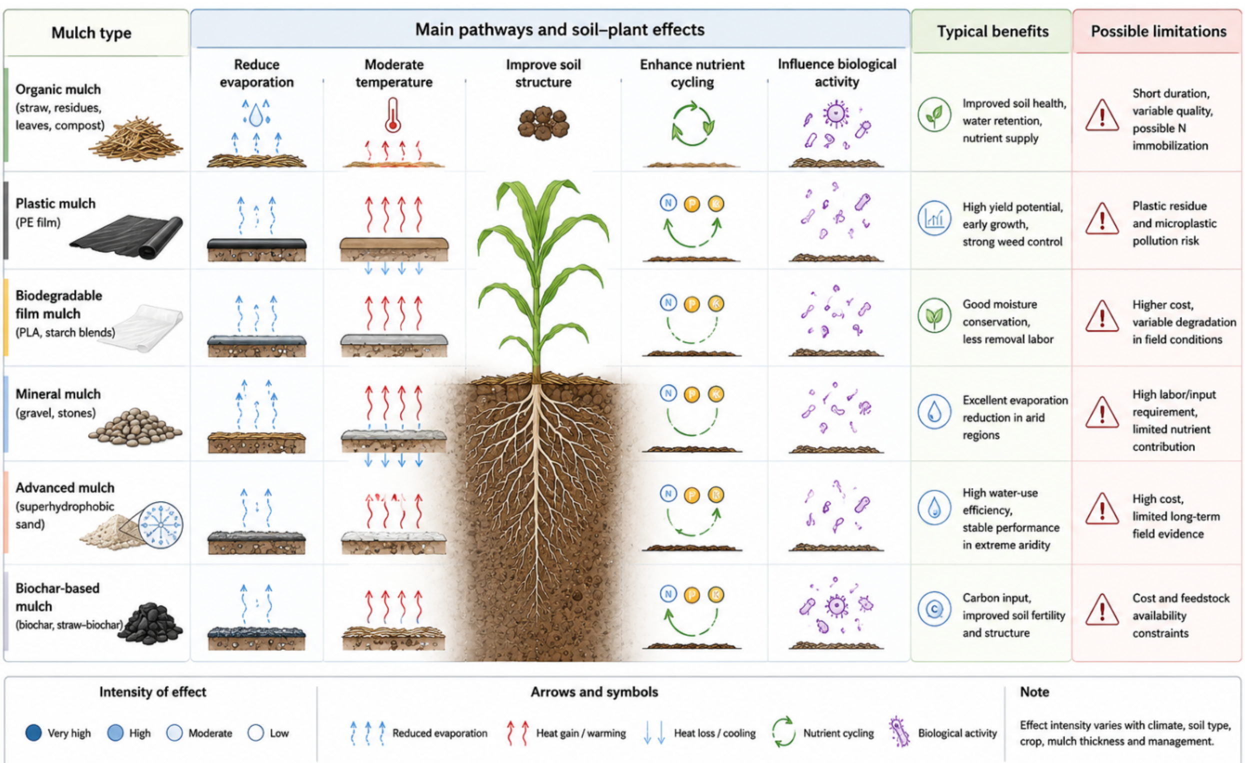

Figure 2. Pathways and comparative effects of major mulch materials on soil processes and crop performance

Table 2. Comparative performance of major mulch categories

Criterion	Organic mulch	Plastic mulch	Biodegradable mulch	Mineral/ Advanced mulch	Comment
Moisture retention	High	Very high	High to very high	High to very high	Plastic and advanced mulches usually show the strongest evaporation suppression, while organic mulch improves both cover and infiltration[4,7,18,31,32,34]
Soil warming	Low to moderate	High	Moderate to high	Variable	Black and transparent plastic films generally increase soil temperature more strongly than organic residues[9,20,34,36]
Temperature buffering	High	Moderate	Moderate	Variable	Organic mulch is more effective for reducing extreme temperature fluctuations rather than rapid warming[1,2,18,38]
Nutrient contribution	High	None	Low	Low to none	Organic mulch contributes nutrients during decomposition, while plastic and most films mainly provide physical protection[1,6,29,60–62]
Soil organic matter effect	Positive	Neutral or negative over time	Variable	Variable	Organic mulch generally increases organic inputs; plastic residues may affect soil biological processes negatively under long-term use[10,19,48,64]
Weed suppression	High	Very high	High	Moderate	Plastic films provide strong weed control; organic mulch effectiveness depends on layer thickness and decomposition rate[1,2,9,31]
Microbial response	Usually positive	Variable to negative long-term	Variable	Insufficient evidence	Organic mulch often stimulates microbial activity; film residues and microplastics may disturb microbial communities[13,14,48,59–64]
Environmental risk	Low to moderate	High	Low to moderate	Uncertain	Plastic mulch has the clearest long-term residue problem; biodegradable and advanced materials still require field-scale evaluation[10,12,15,19,45,47,49,53]
Cost and availability	Variable	Low to moderate	Moderate to high	Often high	Organic mulch depends on local biomass availability; biodegradable and advanced materials may be cost-limited[15,27,42,53]
Overall sustainability	High	Low to moderate	Moderate to high	Promising but context-dependent	Sustainability depends on soil, crop, climate, cost, and end-of-life management[1,3,4,27,28]

5. Effects on soil physical properties

Soil moisture is the most direct and frequently reported property affected by mulch. Mulching reduces evaporation from the soil surface and increases the duration of water availability in the root zone. In rainfed and semi-arid systems, this can be critical for crop establishment and yield stability. Straw strip mulch, plastic film mulch, gravel mulch, and biodegradable film mulch have all been shown to improve soil water conservation, although the magnitude of improvement depends on rainfall, irrigation, soil texture, soil surface condition, and mulch thickness. Soil temperature is more material-dependent. Plastic films often increase soil temperature, which can accelerate germination and early growth in cool or temperate regions. However, excessive warming may become harmful in hot environments, particularly where root-zone heat stress is already limiting. Organic mulches generally buffer temperature rather than strongly increase it. This makes them valuable in hot and water-limited environments, where reducing extreme soil temperatures may be more important than early warming. Soil structure is affected primarily by organic and biochar-based mulch materials. Organic residues reduce crust formation, protect aggregates from raindrop impact, and gradually improve soil organic matter. Biochar-based mulches may reduce erosion and improve water retention in degraded soils, especially when combined with straw or other organic covers. Plastic films do not directly improve structure and may contribute to structural degradation if residues accumulate over many years. Bulk density and compaction are important because they determine whether conserved water is actually available to roots. Mulch can reduce surface sealing, but it cannot fully correct deep compaction or poor seedbed structure. Research on soil preparation under plastic film for melon crops shows that leveling, compaction control, and combined strip tillage parameters can influence the physical condition of the soil beneath the film.[21] Studies on strip tillage, minimum tillage, chisel tillage, and traditional mouldboard tillage further confirm that soil density, hydraulic function, and soil mechanical condition strongly influence crop response.[21,22] Therefore, mulch should be evaluated together with tillage and seedbed preparation. The main effects of mulch materials on soil physical, chemical, biological, and crop-performance indicators are summarized in Table 3.

6. Effects on soil chemical and biological properties

Organic mulches influence soil chemistry mainly through decomposition. As residues decompose, they contribute organic carbon and may release nitrogen, phosphorus, potassium, and other nutrients. The rate and balance of nutrient release depend on residue composition. Low carbon-to-nitrogen ratio (C:N) materials, such as grass clippings, can release nutrients relatively quickly, whereas high C:N materials, such as straw, bark, and wood chips, may temporarily immobilize nitrogen. This is not necessarily negative over the long term, but it can reduce short-term nitrogen availability if nutrient management is not adjusted. Nutrient cycling under mulch is also connected to microbial activity. Organic mulch creates a more stable and moister soil microenvironment, which can increase microbial biomass and enzyme activity. Improved microbial functioning can accelerate organic matter transformation and nutrient mineralization. However, the direction of microbial response depends on soil moisture, temperature, substrate quality, and management system. For example, living grass mulching in orchards can enhance enzyme activity through increased nutrient availability, whereas stover mulching can alter microbial functional guilds in the rhizosphere and endosphere. Biodegradable films also interact with microbial communities because

Table 3. Effects of mulch materials on key soil properties and crop performance

Soil or crop parameter	Main effect of mulching	Strongest material group	Important limitation	References
Soil moisture	Reduces direct evaporation and increases water availability in the root zone	Plastic, biodegradable, straw, gravel, superhydrophobic sand	Effect depends on rainfall, irrigation, soil texture, and mulch thickness	4,7,18,28,31,32,34,37,55,56,69
Soil temperature	Alters heat transfer between atmosphere and soil surface	Plastic and biodegradable films for warming; organic mulch for buffering	Excessive warming may be harmful in hot climates	2,9,20,34,36,38,39
Soil structure	Improves aggregation and reduces crusting when organic materials decompose	Organic mulch, straw, compost, biochar-based mulch	Benefits develop gradually and depend on biomass quality	1,5,29,31,39–41,58
Bulk density and compaction	Mulch can reduce surface sealing, but the underlying tillage system remains critical	Organic mulch combined with conservation tillage	Mulch alone cannot correct severe compaction	21–25,30,40,57
Nutrient cycling	Organic materials add carbon and nutrients and stimulate microbial transformations	Straw, compost, grass, crop residues	High C:N residues may temporarily immobilize nitrogen	1,6,18,26,29,60–62,67
Microbial activity	Improves enzymatic activity and microbial biomass under favorable conditions	Organic mulch and some biodegradable materials	Plastic residues may shift or disturb microbial communities	13,14,18,48,59–64
Weed suppression	Blocks light and reduces weed emergence	Plastic films, thick organic mulch, biodegradable films	Organic mulch may introduce weed seeds if poorly managed	1,2,9,31
Erosion control	Protects soil from raindrop impact and runoff	Straw, fiber-based mulch, biochar mulch, double mulch	Performance depends on slope, rainfall intensity, and cover persistence	1,40,41,58
Yield	Often increases yield through improved moisture, temperature, and nutrient conditions	Plastic, biodegradable, straw, organic mulch depending on crop	Yield response is strongly site- and crop-specific	7,18,20,28,30,31,33,36,37,42–44,54–56,68–70
Water-use efficiency	Increases crop output per unit of water used	Plastic film, straw strip mulch, gravel mulch, biodegradable film	Gains are smaller when water is not limiting	4,7,16,28,30,32,36,37,55,56

Abbreviation: C:N: Carbon-to-nitrogen ratio.

degradation depends partly on microbial activity. Studies have shown that biodegradable film mulching can influence microbial community composition, but responses differ between soils and materials.[13,14] This variability is important because biodegradable films are often promoted as environmentally friendly alternatives, but their actual effects depend on the degradation pathway and the fate of residues or additives. Plastic mulch may influence nutrient cycling indirectly through improved soil moisture and reduced leaching, but long-term plastic residues can disturb microbial processes. Macroplastic and microplastic accumulation may alter microbial community structure, enzyme activity, and nutrient limitation patterns. Such findings indicate that the short-term benefits of plastic mulch should be weighed against possible long-term soil biological costs. The fertilization system also affects the apparent performance of mulch. A mulch material may conserve water effectively, but yield response will remain limited if nutrient availability is insufficient. Vegetable studies, including research on white cabbage, show that fertilization systems can substantially influence agrochemical soil indicators and productivity. Therefore, mulch selection should not be separated from nutrient management

7. Advantages and limitations of the main mulch types

The practical value of a mulch material depends on its balance of benefits and limitations. Straw and crop residues are widely available in many farming systems and provide water conservation, erosion protection, and organic matter input. Their limitations include variable decomposition, possible nitrogen immobilization, and the need for sufficient residue supply. Compost mulch improves fertility and biological activity but can be expensive or logistically difficult to apply at large scale. Wood chips and bark provide long-lasting cover but may be more appropriate for orchards, vineyards, and perennial systems than for annual field crops. Polyethylene film mulch provides strong and reliable short-term performance. It is especially effective for intensive vegetable production, early planting, and drip irrigation. However, the environmental consequences of film residues are a major limitation. Biodegradable film mulch reduces removal labor and may lower plastic-waste pressure, but its cost, durability, and degradation behavior remain variable. Mineral mulch and superhydrophobic sand can be highly effective in water-limited regions, but they may require high labor or input costs and are not equally suitable for all production systems. The principal advantages, limitations, and practical recommendations for the main mulch types are summarized in Table 4.

8. Decision-support framework for mulch selection

Mulch selection should be based on site-specific conditions rather than general material rankings. Climate is the first major factor. In dryland and semi-arid systems, the main priority is usually water conservation. Straw mulch, gravel mulch, plastic film, biodegradable film, and superhydrophobic sand may all be relevant, but the final choice depends on crop value, water limitation, labor availability, and environmental risk. In cool climates, plastic and biodegradable films may be selected for their warming effect. In hot climates, organic mulches may be more suitable because they reduce temperature extremes. Crop system is the second major factor. Intensive vegetable production often benefits from film mulches because these materials support early establishment, weed control, and efficient irrigation. Perennial crops, orchards, and vineyards may be better suited to wood chips, bark, compost, living mulch, gravel mulch, or locally available organic residues because long-term soil improvement is often more important than short-term soil warming. Field crops such as maize, wheat, millet, potato, barley, and alfalfa may respond well to straw mulch, strip mulching, plastic film, or conservation tillage combinations depending on rainfall and soil structure. Soil constraints must also be considered. In compacted soils, mulch should be combined with appropriate tillage, biological restructuring, or controlled traffic management. In erosion-prone soils, straw, fiber-based mulch, biochar-based mulch, and double mulching may be more effective because they protect the surface from raindrop impact and runoff. In saline or saline-alkaline soils, mulch may reduce evaporative salt accumulation near the surface, but irrigation and drainage management remain essential. The decision-support framework for selecting mulch materials according to climate, crop system, soil constraints, management goals, and sustainability priorities is presented in Figure 3.

A practical decision matrix for selecting mulch materials under contrasting agricultural conditions is provided in Table 5.

9. Plastic mulch, biodegradable films, and environmental risk

The environmental sustainability of mulch materials is a central issue in modern soil and resource management. Polyethylene film mulch has provided major agronomic benefits for decades, but incomplete retrieval and poor disposal have created a persistent pollution problem. Plastic fragments can remain in agricultural soils after harvest and gradually break down into smaller particles. These particles may alter soil structure, water movement,

Table 4. Advantages and limitations of the main mulch types

Mulch type	Main advantages	Main limitations	Practical recommendation
Straw and crop residues	Improves soil moisture, reduces erosion, supports organic matter accumulation, and enhances microbial activity	May immobilize nitrogen, decompose unevenly, and require regular renewal	Best for conservation agriculture, dryland systems, and soils needing organic matter improvement
Compost mulch	Adds nutrients, improves fertility, stimulates biological activity, and increases water-holding capacity	Can be costly or unavailable at large scale; quality depends on compost maturity	Suitable for vegetables, orchards, degraded soils, and organic production
Wood chips and bark	Long-lasting cover, strong weed suppression, erosion control, and gradual soil improvement	Slow decomposition and possible temporary nitrogen immobilization	Better for orchards, perennial crops, landscaping, and long-term soil cover
Grass clippings and leaves	Low-cost, locally available, rapid decomposition, and quick nutrient release	Short persistence; may contain weed seeds or pathogens if unmanaged	Suitable for small-scale horticulture and local circular biomass use
Polyethylene plastic film	Very strong moisture conservation, rapid soil warming, high weed suppression, and yield increase	Plastic waste, microplastic accumulation, disposal costs, and soil contamination risk	Agronomically effective but should be used with strict retrieval and recycling management
Biodegradable film	Similar field function to plastic film with reduced removal requirement	Higher cost, variable degradation rate, uncertain long-term residue behavior	Promising alternative, but field validation under local soil and climate is required
Gravel or stone mulch	Durable, reduces evaporation, protects surface, and may improve water productivity in arid regions	Labor-intensive, difficult to remove, limited nutrient contribution	Suitable mainly for arid regions and perennial systems
Superhydrophobic sand	Strong evaporation reduction and high potential in arid environments	High cost, limited field evidence, uncertain long-term environmental behavior	Experimental or specialized technology; not yet a universal replacement for conventional mulch
Fiber-based mulch	Biodegradable, good insulation, erosion control, and renewable origin	Mechanical durability and cost can vary strongly	Useful for erosion control, horticulture, restoration, and environmentally sensitive areas
Biochar-based mulch	Adds stable carbon, may improve water retention and soil structure	Cost, feedstock availability, and variable material properties	Useful for degraded soils, erosion-prone sites, and carbon-oriented soil management

microbial activity, and plant growth. Microplastic accumulation is particularly concerning because it is difficult to reverse once residues are incorporated into the soil. Long-term plastic-film use has been associated with macroplastic and microplastic accumulation in agricultural soils. The effects of microplastics depend on polymer type, particle size, concentration, soil texture, climate, crop system, and exposure duration. Nevertheless, the evidence is sufficient to show that plastic mulch should not be evaluated only through short-term yield effects. Its long-term environmental cost must also be included. Chemical leaching from mulching films is another concern. Polyethylene films and other plastic materials may contain additives, stabilizers, pigments, and processing residues. Under field conditions, some compounds may leach into soil, especially in high-value systems such as strawberry production. This issue remains less studied than visible plastic residues, but it reinforces the need for improved material design and careful environmental assessment. Biodegradable films offer a possible alternative, but their sustainability depends on true field degradation rather than simple fragmentation. In many crop systems, biodegradable films can provide moisture conservation, temperature regulation, and yield performance comparable to polyethylene films. However, degradation rates vary widely. Some films may degrade too quickly and lose agronomic function before harvest, while others may persist longer than expected. Therefore, biodegradable mulch should be assessed using multi-year field trials, residue monitoring, microbial analysis, and life-cycle assessment. Life-cycle thinking is necessary because each mulch type has hidden environmental costs. Organic mulch may require transport, labor, and repeated application. Plastic mulch requires production, removal, and disposal. Biodegradable films require polymer production and may not fully degrade under all

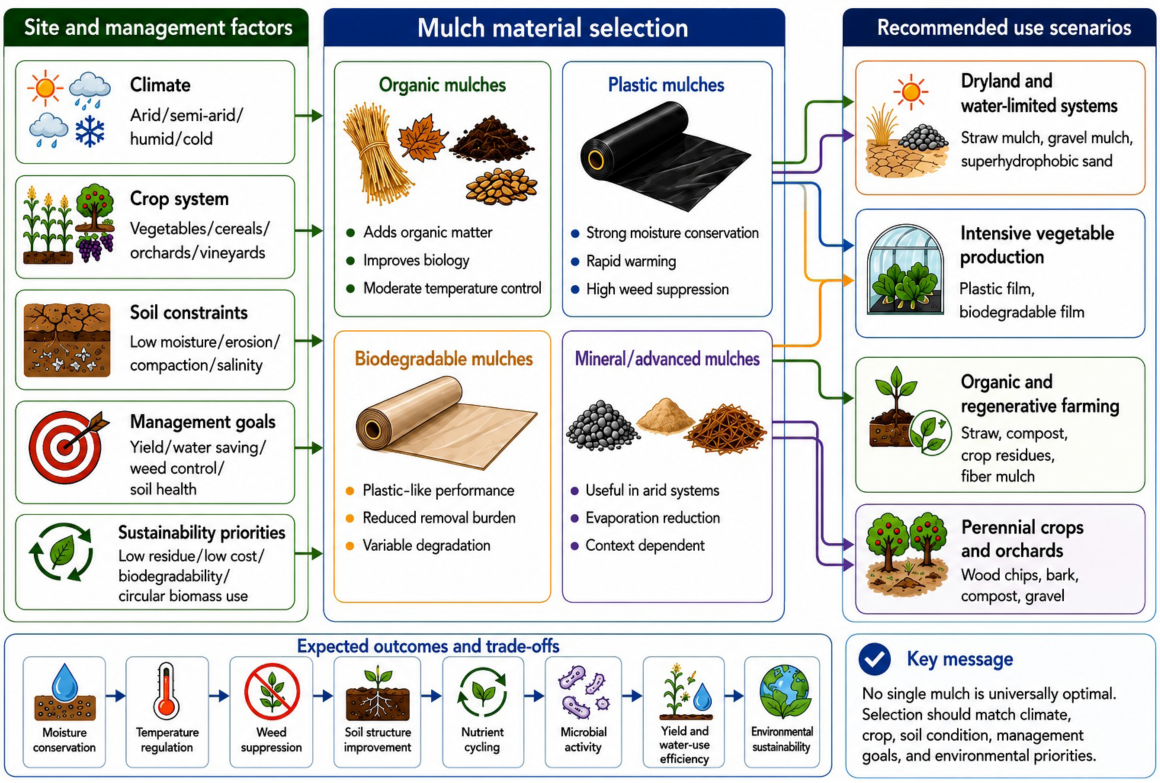

Figure 3. Decision-support framework for selecting mulch materials according to climate, crop system, soil constraints, management goals, and sustainability priorities

Table 5. Proposed decision matrix for selecting mulch materials under different agricultural conditions

Farming condition	Preferred mulch type	Secondary option	Main reason	Caution
Dryland cereal production	Straw mulch or straw strip mulch	Gravel mulch in arid regions	Conserves water and buffers temperature	Nitrogen immobilization may occur with high C:N residues
Intensive vegetable production	Plastic or biodegradable film	Compost mulch	Strong moisture conservation, warming, and weed control	Plastic film requires removal and residue control
Organic farming	Straw, compost, crop residues, grass clippings	Fiber-based mulch	Improves soil health and avoids synthetic residues	Organic material quality must be controlled
Arid and desert agriculture	Gravel mulch or superhydrophobic sand	Plastic film under drip irrigation	Strong evaporation reduction	Cost and scalability may limit advanced materials
Orchards and vineyards	Wood chips, bark, compost, living mulch	Gravel mulch	Long-term surface protection and improved soil structure	Competition for water may occur with living mulch
Saline or saline-alkaline soils	Straw mulch or plastic film with controlled irrigation	Biodegradable film	Reduces evaporation-driven salt accumulation near the surface	Poor irrigation management may still increase salinity
Cold early-season cropping	Black or transparent plastic film	Biodegradable film	Increases soil temperature and accelerates establishment	Excess heat may become harmful later in the season
Erosion-prone slopes	Fiber-based mulch, straw, biochar mulch	Wood chips	Reduces runoff and raindrop impact	Mulch must remain stable during heavy rainfall
Degraded soils	Compost, straw, biochar-based mulch	Crop residues	Rebuilds organic matter and improves structure	Effects require time and repeated application
High plastic-pollution risk areas	Biodegradable film or organic mulch	Fiber-based mulch	Reduces persistent plastic residue input	Biodegradation must be verified under local conditions

Abbreviation: C:N: Carbon-to-nitrogen ratio.

conditions. Mineral mulches may involve high labor and material movement. A credible sustainability assessment should include production, transport, field performance, end-of-life fate, residue persistence, labor demand, cost, and soil health

10. Evidence matrix and research directions

The reviewed literature shows that mulch research is broad but uneven. General effects on moisture conservation, soil temperature, and yield are well documented. However, long-term evidence on biodegradable mulch degradation, microplastic accumulation, advanced materials, and integrated mulch–tillage systems remains incomplete. Table 6 summarizes the main research directions and source groups supporting them.

The most important research gap is the lack of standardized comparison among mulch types. Many studies differ in crop species, soil type, mulch rate, irrigation regime, and climate, making quantitative comparison difficult. Future studies should report common indicators such as soil moisture, soil temperature, bulk density, infiltration, nutrient availability, microbial activity, residue persistence, yield, water-use efficiency, cost, and environmental risk.

A second research gap concerns biodegradable mulch. Field degradation should be evaluated over multiple years and under contrasting climates. Laboratory biodegradation tests are insufficient because soil temperature, moisture, microbial activity, and film burial conditions differ significantly across regions.

A third research gap concerns the integration of mulch and tillage research. Mulch studies often focus on surface cover, while tillage studies focus on soil loosening, density, and structure. In practice, the two are inseparable. Mulch effectiveness depends on the soil condition created before application, especially in film-covered systems. The main research gaps and future directions in mulch-material studies are summarized in Table 7.

11. Discussion

The reviewed evidence demonstrates that mulching is not a single technology with a uniform effect. It is a group of soil-surface management practices whose outcomes

Table 6. Evidence matrix for major mulch-related research directions

Research direction	Main question	Recommended source group	Why these sources are useful
General mulch benefits	How does mulch affect water, temperature, soil fertility, and yield?	1,2,4,7,28	These sources provide broad review or meta-analysis evidence on mulch effects
Organic mulch and soil health	How do straw, compost, and plant residues affect soil quality?	5,6,18,29,31,37,38,41,59–62,67	These studies support discussion of organic matter, microbial activity, enzymes, and nutrient cycling
Plastic mulch performance	Why is polyethylene mulch still widely used?	9,20,34,36,43,44,54–56,68	These sources support the agronomic value of film mulch for moisture, temperature, water-use efficiency, and yield
Plastic pollution and microplastics	What are the long-term environmental risks of plastic mulch?	10,11,17,19,35,46–51,64	These references address residues, microplastics, leaching, soil pollution, and microbial effects
Biodegradable mulch films	Can biodegradable films replace polyethylene mulch?	3,12–15,20,27,33,42–45,52,53,66	These sources cover formulation, degradation, field performance, microbial effects, and life-cycle aspects
Mulching in arid and semi-arid regions	Which mulch systems improve water conservation under drought?	16,18,28,30,32,33,34,37,55,56,69	These studies support dryland water conservation and water-use efficiency arguments
Soil physical condition and tillage interaction	Why does mulch efficiency depend on soil preparation?	21–25,30,40,57	These works support the idea that mulch performance depends on soil density, hydraulic function, and seedbed preparation
Vegetable and field crop response	How do crop species respond to mulch and related soil management?	18,20,26,30,31,33,36,42–44,54,68,70	These studies provide crop-specific support for yield and quality responses
Erosion and soil conservation	Which mulch types protect soil surface against runoff and erosion?	1,40,41,58	These sources support discussion of erosion control and surface stabilization
Future mulch technologies	What materials require further development?	16,27,52,53,58	These references support discussion of advanced materials, biodegradation, life-cycle assessment, and field scalability

Table 7. Main research gaps and future directions in mulch-material studies

Research gap	Why it matters	Recommended future work	References
Lack of standardized comparison between mulch types	Studies often compare different crops, climates, soils, and management systems	Use common indicators: soil moisture, temperature, water-use efficiency, yield, residue persistence, cost, and environmental risk	1,3,4,27,28
Limited long-term data on biodegradable mulch	Field degradation may differ from laboratory expectations	Multi-year trials under contrasting soil textures, moisture regimes, and temperatures	12–15,33,45,52,53
Insufficient data on microplastic accumulation	Plastic residues can persist and alter soil processes	Monitor macroplastic and microplastic residues after repeated film use	10,11,19,46–51
Weak integration of mulch and tillage research	Mulch effects depend on soil structure, density, and seedbed quality	Study mulch performance together with tillage depth, compaction, surface roughness, and hydraulic function	21–25,30,40,57
Limited economic assessment	Farmers choose materials based on cost, labor, and availability	Include cost–benefit analysis, labor demand, removal cost, and material availability	15,27,42,53
Unclear microbial consequences	Organic, plastic, and biodegradable mulches can shift microbial communities differently	Combine microbial sequencing, enzyme assays, and soil chemical monitoring	13,14,48,59–64
Advanced mulches remain under-tested	Superhydrophobic sand and engineered fibers show promise but lack broad validation	Conduct field trials across arid, semi-arid, and irrigated systems	16,27,32
Limited life-cycle assessment	Agronomic benefits may be offset by production or disposal impacts	Compare organic, plastic, biodegradable, and advanced mulches using life-cycle assessment	10,15,27,53
Crop-specific responses are under-generalized	A mulch useful for vegetables may not work equally for cereals, orchards, or root crops	Develop crop-specific recommendations by climate zone and production system	18,20,26,31,33,36,42–44,68,70
Need for decision-support tools	Material selection is context-dependent	Build selection frameworks using soil, crop, climate, cost, and environmental criteria	1,3,4,27,28

depend on material properties, soil condition, climate, crop system, irrigation, tillage, and management goals. The common claim that mulch conserves water and increases yield is broadly correct, but incomplete. Mulch acts through multiple pathways, and these pathways may reinforce or contradict each other depending on context. Organic mulch is the most biologically integrated option. Its value lies not only in surface protection but also in long-term improvement of soil quality. Organic residues can increase soil organic matter, stimulate microbial activity, improve structure, reduce erosion, and enhance nutrient cycling. However, organic mulch is not universally superior. Its effectiveness depends on residue quality, C:N, application rate, decomposition rate, and nutrient management. In systems requiring rapid warming and strong early weed suppression, organic mulch may be less effective than film mulch. Plastic mulch remains highly effective for short-term agronomic performance. It is especially useful for intensive vegetable production, early-season cropping, and drip irrigation. However, its environmental disadvantages are substantial. Residue persistence, microplastic accumulation, disposal difficulty, and potential soil biological disturbance make long-term reliance on polyethylene mulch problematic. The future of plastic mulch should involve improved recovery, recycling, residue monitoring, and substitution with biodegradable or organic alternatives where appropriate. Biodegradable mulch films are promising, but they should be discussed carefully. Their potential lies in reducing removal labor and persistent plastic waste while maintaining film-like agronomic performance. However, their actual sustainability depends on field degradation, residue fate, cost, mechanical strength, and possible effects on microbial communities. Thus, biodegradable films are not a universal solution, but rather one component of a broader transition toward lower-impact mulch systems. Advanced materials such as superhydrophobic sand are scientifically interesting because they address evaporation at the physical level of capillary disruption and vapor diffusion. Such materials may be valuable in desert agriculture and extreme arid systems. However, they are still specialized technologies. Wider adoption will require evidence on cost, durability, environmental fate, scalability, and compatibility with real farm operations. One of the most important conclusions of this review is that mulch must be integrated with soil physical management. Mulch can reduce evaporation, but it cannot fully compensate for poor structure, severe compaction, or inadequate seedbed preparation. Therefore, future research and practical recommendations should evaluate mulch as part of a soil–mulch–crop system rather than as a separate input.

12. Conclusion

Soil mulching remains a vital strategy for improving water conservation, temperature regulation, erosion control, weed suppression, nutrient cycling, microbial activity, and crop productivity. However, mulch materials differ strongly in their mechanisms, benefits, limitations, and environmental consequences. Organic mulches provide the greatest long-term benefits for soil health by adding organic matter, supporting microbial processes, improving structure, and reducing erosion. Their limitations include variable quality, decomposition rate, biomass availability, labor demand, and potential nitrogen immobilization. Plastic mulches provide excellent short-term agronomic performance, especially in intensive vegetable production and drip-irrigated systems. Their main disadvantage is the long-term accumulation of plastic residues and microplastics, which creates environmental and soil-quality risks. Biodegradable films are promising alternatives to polyethylene films, but their performance and sustainability are context-dependent. Their degradation rate, durability, cost, and ecological effects must be validated under local field conditions. Mineral, fiber-based, biochar-based, and advanced mulches offer additional opportunities for specific environments, especially arid, erosion-prone, or degraded soils. However, their scalability and long-term effects require further research. No single mulch material is universally optimal. The best choice depends on climate, crop system, soil constraints, irrigation regime, tillage method, nutrient management, material availability, cost, labor, and environmental priorities. Future studies should move toward integrated assessment of soil–mulch–crop systems using standardized indicators of agronomic performance, soil health, residue persistence, economic feasibility, and environmental sustainability.

Acknowledgments

None.

Funding

None.

Conflict of interest

The authors declare they have no competing interests.

Author contributions

Conceptualization: Md Rafiur Rahman
Writing–original draft: All authors
Writing–review & editing: All authors

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data

Not applicable.

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