agronomy

Review

Does It Hold Water? Effectiveness, Feasibility, and Risks of Drought Adaptation Amendments

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Abstract

Increasing freshwater scarcity alongside growing irrigation demand poses a major challenge for agricultural production. One potential response is the use of drought adaptation amendments: materials of natural or synthetic origin that, when applied to soil or crops, either increase water availability or improve plant performance under water stress. Because these amendments range from minerals and microorganisms to polymers and plant-derived compounds, they are often studied in separate disciplinary literatures rather than as a single category of inputs. Here, we review drought adaptation amendments for agricultural use and evaluate them along three dimensions: effectiveness in mitigating drought stress, economic feasibility, and environmental and human-health implications. Across amendment classes, effectiveness is achieved through several recurring pathways, including reduced soil evaporation, altered canopy energy balance, improved infiltration and soil water retention, improved rhizosphere and root access to retained water, and enhanced physiological tolerance to water deficit. No single amendment consistently performs best across all three criteria. Materials that strongly modify soil water dynamics can be effective but may be costly or environmentally risky, while lower-risk options often have smaller or more context-dependent effects. Among the most promising lower-risk options identified in this review are microbial inoculants, certain mineral amendments, and water-based plant extracts, though their effectiveness remains context-dependent. Future research should prioritize amendments that combine drought-mitigating effects with economic feasibility and minimal environmental or health risks.

Keywords: water stress; soil–plant–atmosphere continuum; organic amendments; biostimulants; microbial inoculants; mineral amendments; superabsorbent polymers; surfactants

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1. Introduction

Global aridification is an important consequence of climate change [1]. Globally, drought and heat account for an estimated 10% reduction in major crop yields [2]. While drought and other stressors reduce global food production, demand for food is projected to double by 2050 due to population growth, dietary shifts, and the production of bioenergy [3]. Although drought and its impacts on crop productivity have been extensively documented [4], more research is needed to develop agricultural practices to adapt to these impacts [5].

In general, drought stress affects leaf development, ion balance, and enzyme activity, resulting in reduced crop yield [6]. Plants under drought stress have impaired mitosis, cell elongation, and cell expansion, leading to weak growth, poor stand establishment, and reduced germination [7–9]. Drought also alters the physical environment in ways that affect plant physiological and biochemical processes [10,11].

Agricultural drought adaptation includes a wide range of strategies, including breeding and genetic improvement, variety selection, planting-date adjustment, cultivation practices, nutrient management, and irrigation management [12,13]. These approaches can reduce crop vulnerability to water stress by altering plant traits, improving soil water conservation, or matching water applications more closely to crop demand [12–14]. However, they differ in timescale, cost, and degree of control over the soil–plant–atmosphere continuum.

Alongside these broader strategies, an important but comparatively fragmented area of intervention is the use of what we term drought adaptation amendments: materials applied to soils, plants, or seeds to reduce water loss, improve water retention or uptake, or mitigate the physiological effects of water deficit. These materials range from organic amendments and minerals to microorganisms, surfactants, superabsorbent polymers, and plant-derived compounds, and are therefore often treated in separate disciplinary literatures rather than evaluated together. Reviewing them as a group makes it possible to compare where they act in the soil–plant–atmosphere continuum, how they mitigate drought stress, and what tradeoffs they present in terms of cost and risk.

This review evaluates drought adaptation amendments for agricultural use along three principal criteria: effectiveness in mitigating drought stress, economic feasibility, and impacts on the environment and human health. The contribution of this review lies in bringing together a wide variety of materials that are often considered separately by specialist disciplines for a cross-cutting discussion of their effectiveness, feasibility, and risks in agricultural drought adaptation.

This review was developed through iterative searches of the agronomic, soil science, plant physiology, and environmental literature using combinations of terms related to drought stress, soil amendments, biostimulants, microbial inoculants, mineral amendments, surfactants, superabsorbent polymers, and hydrophobicity. Searches were then expanded through follow-up queries focused on specific candidate materials or concepts identified in the literature, such as particular amendment classes, formulations, or mechanisms. This iterative approach was important because the review process repeatedly revealed additional substances and lines of inquiry that were not part of the initial search terms. Searches continued until additional queries yielded limited new evidence and few newly identified amendment types. Studies were selected for relevance to agricultural drought adaptation, with emphasis on experimental evidence for effects on soil water relations, plant performance under water deficit, application rates, economic feasibility, and environmental or health implications. Because the literature spans different crops, soils, amendment classes, and response metrics, the review is comparative rather than quantitative.

Section 2 introduces a conceptual framework for comparing these materials based on their primary application sites and recurring mechanisms in the soil–plant–atmosphere continuum. Sections 3 and 4 review naturally derived and synthetic drought adaptation amendments, respectively. Section 5 compares effectiveness across amendment classes, while Sections 6 and 7 address economic feasibility and environmental and human-health implications.

2. Defining Drought Adaptation Amendments: Application Site and Mechanisms

Drought adaptation amendments differ widely in composition, but they can be compared by considering where they are applied and which parts of the soil–plant–atmosphere continuum they most directly influence. As shown in Figure 1, these materials may be applied to the soil surface, incorporated into the soil matrix, introduced to the rhizosphere or root zone, applied to foliage, or used as seed or seedling treatments. Across these application sites, their effects tend to converge on a limited number of recurring mechanisms: reducing soil evaporation, modifying canopy energy balance and transpiration demand, improving infiltration or rewetting, increasing water retention in the root zone, improving rhizosphere and root access to retained water, and enhancing plant physiological tolerance to water deficit. This framework is intended as a guide for comparison rather than a rigid classification, since many amendments act through more than one pathway.

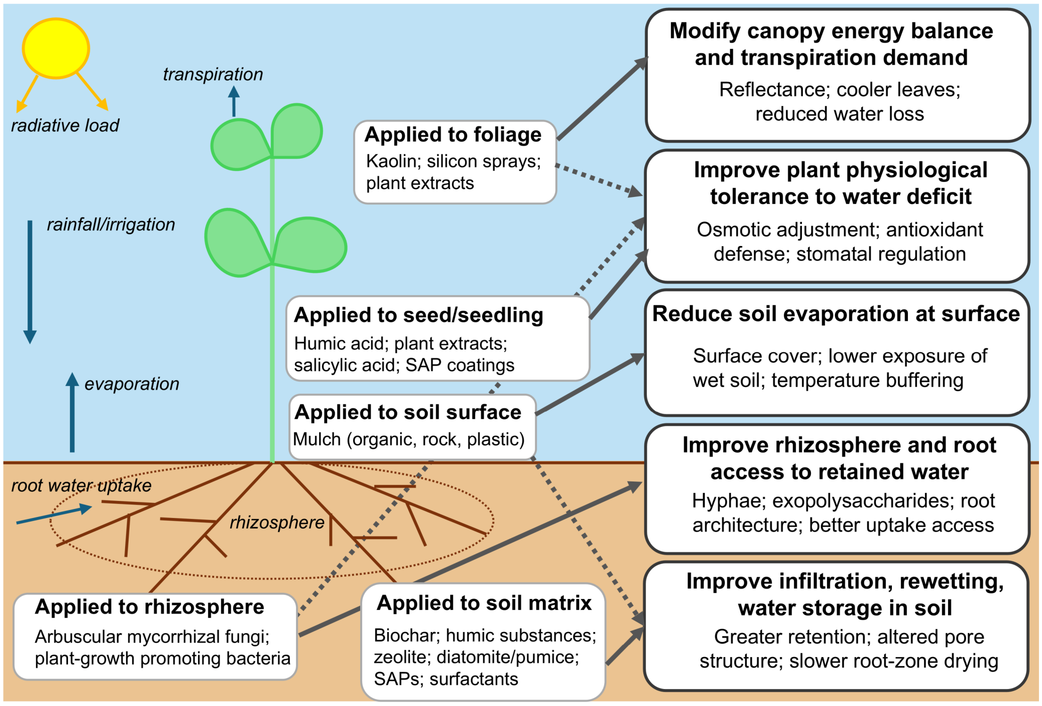

Figure 1. Conceptual framework for drought adaptation amendments in the soil–plant–atmosphere continuum. Example amendments are organized by primary site of application, including the soil surface, soil matrix, rhizosphere/root zone, foliage, and seed/seedling. Across these application sites, they converge on recurring mechanisms: modifying canopy energy balance and transpiration demand, improving physiological tolerance to water deficit, reducing soil evaporation at the surface, improving rhizosphere and root access to retained water, and improving infiltration, rewetting, and water storage in soil. Solid arrows indicate primary pathways and dashed arrows indicate secondary or overlapping pathways. The figure is conceptual and illustrates shared mechanisms rather than equal effectiveness across amendment classes, crops, soils, or drought conditions.

At the soil surface, mulches primarily reduce direct evaporation and buffer temperature. Within the soil matrix, organic amendments, porous minerals, surfactants, and superabsorbent polymers influence how water is stored or distributed through changes in wetting, pore structure, or retention. In the rhizosphere, arbuscular mycorrhizal fungi and plant growth-promoting rhizobacteria improve access to water through mechanisms including extraradical hyphae, root development, and exopolysaccharide production. Other amendments act more directly on the plant: kaolin modifies canopy energy balance by reflecting radiation, while humic acid, silicon, and several plant-derived or chemically defined compounds are discussed in terms of osmotic adjustment, antioxidant defense, stomatal regulation, or related drought-response pathways. The following subsections review naturally derived amendments organized by material type while referencing these application sites and mechanisms.

3. Effectiveness of Naturally Derived Drought Adaptation Amendments

3.1. Organic Materials

The benefits of adding organic matter to soil in the form of manure or compost for moisture retention have been debated since at least the 1930s. Early experiments proposed that adding manure increased the ability of the soil to hold water at field capacity, but that it also increased water held at the permanent wilting point, resulting in little or no gain in plant available water, or PAW [15]. A recent meta-analysis determined that a 1% increase in soil organic carbon by mass would result in an average increase of just over 1% in PAW, with greater impact on coarser soils [16]. However, such apparently small changes in soil organic carbon mass require extremely large volumes of manure or compost to accomplish, approximately 10–20% of soil volume, depending on its density [17].

While changes in PAW may be small, an increase in water holding capacity at saturation may increase the ability of the soil to absorb flood water, as demonstrated in studies where heavy applications of manure (30–60 tons/ha) increased infiltration and reduced runoff [18,19]. This could provide a benefit when drought is preceded by flooding. Organic matter may also have a greater effect on readily available water, which is the difference between water held at field capacity and a refill point at which the soil would be watered, rather than the permanent wilting point. One study found that the addition of organic matter increased water held at field capacity without impacting the refill point, facilitating an increase in readily available water [19].

A related organic amendment deserving mention is digestate, or biogas slurry, a stabilized liquid fertilizer that differs from solid manure in both handling and delivery. Because it can be integrated with irrigation systems, it may provide a more operationally flexible way to supply organic inputs under drought; recent studies and reviews also suggest potential benefits for soil water retention, crop growth, and water-use efficiency, although the evidence base remains smaller than for compost, manure, or biochar [20,21].

Biochar, or charcoal produced by heating under low-oxygen conditions (pyrolysis), has also been proposed to enhance soil water holding capacity [22,23]. Biochar can be made from various organic materials at different temperatures, resulting in different chemical and physical characteristics, with greatly varying impacts on soil and crops [24]. Biochar made from cellulose-rich grass or straw sources rather than lignin-dominant woody material has been shown to have a greater effect on the water holding capacity of soils [25].

However, reported effects of biochar on plant available water vary widely across studies. Omondi et al. (2016) [26] calculated an average increase in available water of 15%, while Razzaghi et al. [27] reported larger gains in coarse soils than in medium- or fine-textured soils. Recent meta-analytic evidence likewise suggests that biochar effects on field capacity and available water are generally more pronounced in coarse-textured soils [28]. The large application rates discussed below should therefore not be interpreted as applying uniformly across all soil types.

At least two studies have found that biochar increased soil moisture but did not increase biomass or crop yield [29,30]. One possible explanation is that, even where biochar improves soil moisture retention, water may not remain the most limiting factor for plant growth. Fehmi et al. [29], for example, suggest that any advantage from higher soil moisture may have been tempered by other constraints, including nutrient limitation. On the other hand, Kumar et al. [31] found increased crop growth under drought conditions without an increase in soil moisture, suggesting that biochar may also improve plant performance through stress-mitigation pathways not captured by bulk measures of soil water alone.

As with other forms of organic carbon, the volume of biochar required to induce significant changes in soil water storage can be extreme, with suggested application rates between 30 and 70 tons ha^{-1} [32]. At an application rate of about 100 tons ha^{-1}, the growth and yield of quinoa (*Chenopodium quinoa*) in greenhouse conditions was increased under drought stress conditions [33]. Evidence from a biochar experiment in alkaline desert cropland soils in Arizona (USA) found that a minimum of 79.4 t ha^{-1} is needed to significantly increase PAW [34].

Biochar applications can also affect other soil characteristics related to water, such as increasing porosity. Although an increase in porosity is suggested to enhance the movement of air and drainage while improving water holding capacity of the soil, biochar applications can also decrease the infiltration and hydraulic conductivity of the soil due to the hydrophobic properties of organic matter [35,36].

Another form of organic carbon used to improve drought response is humic acid, which is derived from carbon-rich materials like lignite, leonardite, and peat through the process of humification over millions of years. Humic substances increase soil water retention, regulate soil macroaggregates, aid in carbon sequestration, and impact soil and microbial dynamics [37]. The main issue for their use in agriculture is that materials extracted from these carbon-rich sources are mixed with humins, multivalent cations, and heavy metals, making these substances insoluble [38].

Humic acid can both improve water retention of soil and aid in biological processes that mitigate plant stress by stabilizing the plasma membrane, increasing the activity of antioxidant enzymes, and supporting cellular osmotic regulation [39]. Osmotic regulation is one of the main processes responsible for drought tolerance because plants under drought stress accumulate a large amount of protein and free proline to maintain adequate turgor pressure, resist excessive water loss, and increase uptake of ions and cell permeability [40,41]. In crop trials under drought stress, the addition of humic acid to the soil increased the growth of roselle (*Hibiscus sabdariffa*) [42], crabapple (*Malus robusta*) [43], rapeseed (*Brassica napus*) [44], maize (*Zea mays*), and sorghum (*Sorghum bicolor*) [45].

Organic amendments may also be applied to the soil surface as mulch, creating a protective layer to reduce water loss through runoff and evaporation. Mulch can be made of plant residues which change the soil environment physically, chemically, and biologically [46]. These materials reduce surface evaporation, stabilize soil temperature, increase nighttime water condensation, impede soil erosion, improve water infiltration, and enhance water retention [47]. Materials used for mulching include cereal straws, with the amount ranging from 1 to 18 tons ha^{-1}, and surface coverage from 67 to 100%. The effects of mulching are more pronounced during the earlier stages of crop growth, when the crop canopy is small and the potential evaporation from the soil's surface is at its maximum. According to a review by Ramos et al. (2024) [47], in a wide range of applications, using 1 to 10 tons ha^{-1} of organic mulch reduced soil evaporation by an average of 40% in the early crop stages, 35% in the mid-season, and 33% in the late season stage.

3.2. Plant Extracts, Exudates, and Phytochemicals

Several plants contain compounds that may positively impact germination, development, productivity, nutrient uptake, and tolerance to abiotic stressors—including drought—when absorbed by other plants. Extracts of sorghum (*Sorghum bicolor*), sunflower (*Helianthus annuus*), and moringa (*Moringa oleifera*), made with simple water-based methods, have been shown to increase the performance of wheat under drought stress [48]. In one study, moringa extract, which contains the plant growth hormone zeatin, improved wheat yield by 40% compared to the control [49].

Plant extracts may be applied as a foliar spray or by soaking seeds before planting. Maqbool and Sadiq (2017) [50] found benefits to maize growth by soaking seed in a low-concentration solution of sorghum extract, and Farooq et al. (2018) [51] reported benefits to both seed soaking and foliar application of various extracts.

Extracts of *Yucca* spp. are marketed as natural surfactants to enhance soil wetting under brand names such as "ThermX70" and "Yucca Wet", but no peer-reviewed studies of their effectiveness were located. *Yucca schidigera* has high levels of steroidal and polyphenolic compounds, which may also have potential as biostimulants and fungicides [52].

Many plant roots naturally exude mucilage, which enhances the moisture-retaining properties of the rhizosphere. Applications of plant mucilage from exogenous sources can enhance this effect in target crops. For example, cladodes (cactus pads) of *Opuntia* spp. are rich in highly soluble solids and mucilage, which form a gel when wet. As a result of these properties, amending soil with cactus pruning waste was found to increase water retention capacity [53]. Similarly, seeds of chia (*Salvia hispanica* and other *Salvia* spp.) form a mucilaginous coating when soaked, which can be used to enhance the water holding capacity of soil [54].

Several substances that play a role in inducing plant drought responses through hormonal or other pathways have been used in experiments to improve drought adaptation. These substances are produced by plants in biosynthetic processes and, as exogenous amendments, may be derived from plant sources or created synthetically.

Proline, an amino acid produced by most plants in response to stress, acts as an osmoprotectant. Several experiments with foliar application of proline have shown improved growth under drought conditions with rice (*Oryza sativa*) [55], wheat [56], cowpea (*Vigna unguiculata*) [57], maize [58], and cauliflower (*Brassica oleracea* var. *botrytis*) [59]. Synergistically, proline and salicylic acid improved drought tolerance in barley [60], while proline in combination with methionine enhanced cauliflower yields under drought stress [59]. Synergistic effects were also found when using proline with silicon on sugar beets (*Beta vulgaris*) [61], and proline with glutathione and ascorbic acid on chickpea (*Cicer arietinum*) [62].

Salicylic acid, another osmoprotectant, has been shown to improve drought tolerance in several crops. In addition to the synergistic effects with proline, Habibi et al. (2012) [63] found that salicylic acid mitigated drought effects on barley. In a review of salicylic acid effects on sunflowers, Damalas and Koutroubas (2022) [64] found seven studies showing improved tolerance to drought and other stresses, including salt, heat, cold, and heavy metals. Several studies reviewed by [65] found improved drought tolerance by soaking seeds of tomatoes (*Solanum lycopersicum*) and beans (*Phaseolus vulgaris*) in a salicylic acid solution, with some showing better results at lower concentrations.

Hussain et al. (2008) [66] compared the effects of salicylic acid and glycinebetaine, an osmoprotectant derived from sugar beet molasses, on sunflowers. They found the greatest effect with glycinebetaine when applied at the flowering stage. Other studies with glycinebetaine have shown positive results, including improved growth of tomatoes under both well-watered and drought conditions [67], and olives (*Olea europaea*) [68] under drought stress.

Ascorbic acid showed similar positive effects on drought tolerance to salicylic acid in an experiment with maize [69]. In field studies, ascorbic acid mitigated drought stress on wheat [70] and quinoa [71].

Melatonin, which reduces oxidative stress in plants, has also been applied exogenously in several drought experiments. Improved drought tolerance was found in studies with maize [72], tomato [73], and Chinese hickory (*Carya cathayensis*) [74]. In a study with coffee (*Coffea arabica*), Campos et al. [75] found improved drought tolerance at a moderate melatonin concentration (300 μM), but negative effects at a higher concentration (500 μM), suggesting that benefits may diminish or reverse above an optimal concentration range.

Hydrogen peroxide, which induces the production of oligosaccharides to maintain leaf water content or causes stomatal closure to conserve water, has also been the subject of drought tolerance studies. Positive results were found with cucumber (*Cucumis sativus*) [76], rice [77], and soybean (*Glycine max*) [78]. Like the dosage response of coffee to melatonin, Basal et al. (2024) [79] found improved drought tolerance in soybean with lower application rates of hydrogen peroxide (1.5 mM), but not the highest rate (10 mM).

Another compound with significant drought adaptation potential is thiourea, also known as thiocarbamide, an organosulfur compound similar to urea, but with oxygen atoms replaced by a sulfur atom (CH_4N_2S) [80]. Thiourea has been shown to increase membrane permeability, osmotic adjustment, and proper maintenance of enzymatic activity, leading to enhanced drought tolerance [81]. It also increases chlorophyll content and the accumulation of osmolytes, benefiting Rubisco activity and leading to an overall increase in photosynthetic rate even under drought conditions [82].

Thiourea has been documented to increase the growth and yield of many plants under drought stress. A study performed on potatoes under drought stress determined that application of thiourea at 0.5 and 0.75 mM resulted in an increase in the total number of leaves and leaf area, as well as protein, sugar, and proline content [83]. This effect may be due to the stimulation of growth through direct interference with enzymes responsible for the biosynthesis of growth-promoting compounds [84]. Similar benefits in the leaves of plants treated with thiourea have been observed in other crops, including maize [80], wheat [85], chickpea [86], and guar (*Cyamopsis tetragonoloba*) [82] under drought conditions.

3.3. Fungal and Microbial Inoculants

Cultures of various fungi and bacteria have been considered for their ability to enhance crop drought tolerance when applied to soils. Arbuscular mycorrhizal fungi can colonize the roots of around 80% of terrestrial plants, helping the host plant extract water and nutrients from the soil while feeding the fungi [87]. Such symbiosis is thought to protect host plants from the detrimental effects of drought [88], but the underlying mechanisms are still not fully understood. One possible pathway of improving crop drought tolerance is an extension of root extraradical hyphae, which increases the uptake and translocation of nutrients and water from soils into the roots [89]. Arbuscular mycorrhizal fungi can also improve polyamine accumulation, root diameter, and fine root production [90], thus increasing nutrient uptake and maintaining root system architecture capable of sensing and adjusting to soil water availability [91]. Arbuscular mycorrhizal fungi can improve the accumulation of potassium, calcium, magnesium, glucose, fructose, and sucrose to improve osmotic adjustment and can help crops develop antioxidants to defend against oxidative damage under drought, salinity, and high temperature stress [92]. Finally, arbuscular mycorrhizal fungi can secrete glomalin, which acts as a sort of “glue” to hold water in the rhizosphere [90,93].

Under drought conditions, arbuscular mycorrhizal fungi inoculation had a positive impact on the growth and nutrient content of pistachio seedlings (*Pistacia vera*) [94]. In a study of winter wheat (*Triticum aestivum*), two species of fungi were used to inoculate plants prior to emergence—*Glomus mosseae* and *G. etunicatum*. Plant growth and yield was increased by the inoculation of both fungi under drought and normal conditions but inoculation with *G. etunicatum* resulted in higher biomass and grain yields [95]. The effect of *G. mosseae* and *G. hoi* was investigated on sunflowers grown under drought stress [96]. When irrigation was restricted by up to 40%, plants inoculated with fungi produced more dry matter, bigger seeds, and greater seed and oil yields than plants devoid of fungal inoculation, with better results for those treated with *G. mosseae*.

Plant growth-promoting rhizobacteria are another group of microorganisms that may provide enhanced drought tolerance. Mechanisms include stimulating the production of hormones that aid in drought tolerance, secretion of osmolytes (compounds such as proline or sugars that aid in stress tolerance), or inducing plants to activate drought response genes [97]. Plant growth-promoting rhizobacteria provide plants with systemic resistance and promote plant growth [98]. These bacteria can influence the synthesis of phytohormones (cytokinins, auxins, or gibberellic acid) which improve plant growth, root development, water and nutrient uptake, and the production of exopolysaccharides [99,100].

Bacteria that have been genetically engineered to over-produce trehalose (a sugar and osmolyte) have been shown to improve drought tolerance in beans and maize [101,102]. Bacteria containing the enzyme ACC-deaminase, which decreases production of the plant stress hormone ethylene, have improved drought tolerance in peas, tomatoes, and peppers (*Capsicum annuum*) [103]. Numerous other studies have shown increased drought tolerance with plant growth-promoting rhizobacteria in maize [104], wheat [105], grapes (*Vitis vinifera*) [106], and lavender (*Lavandula* spp.) [107]. Fungi and bacteria may also be beneficial in combination, as found in a study with rice [108].

Commercial microbial inoculants merit brief mention here because the transition from experimental evidence to practical application is unusually complex in this category. In contrast to many mineral or chemical amendments, the effectiveness of microbial products may depend strongly on organism identity, host crop, soil conditions, inoculum quality, and post-application establishment. As a result, commercially available products do not always correspond closely to the species or strains evaluated in drought-stress experiments, complicating direct comparison between the research literature and marketed inputs [109].

3.4. Minerals

The addition of mineral amendments can lower soil bulk density, resulting in increased pore space, thereby enhancing aeration and water holding capacity [110]. The addition of inorganic nutrients to the rhizosphere of plants under drought stress results in the protection of various cellular organelles [111]. A variety of minerals have been considered as drought adaptation amendments, especially those high in various silicon-based substances.

Silicon (Si) is the second most abundant element found in soils, and while not considered an essential plant nutrient [112], it has shown benefits to plants under stress, including from salt, high temperatures, and heavy metals [113,114], and to have beneficial impacts on water relations, photosynthesis, and other physiological traits of plants under drought stress [115].

Most studies using silicon focus on its introduction through the roots, though beneficial impacts have also been documented as a foliar amendment [116]. Under drought conditions, several wheat cultivars showed improved plant growth and increased photosynthesis and yield following foliar applications of silicon [117]. Nano-silicon (<100 nanometers) has also been used experimentally as a foliar treatment to enhance crop drought tolerance. Nano-silicon may be derived from mineral or biogenic sources, like rice husk, or synthesized [118]. Foliar spray of nano-silicon has been shown to mitigate drought stress in olives [119] and maize [120]. It has also shown positive results as a soil amendment with barley [121] and as a seed treatment for wheat [122].

Silica (silicon dioxide), which is accumulated by many plants in the form of silicic acid and therefore depleted by crop harvests, has recently been suggested as a key driver of plant available water in soils [123]. This study found that adding 1% silica by weight to a sandy clay loam increased plant available water (PAW) by more than 40%, while 5% silica increased PAW by more than 60%. In this case, silica was extracted from rice straw, though a more commonly available form is diatomaceous earth or diatomite, a mineral composed of fossilized siliceous phytoplankton.

Aksakal et al. (2012) [124] found an increase in PAW, with increasing rates of diatomite application up to 30% by volume, while [125] found similar results alongside increased growth in potted strawberries. A study of guar under deficit irrigation found increased growth with diatomite application [126]. A greenhouse study of tomatoes under drought stress found that treatment with potassium silicate (a mineral form that may be either naturally occurring or synthetic) reduced stress by enhancing root hydraulic conductivity and water uptake [127].

Several other types of silica-rich minerals have been considered for water retention and other benefits. Pumice, a porous volcanic glass, was shown in a greenhouse study of maize to increase soil moisture retention as well as growth and yield parameters when applied at rates up to 0.3% by weight [128]. An experiment with pumice and biochar in sandy soil irrigated with saline water found greater water retention as well as salt removal with pumice, with the strongest effect at the highest application rate of 12% by volume [129]. A related study found improved growth of alfalfa (*Medicago sativa*) with the same 12–by-volume pumice application under saline irrigation [130]. One study comparing several inorganic amendments found the greatest increase in plant available water with pumice [131], while other studies have found better water retention with calcined diatomaceous earth [35,132].

Zeolites are porous aluminosilicate minerals that have been considered for their water-retaining properties as well as for the formulation of slow-release fertilizers, absorption of heavy metals, and reduction of nitrate leaching [133,134]. Studies of zeolites' effects on soil moisture and crop performance under water stress have shown mixed results. A study with rice found that zeolite applied at 10 tons ha^{-1} along with an alternate-wetting-drying irrigation regime increased yields by 10%, reduced irrigation by 27.8% and reduced N fertilizer application by 33% [135]. A study of common beans (*Phaseolus vulgaris*) found that zeolite amendment partially mitigated the effects of deficit irrigation [136], while a study in fields of silty-clay soil amended with 50–150 tons ha^{-1} zeolite found that irrigation applications were reduced by half over two years compared to control plots [137]. However, a study in sandy soils found that zeolite increased soil moisture but hindered plant growth when applied at high rates [138]. The authors attribute this to the presence of sodium ions in the zeolite.

Kaolin, a type of aluminosilicate clay, can potentially enhance drought tolerance when applied as a foliar spray. In this case, the white clay applied to leaf surfaces increases albedo, reflecting excess radiation. In their review, Brito et al. (2019) [139] emphasize that the mechanisms by which kaolin film may improve tolerance to drought (as well as heat, salt, and pest stress) remain poorly understood. However, many studies have found a benefit to foliar kaolin application under drought stress conditions, including with basil (*Ocimum basilicum*) [140], peppers [141], tomatoes [142], grapes [143], olives [144], and walnuts [145].

Brito et al. (2019) [139] determined that under non-stress conditions, a reduction in photosynthesis caused by coating leaves with kaolin may reduce plant growth, but under harsh conditions, when plants cannot use all available radiation, benefits become clearer. However, these benefits may be more pronounced under moderate stress than under severe stress.

Similarly, foliar applications containing pigments commonly used on golf courses to artificially enhance turfgrass surfaces by masking damage and imperfections have been suggested to decrease canopy temperatures and enhance photosynthetic activity by blocking harmful UVB light (280–320 nm) [146]. These pigments are powders with varying chemical composition depending on the specific color desired: white pigments are commonly composed of titanium dioxide (TiO_2), blue pigments contain phthalocyanine (a copper-based pigment), while green pigments consist of a more stable, chlorinated form of copper phthalocyanine. Under laboratory conditions, Turfscreen® (ZnO, green pigment, and TiO_2) reduced photosynthetically active radiation by 39%, while copper-based pigment formulations (PAR® and Foursome®) only reduced radiation by approximately 20%. Nonetheless, the beneficial impacts of these products were not statistically significant under growth chamber conditions, and negative effects, including the reduction of light available for photosynthesis and blocking of stomata, were also observed [146].

The use of mineral materials (i.e., stones, ash, cinder, pebbles, or gravel) as mulch has a history dating back at least one thousand years in arid and semi-arid regions of the world [147,148]. The effects of this material can be long-lived, as shown in a study of rockpiles used to mulch agave plants by indigenous peoples in the Sonoran Desert around 1200 CE. Root mass under the mulched areas was found to be 2.7 times greater than in the surrounding control plots, corresponding to increased moisture availability [149]. However, the addition of such materials to the soil surface poses an obstacle to modern agricultural operations such as cultivating, amending, and planting.

4. Effectiveness of Synthetic and Semi-Synthetic Drought Adaptation Amendments

4.1. Plastic Mulch

Plastic films are widely used as mulch in the production of many specialty crops [150]. In a study comparing organic and plastic mulch, the latter was found to be more effective at reducing evapotranspiration [47]. A meta-analysis of the effects of plastic mulch on crop production in China found a 24% increase in yield and a 27% increase in water use efficiency, with the best results from black film [151].

4.2. Surfactants

Surfactants, or surface-active agents, are molecules with both a hydrophobic tail and a hydrophilic head that reduce surface tension at the air–water interface and thereby improve the penetration and distribution of water in soil [152,153]. Surfactants are commonly classified as ionic or non-ionic. Ionic surfactants include cationic, anionic, and amphoteric forms, whereas non-ionic surfactants have uncharged hydrophilic functional groups [154,155].

Under drought or deficit-irrigation conditions, surfactants can improve wetting, infiltration, and moisture distribution, although their effectiveness depends strongly on product composition and on soil and irrigation conditions [156,157]. In one study, application of polyether-modified trisiloxane improved lettuce growth, reduced root mass, and increased both irrigation efficiency and yield, suggesting improved uptake of water and nutrients as well as reduced evaporation through inhibition of capillary rise [158]. Other studies have reported positive effects on forage and grain production of maize [159] and potato [160], while one intercrop study found that adding surfactant to irrigation water increased the yield of berseem clover and sweet basil [161].

Much of the practical experience with surfactants comes from turfgrass management, especially on golf courses, where they have been used since the 1970s [162]. This history has clarified their potential to improve irrigation efficiency in agricultural settings, but it has also revealed the importance of formulation-specific effects, proprietary chemistries, and variable application protocols [163]. Non-ionic wetting agents such as ACA864 and AquaGro L® are known to reduce water repellency in turf thatch and the upper soil profile without foliar phytotoxicity under a range of conditions [164]. At the same time, earlier studies suggest that surfactant effects may decline with increasing irrigation duration, underscoring that these products are effective only under particular combinations of soil, water volume, and application regime [165].

Surfactants may also be useful in soilless horticulture, where hydrophobic substrates such as peat, bark, bagasse, and coconut fiber can contribute to uneven wetting and water loss [166,167]. For example, polyethylene glycol has been shown to improve water retention in rock wool and coconut peat and to promote tomato and lettuce germination [168]. At higher concentrations, however, polyethylene glycol is also used experimentally to induce drought stress, highlighting the importance of dose.

4.3. Superabsorbent Polymers

Superabsorbent polymers are hydrophilic polymer networks that absorb and hold a large amount of water and other aqueous solutions relative to their volume [169]. These compounds have been described as polyelectrolytes with a three-dimensional structure and crosslinked polymer chains. Naturally occurring superabsorbent polymers include chitosan, alginate, collagen, dextran, cellulose, and chitin, while synthetic superabsorbent polymers are typically made with compounds such as acrylic acid, methacrylic acid, polyethylene glycol, vinyl acetate, polyvinyl alcohol, and various acrylates [170,171]. The mechanisms responsible for the beneficial impacts of hydrogels on plant growth include increased water retention of the soil, improved ratio of size to number of pores, an increase in the availability of nutrients, increased aeration, and reduction of soil compaction [172].

Synthetic superabsorbent polymers were first developed in the 1960s by scientists at the United States Department of Agriculture, intended for improving water retention in soils [173]. However, the "Super Slurper" product they developed absorbed water but did not release it as easily, leading to wider adoption in other fields, particularly biomedical applications [174].

In 2002, Mexican chemical engineer Sergio Rico Velasco developed a potassium polyacrylate powder capable of absorbing 200–500 times its weight in water and storing water for longer than a month. This product is registered as Lluvia Solida® ("solid rain") and claims to increase water retention of the soil, allowing plants to obtain water as needed for their growth [175]. Using Lluvia Solida®, the yield of strawberry (*Fragaria x ananassa*) significantly increased compared to control conditions [176]. In a study of Lluvia Solida® on maize, irrigation frequency was significantly reduced, with the total volume reduced by two-thirds [177]. Similar hydrogel applications have also resulted in increased yields of chickpea in sandy soils [178].

Other superabsorbent polymer products include commercial formulations such as Acuastock®, which improved the growth of chard (*Beta vulgaris* var. *cycla*) [179]. In this study, application rates were adjusted to soil type, with higher rates resulting in higher infiltration.

Other studies using superabsorbent polymers suggest that the beneficial impact on plants may be due to increased ionic exchange as well as increased moisture retention. For example, Tittonell et al. (2002) [180] found increased germination rate, uniformity, and size of chile pepper seedlings (*Capsicum annuum*) in unamended soils with a SAP compared to compost-amended soil without a SAP.

Superabsorbent polymers can also be used as seed coating and for treating roots during transplanting. In one study comparing superabsorbent polymers, seeds treated with Stockosorb® showed better results than those treated with Geohumus® [181]. Stockosorb® also showed positive results on tree seedlings of Norway spruce (*Picea abies*) during transplant to mitigate the impact of root desiccation [182].

Superabsorbent polymers have been found to benefit other woody perennials, including limes (*Citrus aurantifolia*) under drought conditions [183,184]. Agaba et al. (2010) [185] evaluated the effect of Luquasorb® on tree species, including *Eucalyptus* spp. and others, finding significantly higher survival when using the amendment due to an increase in plant available water. Another study evaluating the use of superabsorbent polymers on *Eucalyptus microtheca* found positive effects on stomatal conductance under drought conditions, along with significantly increased survival [186].

In recent years there has been a surge of research into composite superabsorbent polymers derived from natural materials, including food waste and crop residue, crosslinked with synthetic chemicals such as acrylic acid or acrylamide into a hydrogel-forming matrix. The absorption capacity of various composite superabsorbent polymers and their source materials are listed in Table 1, showing wide variation.

Table 1. Absorbency of selected composite superabsorbent polymers (SAPs), verified preparation methods, and study context. Absorbency is measured as grams of distilled water absorbed by one gram of SAP.

Principal Source Materials	Absorbency ($g\ g^{-1}$)	Preparation Method	Study Context	Ref.
Mushroom substrate (sawdust), acrylic acid	1701	UV-irradiated poly(acrylic acid) grafting on mushroom substrate	Materials/swelling study	[187]
Cellulose, sodium alginate	1585	Physically crosslinked NaCMC/HPC/NaAlg hydrogel blend	Agricultural water storage and controlled nutrient release	[188]
Sodium alginate, sodium humate, acrylic acid	1380	Graft copolymerization	Materials/swelling study	[189]
Eggshell, potassium polyacrylate	1256	Acrylic-copolymer composite hydrogel with eggshell biofiller	Materials/swelling study	[190]
Corn (maize) cob, acrylic acid, bentonite, PVP, urea	1100	Microwave-assisted semi-IPN composite	Slow-release fertilizer/water-retention study	[191]
Rice husk ash, NPK fertilizer, acrylic acid	1070	NaAlg-g-poly(AA-co-AAm) nanocomposite	Fertilizer-release study	[192]
Wheat bran, laterite, acrylic acid	647	Free-radical graft copolymerization	Materials study; proposed agricultural application	[193]
Guar gum, sodium humate, acrylic acid	532	Graft copolymerization	Slow-release/swelling study	[194]
Orange peel, banana peel, sodium trimetaphosphate	529	Sodium-trimetaphosphate-crosslinked hydrogel	Greenhouse tomato drought study	[195]
Cotton fiber, succinic anhydride	400	Succinic-anhydride modification of cellulose	Materials/swelling study	[196]
Wheat straw, acrylic acid, PVA, urea, phosphate	198.5	Cellulose-based semi-IPN hydrogel	Controlled-release fertilizer study	[197]
Diatomite, chitosan, acrylic acid, urea, NPK fertilizer	75	Double-coated fertilizer with chitosan inner coat and crosslinked outer hydrogel coat	Slow-release fertilizer study	[198]
Wood pulp byproduct (sodium lignosulfate), algae (sodium alginate), konjac flour (*Amorphophallus konjac*)	41.2	Crosslinked biopolymer hydrogel	Slow-release fertilizer study	[199]
Yeast, chitosan	31.7	Hybrid biopolymer hydrogel beads	Materials study with proposed agricultural applications	[200]

The earliest examples of composite superabsorbent polymers date to the 1990s, such as research in Russia leading to the development of a product called Aquapastus derived from peat, humates, and an acrylic polymer [201], and a guar gum-based superabsorbent polymer [202].

Composite superabsorbent polymers have been produced experimentally using a wide array of materials including wheat bran [193], wheat straw [197], millet straw [203], sugar cane bagasse [204], sea buckthorn branches [205], mulberry branches [206], pineapple peels [207], algae-derived materials [199], yeast- and chitosan-derived materials [200], eggshells [190], rice husk ash [192], moldy bread [208], biochar [209], and various types of clay [210–212]. The methods for preparing these substances are thoroughly reviewed by [213].

Thee results in Table 1 indicate the mass of distilled water absorbed by the polymer (g g^{-1}). While several can absorb more than 1 kg of water per gram, this absorbency is reduced as the salt content of water increases, and as pressure is applied to SAPs (as when buried in soil), posing a major limitation to their practical application [213]. For example, potassium polyacrylate superabsorbent polymers under 30 cm of soil can have their absorption capacity reduced by 97% [214]. Even minor impurities in water can severely reduce the absorbency of superabsorbent polymers; for example, a flax yarn waste-based polymer developed by [215] absorbed 875 g g^{-1} of distilled water, but only 490 g g^{-1} of rainwater. In a 0.9 wt% NaCl solution, it was reduced to 90 g g^{-1}.

Several of the listed composite superabsorbent polymers with lower absorbency have mineral fertilizers (i.e., salts) incorporated into them, creating a hydrogel that regulates the release of fertilizer and potentially reduces application levels. Notably, Olad et al. (2017) [192] achieved over 1000 g g^{-1} absorbency in distilled water while also including fertilizer. The two lowest absorbencies listed [199,200] are notable because these superabsorbent polymers were synthesized entirely with naturally occurring source materials rather than the acrylic acid and acrylate used in most formulations.

Another emerging biopolymer deserving brief mention is γ-polyglutamic acid (γ-PGA), a microbially produced polymer of glutamic acid that has been investigated in agriculture both as a fertilizer synergist and as a precursor for highly biodegradable superabsorbent polymers [216–218]. As a soluble amendment, γ-PGA has been reported to improve biomass, root growth, water and nutrient use efficiency, and drought resistance in several crops [219–222]. However, the available evidence also suggests important limitations. Effective rates can be relatively high, and γ-PGA itself should not be treated as equivalent to crosslinked γ-PGA SAPs. γ-PGA is a single-chain water-soluble molecule, whereas γ-PGA SAP is a three-dimensional insoluble polymer with more direct water-retention effects in soil [218,223]. In winter wheat, for example, γ-PGA SAP increased soil water content more consistently, whereas γ-PGA itself was associated more strongly with yield improvement through nutrient-related effects than through increased soil water retention [223]. This distinction, together with the degradation of γ-PGA SAP into glutamic-acid-based products over time, suggests that γ-PGA is promising but still complex as a drought adaptation amendment, with agronomic effects that depend strongly on formulation, rate, and timing [223,224].

Several experiments have tested the efficacy of composite superabsorbent polymers under drought stress or deficit irrigation conditions. Experiments with Pusa® hydrogel, a cellulose-acrylate polymer developed by the Indian Agricultural Research Institute and commercially available in India, showed increased plant population, growth, and yield of rainfed wheat when applied at 5 kg ha^{-1} [225]. At the same application rate, Indian mustard (*Brassica juncea*) showed increased growth under all irrigation levels, with the greatest improvement from the control under rainfed conditions [226]. Similarly, cabbage (*Brassica oleracea* var. *capitata*) had increased growth under full irrigation with Pusa, and increased water productivity (ratio of yield to water applied) when using it under 75% ET irrigation [227]. Peppers showed increased growth under extended watering schedules (every 11 days compared to the control of every 7 days) with 15 or 20 kg ha^{-1} of Pusa [228].

Zeba (UPL Limited, Mumbai, India), a SAP derived from cornstarch grafted with acrylamide-acrylic acid copolymer, was evaluated using cotton (*Gossypium hirsutum*) grown from seed in a growth chamber. This compound can absorb up to 400 times its weight and slowly release moisture to plant roots [229]. Under drought conditions, the use of Zeba® resulted in significant benefits in emergence, root length, and shoot length of cotton [230].

Using the Russian product Aquapastus in a trial of furrow-irrigated potatoes in Uzbekistan at a rate of 2.5–5 g per plant reduced water consumption by 50% while maintaining yield [204]. Several potted plant experiments using composite SAPs under drought stress have also shown promise, with peppers [203], tomatoes [195], and arugula (*Eruca sativa*) [201].

5. Effectiveness Across Amendment Classes

Across amendment classes, differences in effectiveness are most clearly understood in terms of where materials act most directly in the soil–plant–atmosphere continuum. Mulches and foliar coatings such as kaolin primarily reduce non-productive water loss, though at different points in the continuum. Organic amendments, silica-rich minerals, surfactants, and superabsorbent polymers more often act by changing how water is retained, redistributed, or made available in the root zone. Microbial inoculants primarily act through the rhizosphere, improving access to water through extraradical hyphae, exopolysaccharides, root development, and related processes. Plant extracts and signaling compounds are less likely to transform bulk soil water storage, but can still improve drought performance by enhancing osmotic adjustment, antioxidant defense, stomatal regulation, or other physiological responses to water deficit. Some amendments span more than one category. Humic acid, for example, can affect both soil water relations and plant stress response, while silicon has been applied through roots, foliage, and seed treatments.

At the same time, effectiveness is not expressed in a single, uniform way. The studies reviewed here report outcomes including changes in soil moisture, plant available water, germination, biomass, yield, water-use efficiency, and physiological indicators of stress. These outcomes are not directly interchangeable, and the literature spans different soils, crops, amendment rates, and experimental settings. As a result, direct comparison across amendment classes is difficult even when the general goal is similar. This helps explain why it is challenging to identify a single metric that captures drought adaptation performance across all materials reviewed here. The effects and limitations of various amendments, along with their application sites and mechanisms, are reviewed in Table 2.

Taken together, the literature suggests that no single amendment class consistently excels across all drought contexts. Materials that more strongly alter soil water storage or distribution may produce larger direct effects on soil moisture dynamics, while microbial inoculants, plant extracts, and other biologically active compounds may improve drought tolerance through effects on uptake and stress physiology that are less easily captured by bulk soil metrics.

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Table 2. Comparative summary of effectiveness across drought adaptation amendment classes. Note: This table is comparative rather than quantitative. Reported effects are heterogeneous across crops, soils, amendment rates, and experimental settings, so classes are summarized descriptively rather than ranked by a single metric of effectiveness.

Amendment Class	Primary Application Site	Main Mechanism(s)	Representative Effects in This Review	Common Limitations/Context Dependence
Organic amendments (manure, compost, digestate)	Soil matrix	Water retention, aggregation, infiltration, fertility effects	Can improve soil moisture retention, infiltration, or water holding capacity; crop effects may also reflect nutrient inputs	Often require large volumes; bulky to transport and apply; digestate is less studied for soil-water effects
Biochar	Soil matrix	Altered porosity, aggregation, and water retention; possible stress-mitigation pathways	Can increase plant available water, especially coarse-textured soils; some studies report higher soil moisture without yield gains; others report improved growth without clear soil-moisture increases	Strongly dependent on feedstock, soil texture, and application rate; high effective rates may be needed in some arid soils
Humic acid/ humic substances	Soil matrix; seed/seedling; sometimes foliage	Water retention, membrane stabilization, antioxidant activity, osmotic regulation	Often improves growth or physiological drought tolerance; direct soil-water effects appear smaller than for bulk amendments	Product composition varies; much evidence comes from pot or seed-soak studies
Mulch (organic, rock, plastic)	Soil surface	Reduced evaporation, temperature buffering, improved infiltration	Reduces surface evaporation and improves near-surface water conservation, especially early in the season	Effects are concentrated at the surface; plastic mulch raises disposal and residue concerns
Plant extracts/ osmoprotectants/ signaling compounds	Foliage; seed/seedling; sometimes soil	Osmotic adjustment, antioxidant defense, stomatal regulation, stress signaling	Often improves drought tolerance through physiological pathways	Dose dependence can be important; field-scale practicality varies by compound
Microbial inoculants (AMF, PGPR)	Rhizosphere/ root zone	Hyphae, exopolysaccharides, root development, nutrient uptake, osmotic adjustment	Frequently improves drought tolerance, growth, or nutrient status through rhizosphere and root-mediated pathways	Responses depend on crop, soil conditions, and strain; commercial products may not match experimental organisms
Mineral amendments (silica, diatomite, pumice, zeolite, kaolin, silicon)	Soil matrix; foliage; seed/seedling	Water retention and pore-space effects (soil-applied); reflectance and reduced heat load (kaolin); physiological benefits (silicon)	Porous minerals can improve water retention or plant available water; kaolin and some silicon applications can improve drought performance through canopy or physiological pathways	Very heterogeneous class; mechanism and required rate depend on mineral type and application route
Surfactants	Soil matrix/ irrigation water	Improved wetting, infiltration, rewetting, and water distribution	Can improve infiltration and water distribution, especially in hydrophobic soils or media; some studies report improved irrigation efficiency and crop response	Strongly product- and context-dependent; proprietary formulations complicate comparison; toxicity concerns vary by surfactant type
Superabsorbent polymers (SAPs)	Soil matrix; seed coating; transplant/root treatment	Hydrogel formation, increased water retention, slower drying	Often reduces irrigation frequency or improves survival, growth, or water retention under deficit conditions	Performance declines in saline water and under soil pressure; formulations vary widely; synthetic versions raise environmental concerns

6. Economics of Drought Adaptation Amendments

Economic evaluation of drought adaptation amendments is inherently difficult because the available evidence spans different crops, soils, climates, amendment formulations, application methods, and experimental scales. Studies that explicitly address costs are few, and many report application rates in ways that do not translate directly to field production. In addition to summarizing the available economic findings, we compiled costs of commercially available products and used application rates reported in the cited studies to infer approximate costs per hectare (Table 3). These estimates should be interpreted as a first-order comparison rather than a universal ranking, since in many cases they rely on extrapolation from pot experiments, incomplete reporting of field-equivalent rates, or commercial products that do not fully correspond to the materials tested experimentally. In several cases, the products used for cost estimation should be understood as approximate commercial equivalents rather than exact matches to the materials evaluated experimentally. Even with these limitations, the results are useful for identifying which amendment classes are likely to be economically plausible under agricultural conditions and which are likely to remain cost-prohibitive.

In many cases, the underlying studies do not provide the information needed to infer costs for field production. For example, a recent study showing positive results with humic acid provides the concentration of a seed soaking solution, but not the total volume used [45]. Based on the concentration of 100 mg L^{-1} and the price of commercially available bulk humic acid, 1000 L would cost $1 USD. This may be cost-effective, but additional study is required to test this hypothesis.

One creative instance of cost reduction is found in [72], where orange juice was found to be equally effective as isolated ascorbic acid for improving drought tolerance of quinoa. However, since this was a pot experiment with individual plants, it is difficult to infer an application rate that would apply to field production.

A study of polyacrylamide application to eucalyptus seedlings found that the cost per tree was between $0.016 and $0.026, concluding that this would be a cost-effective way to increase survival [187]. However, considering this study is more than 30 years old, this calculation would need to be updated. Two studies of Lluvia Sólida in Latin America found that it would likely be cost-prohibitive for small-scale farmers, despite effectively reducing water requirements [176,178].

In one of the more robust economic analyses of a drought adaptation amendment, Chaichi et al. (2015) [159] found that for maize production in southern California, application of a surfactant increased costs by about 5% while reducing water use by 40% and increasing profits by about 20%. However, the commercial version of the surfactant described (IrrigAid Gold, Aquatrols, Paulsboro, NJ, USA) is no longer available. A similar product from the same company, "Revolution," currently retails for more than seven times the price cited in [159].

Mycorrhizal inoculants are among the cheapest amendments considered here, in part because application rates are low and living organisms may multiply following establishment. Their commercial availability also shows that microbial inoculants are already established as agricultural inputs rather than remaining purely experimental. However, marketed products do not always correspond closely to the organisms evaluated in drought-stress studies. In [89], for example, the fungi were *Glomus mosseae* and *G. hoi*, whereas the commercial product AgTiv Reach contains *G. intraradices*, a fungus of the same genus that has not been evaluated for its effect under drought conditions. Commercial mycorrhizal products are also known for inconsistent performance in the absence of standards and regulation for quality control [109]. Similarly, although bacterial inoculants are commercially

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available, we did not identify products corresponding closely to the species and strains that have shown benefits for drought adaptation experimentally.

Table 3. Application rates and costs of various drought adaptation amendments. Experimental results were used to estimate an application rate per hectare for field production. In some cases, this has involved extrapolating from a per-plant application using data from the University of California Extension on typical plant density for each crop in commercial production. Prices of equivalent products found online were used to determine a per unit area price. Costs per hectare are rounded to the nearest $10 if under $200, and to the nearest $100 if over. These estimates should be interpreted as a first-order comparison rather than a universal ranking.

Type	Crop	Rate	Reference	Product	Package Price	$ ha^{-1}
Acid esters of block copolymers	n/a (soil only)	1.12 kg ha^{-1}	[157]	AgStone 15	$65/gal	$20
Mycorrhizal inoculum	Sunflower	5 kg ha^{-1}	[89]	AgTiv Reach	$145/5 lb	$40
Cellulose-acrylate copolymer	Wheat	5 kg ha^{-1}	[225]	Pusa hydrogel	$13/kg	$65
Starch copolymer	Cotton	5-10 kg ha^{-1}	[230]	Zeba	$5/kg	$50–75
Kaolin	Olive	28.2 kg ha^{-1}	[144]	Surround WP	$50/25 lb	$120
Hydrogen peroxide	Cucumber	1.5 mM plant^{-1}	[76]	Lab Grade Hydrogen Peroxide 34%	$1925 /270 gal	$400–900
Diatomite	Strawberry	14.5 Mg ha^{-1}	[125]	Agricultural Grade Diatomaceous Earth	$54.25/ton	$800
Potassium polyacrylate (SAP)	Maize	60 kg ha^{-1}	[177]	Lluvia Sólida	$362/25 kg	$900–$1200
Zeolite	Rice	10 tons ha^{-1}	[135]	KMI Zeolite	$130/ton	$1300
Nonionic surfactant	Turfgrass	51 L ha^{-1}	[164]	Cascade Plus (Precision Laboratories)	$274.20/2.5 gal	$1500
Modified alkylated polyol (surfactant)	Turfgrass	57 L ha^{-1}	[164]	Revolution (Aquatrols)	$342/2.5 gal	$2100
Composted manure (wet)	Maize	30–60 Mg ha^{-1}	[18]	Manure	$88/ US Ton	$2400–$4800
Pumice	n/a—sandy soil	12% $v\,v^{-1}$	[129]	Bulk pumice	$199/ cubic yard	$5200
Potassium polyacrylic acid	Maize	1184 kg ha^{-1}	[231]	Stockosorb 660	$435/55 lb	$21,000
Proline	Cauliflower	485 kg ha^{-1}	[59]	Bulk L-Proline	$3000/5 kg	$291,000

A hydrogel composite of natural materials crosslinked with acrylate, Pusa Hydrogel, has been shown to be effective at a relatively low cost. However, it is available only in India. Zeba (UPL Limited, Mumbai, India) has wider international distribution. However, the cost in Table 3 is based on prices for customers in India. Based on prices for a U.S. supplier, the cost is closer to $300 ha^{-1}.

Kaolin clay, as a foliar application, is a relatively inexpensive material with a low application rate, since it is used to coat foliage rather than change soil properties. Using cost estimates for olive production in California [232], a single application of kaolin at the rate recommended in [144] would increase operating costs by about 3%.

The lowest cost in Table 3 corresponds to the application of acid ester of block copolymer in [158]. However, it should be noted that this experiment tested the effect on soil only, finding an increase in soil moisture, but not on crop response.

A potentially promising category is water-based plant extracts, which can be made from crop residue. However, the costs of these are difficult to estimate, particularly for producing at a large scale. Producing these extracts on-farm implies a labor cost that may be impractical for many farmers, even if the source materials are essentially free.

Biochar also deserves mention in economic terms. Although its persistence in soil may allow benefits to accumulate over multiple years, studies showing improved plant available water often involve high application rates, making it likely to be among the more expensive amendment options at the field scale.

Two additional caveats should be kept in mind when interpreting the results of Table 3. First, the costs are calculated for a single application of each amendment without regard to the duration of its efficacy. Some may require multiple applications in a season (e.g., kaolin), while others may continue to have an effect for multiple years (e.g., pumice, zeolite, biochar). Second, these estimates do not include the cost of transportation and application, which could be significant, especially when large volumes of material are required (e.g., manure, biochar).

7. Environmental and Human Health Considerations

Environmental and human health considerations vary widely across drought adaptation amendments. In some cases, especially manure, biosolids, and surfactants, the literature identifies plausible direct pathways of human exposure through contaminants, water pollution, or contact with hazardous compounds. In other cases, the discussion is more indirect and centers on environmental co-benefits or risks, such as nutrient retention, heavy-metal mobility, greenhouse gas emissions, plastic residues, or persistence in soil. These considerations are addressed together because they stem from the same underlying question: what happens when drought adaptation amendments are introduced into agricultural environments, and what environmental or human-health implications may follow?

7.1. Organic Amendments

The principal use of manure as an agricultural amendment is not for its effect on soil moisture, but for its benefits to crop fertility and yield [233,234]. However, there are numerous environmental risks associated with its application due to the microbial, organic, and inorganic substances present in the material [235,236]. Manure and biosolids can include pathogenic microorganisms, heavy metals, antibiotics, hormones, and other classes of micropollutants [237–240]. These contaminants create clearer direct human-health pathways than for most amendment classes reviewed here, since exposure may occur through crop uptake, surface water contamination, or leaching to groundwater [241,242].

Organic mulch materials are the inverse of manure: their primary application is related to water conservation, but they can also confer benefits related to crop fertility, including increased cation exchange capacity, increased enzyme activity, and the presence of soil biota that improve nutrient availability [243]. However, there are minor risks to consider as well. Straw mulch and its leachate can produce phenolic acids with phytotoxic properties that inhibit crop growth [244]. Weed control via phytotoxicity can be a benefit of mulching [245,246], but it is important to understand how these materials affect the germination and growth of the intended crop [244,247]. The toxic effect of phenolic compounds may be ameliorated by arbuscular mycorrhizal fungi [248].

Yucca extracts also contain high amounts of phenolic compounds and saponins capable of inhibiting plant growth at high concentrations and have antimicrobial properties that could interfere with fungi or bacteria that might otherwise mitigate drought stress [52,249].

Biochar has numerous potential co-benefits alongside its effects on soil moisture, including carbon sequestration and increased nutrient-use efficiency. Improvements to crop production, however, are more pronounced in degraded soils than in healthy ones. There are also risks: certain feedstocks may contain heavy metals that impair soil health [250].

7.2. Fungal and Microbial Inoculants

Arbuscular mycorrhizal fungi can confer multiple benefits to crops in addition to potentially enhancing drought tolerance. These include enhanced tolerance to salinity and heavy-metal toxicity and improved nutrient uptake [251–253]. This review did not identify direct human-health risks associated with AMF inoculation.

Plant growth-promoting rhizobacteria can offer a similar array of benefits, including enhanced tolerance to a variety of stressors and increased nutrient uptake [254]. However, there are potential risks associated with these bacteria. Many of these microorganisms contain antibiotic resistance genes that could be transferred within soil ecosystems, contributing to the evolution of pathogens and therefore creating a plausible human-health concern as well as an ecological one [255,256]. They may also paradoxically disrupt plant growth by triggering defense mechanisms [257].

7.3. Minerals

For mineral amendments, the literature reviewed here is concerned mainly with environmental co-benefits and agronomic side effects rather than direct human-health risks. Reactive forms of silica, such as the amorphous silica found in diatomite, confer numerous benefits to soil health beyond the effect on soil water availability, including improved nutrient availability, growth of soil microbes, and increased carbon sequestration, while reducing the mobility of toxic metals, mitigating salinity stress, and reducing the abundance of pathogens [258]. Minerals that contain non-reactive silica, such as pumice, can also confer additional benefits, such as increased tolerance to salinity/sodicity stress and decreased crop uptake of heavy metals [130,259].

Some zeolites contain sodium ions that stress crops at high application rates but have been found in some instances to increase resilience to salt stress [260]. Other studies have reported improved growth and crop yield with zeolite addition in the absence of water stress [261], suggesting benefits related to nutrient availability and uptake rather than drought adaptation. Zeolites have also been found to reduce heavy metal toxicity and nutrient leaching [262].

7.4. Plastic Mulch

Despite benefits to crop production and water-use efficiency, plastic film is difficult to remove and its accumulation in the soil can impede water infiltration [263,264]. The persistence of macro- and microplastic residues in agricultural soils is therefore an environmental concern, and also raises broader concerns about human exposure through mulch-derived additives and microplastics in agricultural systems. Plastic film mulching has been linked to phthalate contamination and associated dietary-risk concerns, while mulch-film additives such as DEHP and BPA may migrate into soils and enter plant uptake pathways [265,266]. One study found that the presence of plastics impaired wheat growth, although this effect was mitigated by the presence of earthworms [267]. Use of plastic mulch has also been found to increase greenhouse gas emissions of crop production [268].

7.5. Surfactants

The use of surfactants can pose significant risks to the environment and human health. Due to their many industrial applications and extensive use, surfactants are discharged into the environment through wastewater, potentially harming ecosystems and contaminating water sources used for human consumption [269–272]. Anionic surfactants, which are predominantly linear alkylbenzene sulfonates, have been shown to cause biochemical and physiological effects in aquatic and terrestrial environments [273–275].

Several toxic effects of surfactants have been documented across microorganisms and other exposed organisms [270,272,275]. In general, surfactants can impair microbial growth and cellular function [270,273]. Nonylphenol ethoxylates and related degradation products are also widely recognized as contaminants of concern because of their endocrine-disrupting potential. Surfactants may also raise human-health concerns through contaminated water and other exposure pathways [270,275].

The formation of foam due to the presence of surfactants can degrade water quality by reducing the oxygen content of natural bodies of water. Surfactants can also affect the mobility and environmental behavior of other contaminants. Their occurrence, behavior, and treatment in environmental systems are complex and depend on processes including sorption and biodegradation [270,271].

7.6. Superabsorbent Polymers

The concerns associated with superabsorbent polymers are also primarily environmental, although their persistence may create broader exposure concerns. Superabsorbent polymers are widely used in hygiene and biomedical applications, construction, ecological remediation, and agriculture [276]. Most commercially available superabsorbent polymers are polyacrylate-, polymethacrylate-, and polyacrylamide-based [276]. Claims that composite SAPs are biodegradable or sustainable should be interpreted cautiously when the absorbent network still contains acrylic-based polymers, since reduced fossil content or the use of natural fillers is not the same as demonstrated biodegradation of the full material under soil conditions [277,278]. Although fully biodegradable alternatives are under development, most commercial SAPs remain acrylic-based, and many “bio-based” agricultural SAPs are composites rather than fully biodegradable substitutes [278]. The behavior of polymeric hydrogels in soil can vary with moisture dynamics, clay content, water quality, and temperature [279–281]. More broadly, degradation of polymer networks is complex and formulation dependent [282]. In the agricultural context reviewed here, the direct human-health implications of SAP residues are less clearly documented than the environmental concerns related to persistence and microplastic-like behavior.

8. Conclusions

This review has examined a wide range of substances that may function as drought adaptation amendments in agriculture. Taken together, the literature suggests that these materials are best understood not as a single category of input, but as a diverse set of interventions that act at different points in the soil–plant–atmosphere continuum. Their effects may arise through reduced soil evaporation, improved infiltration and water retention, improved rhizosphere and root access to retained water, modified canopy energy balance, or enhanced physiological tolerance to water deficit. At the same time, the evidence base is highly heterogeneous. Reported benefits include changes in soil moisture, plant available water, germination, growth, yield, water-use efficiency, and physiological stress indicators, and these outcomes do not always move together.

Various forms of organic matter, such as composted manure and biochar, can improve the availability of soil water, but often require large volumes of material to do so. These amendments may also confer important co-benefits to soil and crop health, although they may pose risks related to contaminants depending on source materials. Their apparent low cost must therefore be weighed against the volume of material required and the costs of transportation and application. Plant extracts are another intriguing avenue for future research and product development. Pure biosignaling molecules such as proline may be prohibitively expensive outside laboratory conditions, but natural alternatives such as ascorbic acid from orange juice concentrate, extracts made from crop residues, or direct application of plant materials such as *Opuntia* cactus appear more promising. These approaches may be especially relevant in small-scale or resource-constrained agricultural systems rather than highly mechanized systems dependent on external inputs.

Biological amendments, particularly arbuscular mycorrhizal fungi, emerge repeatedly in this review as promising candidates for further development. They can provide multiple agronomic benefits with comparatively limited identified risks and, in some cases, low apparent costs. However, their performance remains context-dependent, and a central limitation is the difficulty of linking experimental evidence to reliable commercial products containing the relevant species and strains. More research is needed to clarify their effectiveness across crops and environmental conditions and to develop clearer recommendations for application methods and rates. Silica-rich mineral amendments likewise appear promising in many contexts, often with relatively limited environmental or health concerns, although costs may be high. Foliar-applied kaolin stands out as a lower-cost mineral-based option that has shown promising results across many crops.

Synthetic amendments, including various surfactants and superabsorbent polymers, may be among the most effective materials for directly altering soil water dynamics, but they also raise some of the clearest environmental and human-health concerns discussed in this review. Their costs vary widely, and some can be produced relatively cheaply, but their risks complicate broad recommendations for agricultural use. Persistence is an especially important issue here, although its implications differ by material: persistence in soils may be a benefit for materials such as biochar or some mineral amendments, but a liability for plastic-based amendments whose residues may accumulate in the environment. Composite SAPs that incorporate agricultural waste materials may reduce reliance on fully synthetic inputs, but where acrylic-based polymers remain part of the absorbent network, these materials should not be assumed to eliminate concerns about plastic persistence or microplastic formation. In addition, many such materials remain experimental and are not yet commercially available on a meaningful scale.

Overall, this review does not identify a single amendment class that performs best across effectiveness, economic feasibility, and environmental and human-health considerations. Instead, it suggests that the most promising future directions lie in lower-cost, lower-risk materials, particularly those derived from biological and mineral sources. However, the strength of evidence remains uneven, and much of the literature is based on pot, greenhouse, or other controlled-environment studies rather than field trials. Future research should focus on identifying which amendments are most appropriate for particular soils, crops, and drought contexts, while paying closer attention to product composition, application rates, field-scale performance, and economic and environmental tradeoffs.

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