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REVIEW ARTICLE **OPEN ACCESS**

Does Soil Organic Matter *Matter* for Crop Productivity?

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Abstract:
Soil Organic Matter (SOM) is considered a vital component in soil-based agriculture. It is often used as an indicator of soil health and good soil management and is considered a prerequisite for sustainable plant productivity. However, these conclusions are not unequivocally borne out by evidence, especially from long-term field experiments such as the Magruder plots in Oklahoma, USA, where after more than 130 years of continuous wheat production without any fertilization, yields of 1 t/ha have been produced while soil organic matter declined from 4% to 1%. Furthermore, yields from soil-less production in advanced greenhouses have exceeded 600 t/ha/yr for tomato and up to 1000 t/ha/yr, compared to soil-based yields under 200 t/ha/yr. This is further evidence that soil and its various components are not prerequisites for high yields and maximal plant productivity. This narrative review will critically focus on the fate and role of SOM in crop production systems. The types of SOM, the effects of components such as humic materials, waxes, and organic amendments like composts, and the implications for soil health and the roles of soil microorganisms will be discussed. Physical properties of soils and agronomic practices, such as no-till, will be discussed in relation to SOM, and comparisons with soilless production will be evaluated to elucidate the role of SOM in crop productivity.

Keywords: Soil organic matter, Soilless production, Crop productivity, Soil waxes, Soil hydrophobicity.

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1. INTRODUCTION

Soil Organic Matter (SOM) consists of the non-living material derived from various organisms that exist in soil. The term SOM will be used in preference to the widely used term Soil Organic Carbon (SOC), to distinguish it from elemental carbon such as pyrogenic C that may be present in soils where fires have occurred [1] or from fossil sources. Some authors and institutions use a broader definition of SOM to include both non-living matter of organic origin and living organisms, such as microorganisms (eg bacteria, fungi), fauna (eg nematodes, worms, insects) and flora (eg plant roots) [2, 3]. The broader definition will be applied in this review, considering the interconnected and dynamic relationship between the two components. SOM can have around 58% SOC, but this can be variable depending on the soil and its environment [4, 5].

A growing view that current conventional farming has led to the loss of SOM and a consequent decline in the concept of ‘soil health’ has generated debate across the food supply chain and among all sectors of society. A narrative review of the various issues associated with SOM and its importance for crop productivity is presented.

An instructive starting point to examine this topic is the long-term agronomy trial plot observations. The best-known is the Magruder plot trial, started in 1892 by Alexander C. Magruder on the Oklahoma State University campus in Stillwater and still ongoing. In 2007, Girma *et* *al.* [6] reported that "Following 114 years of continuous winter wheat production under conventional tillage, the check plot that has never received any fertilizer addition continues to produce wheat grain yields of >1 Mg/ha, despite the decline in soil organic matter from 4 to 1%. " There have been changes in the genetics of the varieties planted, which may account for the yields, but this raises the question of the importance of SOM to productivity given the magnitude of the decline in SOM. A similar decline in SOM has also been reported in Oregon State University's Columbia Basin Agricultural Research Centre wheat/fallow trial established in 1931 [7].

2. METHODOLOGY

The main issues will be covered in the following numbered subject sections. The subject headings were selected based on accounts appearing in scientific literature, farming, industry, and trade publications, and media and web-based forums that discussed aspects of SOM, its role, and its contributions to plant productivity.

3. Types of SOM

As stated earlier, SOM would include all living and dead organic matter of plant, animal, and microbial origin. Differences in chemistry, particle size, distribution, origin, *etc* have been used in classification systems. Reviews of the various classifications of SOM can be found in several sources [1, 8, 9].

Lavallee *et al*. [10] proposed a size-based classification of SOM, a silt + clay (< 53 µm) fraction composed of Mineral-Associated Organic Carbon (MAOC) and a sand-sized particle (> 53 µm) fraction with particulate organic Carbon (POC) to demarcate components according to factors such as turnover rates, chemistry, *etc*. Mineral-associated organic carbon is predominantly composed of low-molecular-weight molecules of microbial origin. Particulate Organic Carbon (POC) is mainly composed of partially decomposed plant litter, roots and fungal-derived compounds and has a short turnover time. Pyrogenic organic carbon (PyOC) is what remains after combustion of organic material, usually due to fire. The occurrence of fires is common in Australia (and increasingly in regions such as California, Siberia, Amazon), and PyOC can represent a disproportionate amount of SOC compared to some regions of the world [1].

This review will also focus on less well-discussed components such as recalcitrant organic matter, particularly soil waxes and humic material including composts and humic acid, because of their effects on soils in agricultural ecosystems.

3.1. Soil Waxes

Soil waxes represent a small but important and less well recognised fraction of POC in SOM that can have a significant effect on soil wetting and water holding capacity, hence on soil productivity. In plants, a wax layer on vegetative parts minimizes water loss, protects against UV damage [11], provides a mechanical barrier to pests, *etc*. In Australia (and many climatically similar regions of the world), plants use this strategy to grow in hot and dry environments. Decay of plant material results in these waxes accumulating in soils, potentially leading to adverse properties such as hydrophobicity and dryness, which significantly reduces the capacity of the soil to support biological activity both above and below ground.

Octacosan-1-ol and β-diketones occur in Eucalyptus, legumes and most Poaceae grasses [12]. Ensikat *et al.* (2000) [13] identified two layers: an epicuticular wax outside the plant cuticle and an intra-cuticular layer embedded in the cuticle polymer. Long, odd-chain (> C_{25}) *n*-alkanes are characteristic of epicuticular leaf waxes [14, 15].

Schafer *et al*. [15] reported values from 30-80 mg/kg of *n*-alkanes, which are used as proxy markers for waxes, in samples from Central Europe. Wu *et al.* [16] reported values of 104–2279 mg/kg $C_{23–33}$ *n*-alkanes and 330–1200 mg/kg $C_{22–32}$ *n*-alkanoic acids in leaf litter from the Amazon floodplain along the eastern flank of the Andes. Deciduous forest sites are often dominated by the C_{27} *n*-alkane and C_{28} *n*-alkanoic acid. Conifers produce mainly C_{24} *n*-alkanoic acid. Grasslands are characterized by relatively high amounts of C_{31} and C_{33} *n*-alkanes and C_{32} and C_{34} *n*-alkanoic acids [15].

Microbial degradation of waxes does occur in soils, and [17] studied methods of estimating populations of wax-degrading soil microorganisms. However, waxes are not easily degraded and tend to accumulate in soils. This factor has profound implications for much-promoted practices such as the addition of large amounts of organic matter to improve soils, and as mulches, particularly in agricultural and home garden settings. Xu *et al*. [18] found that cuticular wax limited sorghum straw degradation and nutrient release rates in soil and also altered the microbial profile. According to [19], the wax layer accounts for approximately 1% *w*/w of wheat straw. Use of wax-rich vegetation such as Acacias, Eucalyptus, Pinus *etc* both as foliage in composts, straw in no-till farming and even bark chips as mulches, may not therefore have the desired effect of 'improving' soils, physically and biologically, due to the waxes and resins present.

Conversely, the aliphatic (hydrophobic) hexane-soluble fraction has also been associated with higher aggregate stability, reportedly due to protection of aggregates from water damage [20]. However, while aggregate stability may be enhanced, water-holding capacity and infiltration may be negatively affected.

3.2. Humic Materials

Following studies on the benefits of organic amendments for increasing SOC and Cation Exchange Capacity (CEC), ways to implement economic solutions were investigated [21]. The use of organic amendments, such as farmyard manure, *etc*., requires the addition of large quantities of material. Humic Material (HM) represented a high-C-content resource that could be applied at much lower rates, in the range of 100-300 kg/ha, compared to 50-200+ t/ha of organic material such as farmyard manure (FYM). From around the 1990s to the present, commercial humate products such as Humic Acid (HA) and fulvic acid have been widely promoted and used. However, treatment of a natural product like organic matter or even lignite coal with alkali and acid to obtain humic fractions can reduce biological value in terms of protein and carbohydrate content, and microbial activity; however, some properties like chelating, buffering, and hormone-like effects may be retained. Hence, the contribution of any humic extract to soil health can only be minimal and is therefore no substitute for naturally formed humus. Kussow [22] was sceptical about the benefits of humic extracts to increase CEC in turf, showing that at the rate recommended, the increase in CEC was only marginal and also costly. Lyons and Genc [23], in a critical review, cited the lack of evidence from field studies (rather than controlled conditions) to justify the heavy promotion and use of commercial humates.

Further, the addition of HM was constrained by the dispersive effect of humic components when rates exceeded 0.1 g/kg soil [24], due to high-molecular-weight aromatic and aliphatic polycarboxylic acids [25]. Therefore, high levels of humic acids can lead to dispersive soils, associated with cracking and increased susceptibility to erosion.

Some beneficial effects, though, have been reported under special conditions. Alsudays *et al.* [26] observed an increase in the tolerance of barley plants to salinity stress when the soil was treated with humic acid, for indices such as number of spikes/plant, 1000-grain weight, grain yield/ha, harvest index, uptake of N, P and K in straw and grain. HM's ability to adsorb harmful substances, such as salts and pesticides, has also been reported [21]. This, however, can have both positive (adsorption of salts and toxins) and negative effects (reduce efficacy of soil-applied pesticides). Nunes *et al.* [27] concluded that Humic acid influenced root architecture in maize and the production of antioxidants, such as peroxidase and glutathione, suggesting that its main role was protective.

3.3. Composts & Manures

Composts are of plant origin, while manures are of animal origin. Few environmental topics elicit a more emotional response than the practice of converting agricultural waste and domestic materials to compost. The process of domestic and commercial composting is considered a sign of environmental stewardship across urban centres.

Organic waste in Australian landfills accounts for about 13 million tonnes of greenhouse gas emissions (carbon dioxide equivalent) or approximately 2.5% of Australia's total annual emissions [28]. Methane generation from organic matter in landfills is also a major concern. Composting has been suggested as a partial solution to these environmental issues. As a waste management strategy, small-scale composting saves local councils the costs of managing landfills. Outsourcing part of it to residents can minimise waste-collection costs. However, there is little data on the quality of the compost produced, the environmental implications, such as heavy metal content, odour, vermin, and pathogens, and the impacts composts have on any crops produced using it.

The University of Minnesota, USA, one of the premier institutions that has done much to develop and promote composting technology, has advised caution when too much compost is used, as it can cause problems for the health of plants and the environment. In an extension note [29], stated that practices like deep compost mulch and growing in raised beds with pure compost have created problems for growers, and they also advise against relying on compost as the primary or only soil-building strategy. Nutrient imbalances and increasing soil alkalinity and salinity are some of the problems they have observed.

Martinez-Blanco *et al.* [30] reviewed compost life cycle analyses and concluded that data were available to support the benefits from a nutrient supply and carbon sequestration angle; however, quantitative data were insufficient to support claims such as pest and disease suppression, weed suppression, soil workability, biodiversity, crop nutritional quality, and crop yield, as well as the benefits on soil erosion and soil moisture based on impact assessment methodologies.

4. FATE OF SOM

Most agricultural soil environments are strongly oxidative, meaning that any organic matter will be decomposed by soil organisms at a rate largely dependent on temperature [31]. Other factors, such as soil moisture content, N status, and the absence of toxic chemicals like heavy metals, pesticide residues, and salinity, also play a significant role in decomposition rates. Decomposition represents the recycling of nutrients absorbed during plant growth, often accompanied by an increase in soil microbial biomass. Depending on the availability of SOM, this process can fluctuate. The process involves a reduction in the complexity and size of organic molecules along with the release (loss) of C in the form of CO_2 [32, 33].

In anaerobic environments like impounded rice paddies, marshes, peat bogs, *etc*., organic matter is retained for much longer periods, and degradation is usually a process of particle-size breakdown (comminution) and slow chemical reactions. Soil is acidic (pH<4.5) due to the presence of organic acids, and decomposition mostly involves reduction reactions [34, 35, 36]. Methane can account for a significant part of the release of soil carbon in flooded rice paddies [37, 38]. Sulphur-oxidising bacteria are also active in such anaerobic soils provided S is present, and this property is used to acidify soils to enable cultivation of low pH preference crops like blueberry [39].

In contrast to the complete decomposition process, there is also a partial process, referred to as humification, in which the end product is humus, a material characterised as resistant to further degradation. These can be complex molecules such as lignins and complex polysaccharides. The presence of humus and similar resistant material has been recognised as a key component of the concept of a 'good soil' due to its postulated structural stability, ability to increase soil water-holding capacity, and provision of habitat for soil microorganisms.

5. SOIL HEALTH

SOM has been used as a major indicator of soil health. The term ‘Soil Health’ has become a catch-all phrase to imply what a ‘healthy’ soil should be. To some, it is the colour of the soil: dark is associated with ‘rich’, usually implying fertility and the ability to support plant growth in its natural state without intervention. The ‘capacity of soil to produce’ was proposed by [40], while [41] considered “the continued capacity of soil to function as a vital living system” as a measure of soil health. The USDA criteria are similar to [41] and focus on the presence of the living component of SOM, with the rhizosphere and ‘living roots’ being a key component [42], while FAO (UN Food and Agriculture Organization) states that Soil Health indicators are ‘nutrient availability, workability, oxygen availability to roots, *etc*’ [43]. Presence of visible life such as fungi (mushrooms), worms and some insect stages like maggots are favourably perceived by home gardeners. Therefore, a universal definition of soil health is difficult to state as it is quite subjective. The suggestion that SOC < 2% leads to a decline in soil's ability to sustain crops and affects crop response to fertiliser [44] has been debated [45].

Microbial diversity is a factor that has become associated with soil health and SOM status. The advancement of analytical tools, such as rapid DNA sequencing, has provided substantial eDNA data but with so few interpretive tools [46]. Perhaps such an interpretation requires more time to understand and assign roles to the variety of organisms that the DNA predicts to exist, their relationship with SOM, and their roles in the agroecosystem. The presence of plant pathogenic organisms must also be acknowledged when discussing SOM, as infected plant material is a common source of these yield-impacting microorganisms.

To take advantage of the increased interest in SOM-based products to improve crop productivity, a range of microbial products, living cells, extracts, fermentation products, *etc*., have been promoted by the farming input sector, which has made various claims, such as disease resistance, growth stimulation, nutrient solubilisation, and biological control of pathogens, to name some of the attributes targeted by their products [47]. It is beyond the scope of this review to evaluate all claims, but the evidence suggests that these organisms/products are sometimes effective in a laboratory setting but perform unpredictably in the field and therefore currently do not meet the requirements for a consistent, reliable intervention. Possible reasons for this are, firstly, the inability of the introduced organism to compete/thrive among the existing diversity of microorganisms in the soil; secondly, the inability to adapt to the physico-chemical properties of the soil; and thirdly, the effects of plant root exudates that may or may not be conducive to the introduced microorganism.

6. BENEFICIAL SOIL MICROORGANISMS

The microbial component of SOM has been implicated in processes vital for crop productivity such as soil fertility and nutrient cycling, decomposition and mineralisation of organic matter, as sources of plant growth promoters and as antagonists for pathogenic microorganisms [48]. Examples of such microbial genera that have been found in a variety of soils are *Azospirillum, Bacillus, Burkholderia, Flavobacterium, Methylobacterium, Paenibacillus, Pseudomonas, Rhizobium, Serratia, Staphylococcus* [47, 49]. *Azotobacter*, *Nitrosomonas*, and *Nitrobacter* are important for the N cycle in soils. Use of symbiotic N-fixation is a widespread strategy in agriculture, and increasingly, free-living and endosymbiont N-fixing microorganisms, such as Gluconacetobacter diazotrophicus and Azotobacter salinestris CECT 9690 [50], are commercially available as inputs to supplement N nutrition. In addition to their functional roles, the microbial mass also contributes to the amount of SOM. The plant-fungal association known as Arbuscular Mycorrhizal Fungi (AMF) is a well-documented example of an endophytic component of SOM involved in water and mineral absorption and, hence, contributing to crop productivity [51].

7. SOIL PHYSICAL PROPERTIES

The physical properties of soil for good crop productivity are many, with soil structure and water-holding capacities being the more critical. Soil structure, as measured by the stability of aggregates, is a good measure. Improved soil aggregation is associated with high SOM [52, 53]. However, the positive relationship between aggregate stability and SOM is logarithmic and a defined threshold value may not exist [45].

Soil structure has long been associated with aggregate stability, and microbial secretions and components of organic matter such as polysaccharides are reported to be critical contributors [54]. The role of roots, particularly grass roots, was found to be significant for aggregate stability [55], suggesting a role for root exudates, as well as for the networks of fine roots, root hairs, and mycelia, in binding soil particles. In sandy soils, possibly because of particle size, mechanical support from mainly roots and possibly mycelia plays a greater role in aggregation, whereas in finer clayey soils, root and microbial exudates contribute to particle binding. Tisdall and Oades [52] noted that aggregate stability is greatest under grass (compared to non-grass).

Aggregate stability is a better metric for evaluating the effects of soil amendments than just analytical levels of SOC. Comparison of a range of organic amendments including barley straw, sewage sludge and poultry manure showed that SOC increased in sewage sludge and poultry manure treatments, but barley straw improved aggregate stability more than the other amendments (increase by 59% compared with 23% for sludge and manure) and had the greatest effect on total soil polysaccharide content, infiltration rate and respiration rate [56]. Long-term (38-year) experiments in Sweden where peat was an input did not result in an improvement in aggregate stability, even though SOC increased [57]. Therefore, increasing SOC does not always result in improvement of soil physical properties; other attributes such as the presence of polysaccharides and humic substances are also important [58].

8. AGRONOMY AND SOM

Many agronomic factors are affected by SOM. The role of microorganisms in nutrient cycles is discussed later. Wang *et al*. [59] studied the effect of increasing SOM content (ranging from 2.0, 2.8 and 3.7% w/w) on rice and reported that yield and fertiliser N retention improved in the 28 and 37 g/kg soils. However, this relationship between yield and SOM is not linear, with diminishing returns above a certain level of SOM [60]. For Maize in the US, yield plateaued at ~4% SOM [61]. King *et al*. [62] discussed the various agronomic traits reported to be influenced by SOM. They concluded that the historically ascribed roles of SOM as sources of water and N were inadequate to explain improved plant performance, that improvements in soil water-holding capacity were marginal and restricted to the surface layers, and that SOM can lead to improvements in root performance by mediating better soil aeration and mitigating compaction. The living component of SOM, in the form of deep-rooted cover crop roots, created root channels in the soil [63] that improve the movement of water into and through soil layers and enhance aeration for subsequent crops.

The converse process, in which agronomic practices influence SOM levels, is also of practical importance. Reduced or no-till agriculture is becoming widespread because of claims that SOM is conserved and will increase under this practice [64]. Tillage damages soil aggregates and exposes SOC pools with mean persistence times of decades to active pools with mean times of only weeks [65]. However, this view is contested by evidence that the increase in SOC is limited to the top 30 cm under no-till, whereas layers below 30 cm have higher SOC under conventional tillage [66], thereby suggesting that no-till only affects the distribution of SOC. This problem can also be due to long-term practice of leaving whole plant parts on the ground, and to the effects of a combine harvester with straw shakers in field crops like wheat and corn. Roper *et al*. [67] concluded that many years of contrasting management practices did not consistently result in different amounts of SOM for some soils. Powlson *et al.* [68] also observed that no-till improves soil agronomic properties but not necessarily raises SOM. Other factors such as temperature, rainfall, and topography also influence the persistence of SOM, a process that depends on the equilibrium between soil and its environment.

Long-term studies have also shed light on the SOM/productivity relationship. Ohio State University/Ohio Agricultural Research and Development Centre studies on tillage effects in long-term trials begun in 1962 showed that yields of corn, soybeans, and oats under no-tillage have been similar to or higher than those under ploughed soils. Other long-term studies have corroborated these results (*e.g.*, the University of Kentucky's "Spindletop" Agricultural Experiment Station on wheat since 1970; a 33-year study on no-till soybean/wheat at the INTA Experiment Station, Marcos Juárez, Córdoba, Argentina [7]).

The above reports show that minimum tillage practices are adopted widely and have benefits for productivity while not necessarily increasing SOM, thereby providing evidence of only a tenuous link between SOM and productivity.

9. SOM & WATER HOLDING CAPACITY

It is a widely held view, and even seems intuitive, that a high SOM soil can hold more water and therefore be better for agriculture and crop productivity. Higher infiltration, aggregate formation leading to higher pore volume, voids left after decomposition, *etc* have been cited as possible reasons. According to [69], an increase of 1% SOM can add 1.5% additional moisture by volume at Field Capacity (FC). However, this is not always the case, and the contribution of SOM to WHC can be variable [45]. Rawls *et al*. [70] attributed these variations to differences in pore size and matric potential associated with soil texture. Sandy soil WHC increased most from an increase in SOM, while silty and clayey soils less so. Fine-textured soils showed a greater increase in WHC at FC than at Permanent Wilting Point (PWP), whereas for coarse-textured soils, a larger increase in WHC was observed at PWP. It is also important to avoid confounding the water held by SOM with water plants can absorb from soil pores, not just what is referred to as 'plant available water' – the distinction is nuanced, as absorbing water from tightly held organic matrices can be energetically unfavourable for plant roots.

A meta-analysis [71] concluded that an increase in SOC in soil had only a small effect on soil water content. A 1% increase in SOC mass increased available water capacity by 1.16% volumetrically. Libhova *et al*. [72] reported a similar relationship: a 1% increase in SOM content increased WHC, on average, up to 1.5% of its weight, depending on soil texture and clay mineralogy. Kane *et al*. [73] argued that SOM provided yield resilience in maize in the US corn belt and that an increase of 1% SOM was associated with a yield increase of 2.2 ± 0.33 Mg ha^{-1}; however, their path analysis showed SOM to be only weakly associated with available water capacity.

Overall, the relationship between SOM and WHC is strongly influenced by soil texture, with sandy soils benefiting from increasing amounts of SOM. However, the relationship is not linear, and soils will reach a stage when further additions of organic matter will have no effect on WHC.

10. SOM & NUTRIENT SUPPLY

Essential plant nutrients are a significant contribution of SOM, as mentioned earlier. Cell death, lysis, and degradation release nutrients such as N, P, K, and other inorganic essential nutrients from both dead and living material, providing a future source; this process is referred to as the mineralisation of organic matter. In some scenarios, decaying organic matter can provide significant amounts of nutrients, a good example being the K released from rice straw added to rice fields [74], with rice straw enabling a significant reduction in added inorganic K fertiliser [75].

The role of SOM in supporting a range of beneficial microorganisms involved in the supply of inorganic plant nutrients is of increasing interest. These microorganisms help fix atmospheric N and solubilise locked-up nutrients, to name two processes. Fixation of N by free-living soil microorganisms such as *Azotobacter* and *Nitrosomonas* is a critical process in the N cycle.

Perhaps the best-known example of soil/root/microorganism interaction is N fixation, involving a variety of both symbiotic and free-living microorganisms. Microorganisms involved in nitrification are discussed [76]. *Nitrosomonas, Nitrobacter* and *Azotobacter* are free-living soil bacteria that oxidize N in stages, eventually to nitrates, while the bacterium *Nitrospira* can perform the complete oxidation of ammonia to nitrate [77]. The microaerobe *Gluconacetobacter diazotrophicus* is an endosymbiont in root interstitial spaces of the root cortex that is also mobile in the plant and moves from the site of inoculation/colonisation to other parts [78, 79]. *Azotobacter salinestris* strain CECT 9690 behaves similarly [50]. The fixed N is released into the plant usually after lysis of bacterial cells.

These organisms contribute N, which is vital for plant growth. While N-fixation is hugely beneficial to global N supply, its role in agricultural productivity is limited to some species such as those in the Fabaceae, which form symbiotic associations with *Rhizobium* species. The value of this symbiosis is in the savings from N fertiliser cost, which is partially offset by the N fixed. The amount of N fixed by *Azotobacter* has been estimated at 20 kg N/ha/yr [80], which can partially offset crop N requirements. Agricultural N fixation is estimated to provide around 15% of the global N supply [81].

Tian *et al.* [82] described the role of P-solubilising microorganisms in the soil P-cycle, citing the roles played by organisms such as *Chryseobacterium meningosepticum*, the cyanobacterium *Microcystis aeruginosa* and their ability to produce alkaline phosphatases, phytase-producing yeasts such as *Pichia acacia* and *Candida argentea* that release P from phytic acid in addition to the well-known P-solubilising bacterial genera such as *Bacillus* sp., *Pseudomonas* sp., and fungi such as *Penicillium* sp., *Aspergillus* sp., *Mucor* sp., and *Rhizopus* species. Some AMF such as *Rhizophagus irregularis*, *Glomus aggregatum*, and *Glomus mosseae* have also been reported to solubilise P [83, 84].

A factor that is important for the supply of nutrients from SOM to a crop is synchrony between the rate of supply (decomposition) and the needs of the crop according to its growth stages. This synchrony is affected by a range of environmental factors (eg temperature), the composition of the organic material and the presence of appropriate microorganisms. While SOM can be included in a nutrient budget, synchrony may not always occur, hence the need to allow for discrepancies in the rates of decomposition and hence nutrient supply.

A summary of the effects of SOM on different soil properties is given in Table **1**.

Table 1. Effect of SOM on some physical properties.

Water Holding Capacity	Structure/Aggregate Stability	Nutrient Supply	Infiltration Rate
Increases within a range of SOM, particularly for sandy soils	Improved if SOM is rich in soil-binding polysaccharides	Increased, but rate of nutrient supply variable	Increased

11. SOIL-LESS PLANT PRODUCTION

An objective measure of the role of SOM on plant productivity is the performance under soil and soilless crop production. Soilless production systems function without any equivalent to SOM in the nutrient medium, yet have proven to outyield soil-based production, often by a significant margin. Ferguson [85] obtained 2-4-fold yield increases in greenhouse tomato between soil and soilless systems.

Fussy and Papenbrock [86] compared soil and soilless production of a range of crops and concluded that yields were comparable or mostly higher in soilless systems. The average crop yield per plant (and total yield) was higher in the crops grown in aeroponic systems as compared to those grown in the field [87], though no details on the field-grown crops were provided. An average increase of about 19%, 8%, 65%, and 21% in yield was recorded in basil, chard, red kale, and parsley (leafy vegetables) when grown in aeroponic systems. Similarly, an average increase of about 53%, 35%, 7%, and 50% in yield was recorded in bell pepper, cherry tomatoes, cucumber, and squash (fruit crops), respectively, when grown in aeroponic systems as compared to those plants grown in soil [87]. Ranawade *et al.* [88] reported yields of spinach under aquaponic production of 4455 Kg/acre, hydroponically of 3780 Kg/acre and traditionally field-cultivated spinach of 1615 Kg/acre, indicating that yields were 2-3x higher under soilless production. Even for research trials [89], found that wheat can be grown more effectively in a hydroponics system in the greenhouse than in pots with soil, to evaluate yield and yield components in a breeding program.

One of the common criticisms of soilless production is the effect on quality indices. Treftz and Omaye [90] noted that while dry weight values were similar between soil and soilless media for Strawberry, Brix, ascorbic acid, tocopherol, and total polyphenolic compounds were significantly higher in soilless strawberries compared to soil-grown strawberries. However, for Raspberry, ascorbic acid and total polyphenolic compounds were significantly higher in soil-grown raspberries by 83% and 67%, respectively, compared to soilless-grown raspberries.

The yield advantage of soilless systems is a significant factor in the debate on the role of SOM in productivity of soil-based systems. Economic (capital costs) and environmental (heavy energy dependence) factors are key considerations in the productivity debate in which SOM does not have a role. A study on Lettuce [91] found that hydroponics produced 11 times higher yields, required 12 times less water, but required 82 times more energy than conventionally produced lettuce. Another major advantage of soilless systems is the absence or the possibility of minimising effects of pests and diseases, which are major constraints on crop productivity. In contrast, soils are reservoirs of pathogenic organisms, which are often favoured by the presence of SOM.

12. DISCUSSION

SOM is a vital part of soil systems, contributing to the productivity of soil-grown crops. However, the greater productivity of soilless systems is evidence that SOM is not a critical requirement for crop productivity. Its role in soil-based crop productivity is complex, influencing soil properties such as CEC and WHC, as a source of mineral nutrients and growth regulators, while providing a conducive environment for growth and multiplication of beneficial soil microorganisms. Claims that SOM ensures yield stability are conditional, not universal [73]. However, long-term studies do not support a vital role for SOM, as yields have remained stable while SOM has declined significantly. Observations from the Magruder Plots that a 1% level of SOM gave a stable yield suggest that this may be a ‘sufficient’ rate. The widely held view that there are thresholds for minimum levels of SOM (usually below 1%) has been countered by [45]. Loss of soil structure at very low SOM (<0.5%) is perhaps the main factor that can reduce soil-based crop productivity, while also leading to erosion and land degradation. A SOM threshold therefore becomes relevant in a land stability context [92]. However, while a correlation is hard to establish, SOM levels and crop productivity seem to follow their own ‘mostly-independent’ trends, though positive, saturating relationships for many crops have been reported [60, 61] over a narrow (1-4%) range of SOM.

One practical issue with using SOM as a main or supplementary nutrient source is its unpredictable decomposition rate. Plants grow in distinct phases, broadly from seedling to vegetative, then reproductive and post-reproductive (eg fruit ripening/grain filling), and nutrient needs vary accordingly. The requirement for N during vegetative phases is well recognised, as is the need for K and B during flowering and fruit set, *etc*. Any deficiency of required nutrients retards these growth phases. However, the rate of SOM decomposition and the associated nutrient release may not coincide with plant growth phases, and this asynchrony can affect growth and yield. Hence, any dependence on SOM for nutrients is risky and can have real impacts on crop productivity [93]. A nutrition program independent of any contribution from SOM is a sounder strategy for crop productivity in commercial agriculture.

Desert soils are an example of low SOM environments, and attempts to re-green deserts and rehabilitate industrial sites have involved addition of organic material. SOM may have a role in ‘restoring’ these soils to a state where the essential processes that support biological activity can occur sustainably [94]. Addition of organic matter is a slow and costly strategy to manage SOM. Use of HA and such humic extracts, though widely promoted, has not been demonstrated satisfactorily to provide consistent, measurable benefits for growers. The high propensity for oxidation of organic matter is the main hurdle in management of SOM, particularly in the tropics.

Also, addition of large amounts of organic matter are required to effect small changes in SOM. Importantly, there is also the need to incorporate the material into the soil to realise the benefits to the soil, as well as to slow its rate of oxidation. SOM also declined with land clearing and any form of cultivation [95], which emphasises the dynamic nature of the relationship.

Whether continuous addition of plant organic matter can lead to increasing water repellence of soils has to be validated by experiment. Addition of leaf organic matter to soil also adds cuticular waxes, which can coat soil particles. Mulches like bark have oils and resins at levels of 1-2% [96], which can cause hydrophobicity of soils. They are slow to breakdown and can lead to lower rates of infiltration and hence lower soil moisture at deeper levels. Surface flow can be enhanced, leading to run-off loss of water and soil erosion.

Beneficial organisms like N-fixers and AMF provide tangible contributions to plant productivity, enhancing nutrient supply, absorption of water and nutrients, and secretion of growth regulators in the root zone. Comparison of soil and soilless cultivation is only useful to demonstrate that SOM is not an absolute requirement for productivity in soilless cultivation but that it does have an indirect benefit in soil-based cultivation. Extension of N-fixing interventions in pumice and perlite hydroponic systems for beans [97] to other systems like NFT or aeroponics, as well as use of endosymbionts like *Azotobacter salinestris* CECT 9690 [50], can reduce input costs and become a significant economic & environmental contributor to crop productivity.

CONCLUSION

SOM seems to play only an indirect role in crop productivity. However, the indirect effects of SOM on overall environmental processes such as decomposition and nutrient cycling, its effects on physical properties of soils that give it structure, stability and strength to resist environmental forces such as wind and water, and provide an environment that supports other organisms, from microorganisms in the soil to vegetation that ultimately replenishes SOM, cannot be underestimated for soil-based growing systems. This makes SOM vital for environmental sustainability. By extension, soil-based crop production, which depends on environmental sustainability for its practice and productivity, derives some direct and mostly indirect benefits from a sufficient level of organic matter in the soil.

AUTHOR'S CONTRIBUTION

The author confirms sole responsibility for the following: study conception and design, data collection, analysis and interpretation of results, and manuscript preparation.

LIST OF ABBREVIATIONS

SOM	=	Soil Organic Matter
SOC	=	Soil Organic Carbon
CEC	=	Cation Exchange Capacity
USDA	=	United States Dept of Agriculture
FAO	=	Food and Agriculture Organization
AMF	=	Arbuscular Mycorrhizal Fungi
WHC	=	Water Holding Capacity
FC	=	Field Capacity
HA	=	Humic Acid
HM	=	Humic Material

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CONFLICT OF INTEREST

The authors declare no conflict of interest, financial or otherwise.

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