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The use of soil amendments in crop production: a review

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ABSTRACT

The fertility status of the Namibian soils is very low. In some parts of the country, such as the semi-arid Central Namibia, this phenomenon is much more extreme and, hence, a significant setback for crop growers. The soils are primarily sandy and lack organic matter, further worsened by low precipitation, high temperatures, and high evapotranspiration rates. This paper provides a background on soil amendments, including the two primary ways of categorising them based on the origin and the composition of the material(s) forming the amendments. Secondly, it offers a historical overview of the general agricultural use of soil amendments. Lastly, the paper discusses different soil amendments currently used and their effects on the fertility and productivity of agricultural soils. It is recommended that the effectiveness and the optimal application ratios of locally available soil amendments for crop production be studied.

1. Introduction

As the human population increases, there is a growing pressure to increase food production to meet the increasing demand. In Namibia, the challenge to increase crop for food production is further amplified by different environmental factors, including poor sandy soils, low rainfall and high evapotranspiration rates, as a result of climate change (Ministry of Environment and Tourism [MET], 2019; Watanabe et al., 2019).

Worldwide, the use of different soil amendments (both soil conditioners and fertilisers), such as compost, biochar, horn meal, bone meal, and animal manure, is being promoted to mitigate these environmental challenges faced in crop production (Cataldo et al., 2021; Laghari et al., 2016; Şeker & Manirakiza, 2020). Shinde, Sarkar, and Thombare (2019) defined soil conditioners as materials with limited amounts of nutrients but are beneficial to the soil's physical, biological and chemical nature. On the other hand, fertilisers can be defined as any synthetic or organic materials typically applied to soils to supply nutrient(s) essential for plant growth (Trembley, 1973). The different soil amendments can be classified based on the origin and composition of the materials from which they are made. Amendments can either be synthetic or naturally occurring in origin and can either be organic or inorganic in composition (Shinde et al., 2019). Organic soil amendments such as compost, manure, bone meal, biochar, and crop residues are derived from living things by-products. In contrast, inorganic soil amendment materials are either mined or by-products of manufacturing, which include lime, zeolites, gypsum and hydrogel polymers (Shinde et al., 2019).

Practices involving soil amendments, especially organic ones, can be traced back to 2000 BC and have been commonly attributed to successful sustainable farming in countries like Japan, China, and Korea over the centuries. The materials used at the time, usually composted, included animal manures, wood ashes, green manures, crop residues, canal mud, tree leaves, aquatic weeds, wild grasses and urban sewage (Parr & Hornick, 1992). In Namibia, field experiments on the effectiveness of soil amendments are minimal. Most of the published work is only recommendations based on general knowledge (Kahler, 2014; Mupambwa, Hausiku, Nciizah, & Dube, 2019; Zimmermann, Matzopoulos, & Kwaambwa, 2017) and based on chemical characteristics study of amendments(Katakula, Gawanab, Itanna, & Mupambwa, 2020). This paper aimed to provide an overview of the use of soil amendments in crop production, including discussing different soil amendments that could be used in Namibia and the benefits derived from their application.

2. Amendments and soil quality

Both soil conditioners and fertilisers generally affect the health/fertility of the soils' physical, biological, and chemical health, broadly impacting soil quality and crop production**;** therefore, a combination of soil conditioners and fertilisers is needed for healthy soil. Soil health is "the capacity of soil to function as a vital living system to sustain biological productivity, promote environmental quality, and maintain plant and animal health" (Urra, Alkorta, & Garbisu, 2019). Sustaining and improving soil health is a significant challenge in soil management (Bonilla, Gutiérrez-Barranquero, De Vicente, & Cazorla, 2012), especially given the reliance on synthetic fertilisers. Applying soil conditioners and organic fertilisers can be of utmost importance in addressing this challenge (Sulok et al., 2021). **Error! Reference source not found.** illustrates different components of soil health.

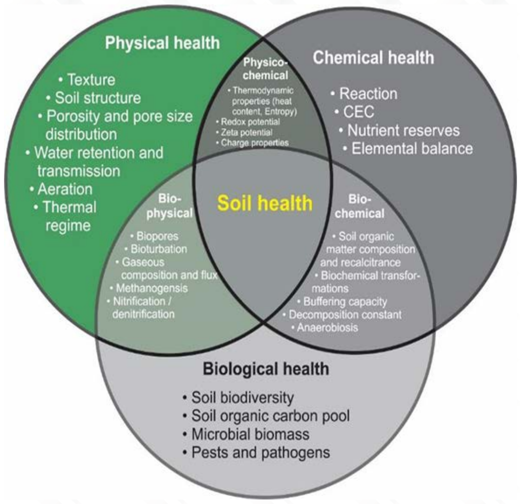

Figure 1 Components of soil health. Adapted from Isaacs (2023).

2.1 Physical soil health

One of the most critical factors to consider in maintaining the appropriate soil structure is aggregate stability, which, with the use of soil amendments, can be controlled by improving pore space necessary for good water retention, gas exchange and microbial activities in the soil (De Roy, Ghosh, Barman, & Dutta, 2016). Soils with good aggregate stability, structure, bulk density, porosity and hydraulic conductivity create a conducive environment for better retention and movement of water and nutrients, resulting in better root growth and, ultimately, higher crop yields (Toková, Igaz, Horák, & Aydin, 2020). In addition, the incorporation of soil amendments with organic matter content (OMC), especially in sandy soils, also improves the soil particle size distribution and surface area, thereby increasing water holding capacity (Bhadha, Capasso, Khatiwada, Swanson, & LaBorde, 2017; Urra et al., 2019).

2.2 Biological soil health

Biological health is another crucial aspect of crop production, which the addition of soil amendments can influence. Soil amendment application can create a conducive environment for microorganisms, such as bacteria, actinomycetes, fungi, protozoa, nematodes, microalgae (De Roy et al., 2016) and earthworms (Shinde et al., 2019), which are essential for organic matter decomposition and nutrient recycling in the soil. The availability of microorganisms as a result of soil amendment can also indirectly improve soil structure due to microbial activities, which reportedly influence soil aggregate stability (Urra et al., 2019).

2.3 Chemical soil health

In addition to Physical and biological health, the application of soil amendments also influences the soil's chemical health, which primarily relates to soil organic carbon (OC) and cation exchange capacity (CEC) (De Roy et al., 2016). Other chemical soil health indicators include macro and micronutrients, OM and pH (Urra et al., 2019). The chemical health status of the soil interrelates with the soil's biological composition. For instance, higher availability of nutrients and growth substrates may also impact soil microbial diversity and composition by improving microbial activities and the ecological interactions between organisms (Tian et al., 2017, as cited in Urra et al., 2019). Likewise, the microbial composition influences the nutritional status of the soil. In a natural ecosphere, most nutrients such as N, P and S are not readily available to plants; thus, soil microorganisms, such as bacteria and fungi, play a crucial role in decomposing and mineralising organic molecules into simple forms of N, P and S, that plants can access (Jacoby, Peukert, Succurro, Koprivova, & Kopriva, 2017).

3. Different soil amendments for possible application in Namibia

3.1 Biochar

Biochar can sequester carbon into the soil for sustainable and improved crop production (Abdrabbo, Hashem, Abul-Soud, Abd-Elrahman, 2015; Zhang et al., 2016). Soil carbon plays a vital role in the soil ecosystem by improving soil structure and water retention whilst also reducing atmospheric carbon dioxide (CO_2) (Zhang et al., 2016). Biochar's effectiveness in crop production is widely documented (Alburquerque et al., 2013; Vitkova, Kondrlova, Rodny, Surda, & Horak, 2017). For instance, a study by Abdulrahman, Al-Wazzan, and Al-Jawadi (2020) investigating the effects of biochar on soil moisture content and maize production has found a significant positive effect on maize grain yield and volumetric water content by 1.75 t ha^{-1} and 10.24% respectively, compared to the control. The increase in yield can be attributed to the effect biochar is reported to have on the soil's physical, chemical and biological properties (Hossain et al., 2020; Laghari et al., 2016; Sun & Lu, 2014). On physical properties, biochar application can improve the soil aggregate stability, bulk density, porosity, pH, and cation exchange capacity (CEC) (Laghari et al., 2016). In addition, a study by Saha, Galagedara, Thomas, Nadeem, and Hawboldt (2020) investigating the influence of biochar on the physico-chemical properties of podzolic soil, the application of powder biochar to the topsoil was found to increase porosity by up to 1.6%, compared to the control. In the same experiment, when granular biochar was used, porosity decreased by 3.1% compared to the control. Furthermore, Sun and Lu (2014) reported the application of wastewater-sludge biochar (WSB) to have improved soil aggregate stability by 31%, compared to the control and other two biochar types: woodchip biochar (WCB) and straw biochar (SB). The authors also found SB biochar to have improved soil water retention capacity (up to 18.4% greater, compared to the control), while pore space improvement was 29% for SB, 12% for WCB, and 16% for WSB, respectively. Moreover, according to Widowati, Sutoyo, Karamina, and Fikrinda (2020), biochar constitutes elements that behave as liming agents for acidic soils, such as potassium, magnesium, phosphorus and calcium.

Equally important, biochar also impacts soil microbial community composition (Xu et al., 2014) and microbial biomass carbon (Liu et al., 2016). Xu et al. (2014) report that applying biochar increased the diversity of soil microbes, including those related to carbon and nitrogen cycling in the soil. In addition, in their study on biochar, Liu et al. (2016) found it to have significantly improved the soil microbial biomass carbon (MBC) content by 18%.

3.2 Zeolites

A Swedish mineralist, Alex Fredrik Crönstedt, was the first Scientist to identify a natural mineral zeolite in 1756 after sampling different crystal stones from a copper mine in Sweden. After experimenting with these mineral stones by heating them immediately after soaking them in water, he discovered that they produced vast amounts of water vapour and, as a result, referred to these stones as zeolites, meaning "boiling stones" in Greek, "zeo", boiling and "lithos", stones (Cataldo et al., 2021; Jakkula & Wani, 2018). After numerous explorations by geologists, it became clear that most of the natural zeolites are deposits of volcanic activities and deposits from marine sediments (Cataldo et al., 2021). Zeolites have diverse applications, including industrial gas separation, waste-water and drinking water treatment, agriculture (crop and animal production), aquaculture, and odour control (Jakkula & Wani, 2018). For agricultural purposes, zeolites can be utilised as heavy metal remover, slow-release fertilisers, and soil conditioners to improve water and nutrient use efficiency, soil hydro-physical properties and crop yield (Jakkula & Wani, 2018). More than 50 natural zeolite types have been revealed to date, including Clinoptilolite, mordenite, analcite, phillipsite, erionite, chabazite (Cataldo et al., 2021), heulandite, laumontite, wairakite (Mumpton, n.d.).

Zeolites improve soil hydro-physical properties, including particle density, bulk density, soil porosity, aeration and water-holding capacity

(Jakkula & Wani, 2018; Mondal et al., 2021). They can hold water more than half of their weight for prolonged periods due to the high porosity of their crystalline structure and can increase crop available water by up to 50% (Kalita, Bora, & Gogoi, 2020). In addition, zeolites are mainly effective under drought and sandy soil conditions (Hazrati et al., 2017). Jakkula and Wani (2018) reported that zeolites improved spinach (*Spinacia oleracea*) seed germination and yield when applied with synthetic fertilisers. Similarly, Kavoosi (2007) reported that zeolite application significantly increased rice grain yield. The author, however, noted that increasing the zeolite application without increasing N fertiliser decreased rice grain yield. Moreover, a field study by Hazrati, Khurizadeh, and Sadeghi (2022) studying the effect of zeolite on water and nitrogen use efficiency as well as oil yield and quality of sage (*Salvia officinalis)* under water deficit stress, results indicated that zeolite overwhelmingly improved fresh and dry weight, N use efficiency, N total uptake (kg N ha^{-1}), soil N (nitrogen residue), oil content and yield. The authors also found that the interaction of nitrogen and zeolite considerably impacted water use efficiency. Generally, nitrogen application affects water use efficiency positively (Duan et al., 2014; Hussain & Al-Jaloud, 1995; Rahimi, Sayadi, Dashti, & Tajabadi, 2013).

In Namibia, zeolites have thus far been confirmed to be found in the Kunene region. Besides the Kunene region, they could also be found along the South-Eastern and North-Western parts of the country where the geological requirements of zeolite deposits have been discovered (Kahler, 2014).

3.3 Hydrogels

Hydrogels are cross-linked polymers containing a hydrophilic group capable of absorbing a large amount of water without dissolving in water (Kalhapure, Kumar, Singh, & Pandey, 2016). Hydrogel polymers are also called superabsorbent polymers (SAP) and can be categorised into two major groups based on their origin: natural- and synthetic-based polymers. Polymers from naturally occurring materials are environmentally friendly and harmless to the human body compared to synthetic materials; however, synthetic materials are more effective due to their superior mechanical properties (Oladosu et al., 2022). Generally, SAPs can potentially absorb water up to 500-600 times their weight by forming gels (Narjary et al., 2013).

The use of hydrogels is specifically effective under dry climates and sandy soil as they can improve the structure and hydro-physical properties of the soil, such as permeability, water retention, infiltration rate, and drainage (Grabowska-Polanowska et al., 2021). Other essential aspects of hydrogels are the increased water holding capacity, microbial activity, aeration and water use efficiency, and reducing soil erosion and water stress, enhancing crop production (Narjary, Aggarwal, Kumar, & Meena, 2013). A study by Rajanna, G Manna, Singh, Babu, and Singh (2022) looking at the effects of hydrogels on crop and water productivity of soybean–wheat system in the water-stressed Indo-Gangetic plains of India showed that a pusa hydrogel (P- hydrogel; a semi-synthetic cellulose product) recorded the highest soybean seed and biomass yields (1.22–1.37 Mg ha^{-1} and 4.9–5.4 Mg ha^{-1}, respectively, over two years), compared to the control and a kaoline derivative of a pusa hydrogel (K-hydrogel; also a semi-synthetic cellulose product). The P-hydrogel also improved wheat grain and biomass yield by 3.0–15.0 and 2.0–6.0%, respectively, compared with the control. A significant effect on water productivity (WP) and irrigation water productivity (IWP) by P- hydrogel was only recorded in the second year of the study.

3.4 Compost, bone meal, animal manure, etc. (Organic fertilisers)

Organic fertilisers are some of the most preferred soil amendments, not only due to their natural nutritional content and positive impact on soil health, but they are also more environmentally friendly than synthetic fertilisers. Their application on crop production helps solve waste management problems while increasing food production. The most essential characteristic of organic fertilisers is their organic matter content, which not only improves soil nutrition but also the soil structure and, ultimately, soil water storage (Terleev et al., 2018). Healthy soil typically contains at least 2.5% organic matter (Yasmin, Khan, & Billah, 2018). Table 1 presents the role and effects of organic matter on soil.

Table 1 Role of organic matter in soil (Amlinger et al., 2007)

Property	Remarks	Effects on Soil
Colour	The typical dark colour of soils is often an indication of organic matter.	It may facilitate warming during spring and summer.
Soil biodiversity	The organic composition in soils nurtures a wide variety of organisms. The	Many functions associated with soil organic matter are related to soil

	composition of the organic materials influences the diversity of the organisms in the soil.	flora and fauna activities.
Water Retention	OM can hold up to 20 times its weight in water.	It helps minimise drying, shrinking and leaching. It may significantly improve the moisture-retaining properties of sandy soils. Increasing water supply may not necessarily increase the available water content except in sandy soils.
Combination with clay minerals	Promote soil aggregation.	Allow gas exchange. Improve aggregate stability. Increases permeability.
bulk density of mineral Soils	Naturally, organic materials have a low density because they are lighter; hence, their addition 'dilutes' the mineral soil.	Increases porosity.
Chelation	Forms stable complexes with Cu^{2+}, Mn^{2+} and Zn^{2+} and other polyvalent cations.	It could increase the availability of micronutrients to higher plants.
Solubility in water	Compositions of OM and clay are insoluble. Combinations of divalent and trivalent cations with OM are not soluble. Isolated organic matter is partially water soluble.	Little organic matter is lost through leaching.
Buffer action	OM regulates soil pH in slightly acidic, neutral and alkaline ranges.	It helps to keep uniform reactions in the soil.
Cation exchange	Total acidities of isolated fractions of organic matter range from 300 to 1400 $cmol_c$ Kg^{-1}	This may increase the CEC of the soil. In many soils, 20 to 70% of the CEC is related to organic matter.
Mineralisation	Mineralisation of OM yields CO_2, NH^{4-}, NO_3^-, PO_3^{4-} and SO_2^{4-}.	It is a source of macro and micro-nutrients for plant use.
Stabilisation of contaminants	Stabilisation of organic materials in humic substances, including volatile organic compounds.	Stability is influenced by the consistency of the soil humus and the amount of carbon within the soil.

Several studies on the use of organic materials indicate that organic fertilisers positively impact soil health and crop yield (Nogalska, 2021; Watanabe et al., 2019). For instance, Watanabe et al. (2019) reported an increased soil organic content (SOC), total soil N, available P, and exchangeable K by 1.7, 1.5, 1.3, and 2.1 times when 62 Mg ha^{-1} of cattle manure was applied in their experiment on the use of cattle manure and intercropping. However, in the same study, cowpea's grain and biomass yields were higher under 31 Mg ha^{-1} than 62 Mg ha^{-1} of cattle manure. These results imply that the over-application of organic fertilisers can have a negative impact on crop yield.

In a different study using bone meal (BM), Nogalska (2021) observed that the application of BM improved maise, wheat and rape yield. Generally, BM contains 8 % N, 5 % P, 1% K and 10% Ca (Asare, 2019; Yasmin et al., 2018). Naturally, BM has a narrow N:P ratio, meaning an insufficient amount of BM results in an N deficit. In contrast, a high amount leads to excessive accumulation of P in the soil (Nogalska, 2021). This is probably so because BM application reduces soil pH (Nogalska, 2021), leading to more available P in the soil. Composted BM is reported to be more effective than powder BM (Yasmin et al., 2018).
Moreover, composts usually contain a range of macro and micro-nutrients and impact the soil's physical, biological and chemical properties such as pH, CEC, porosity and water holding capacity (Abbott et al., 2018). Şeker and Manirakiza's (2020) study showed that compost positively impacted SOM, soil density, particle density, soil total porosity, water retention and soil aggregate stability when added to sandy clay loam soil.

Despite the benefits offered by using organic fertilisers, there are areas of concern as well. For example, Urra et al. (2019) stress some serious adverse effects that applying organic materials can pose, such as harbouring human pathogens, heavy metals, organic pollutants, and some emerging contaminants (including micro-plastics). In addition, Aytenew and Bore (2020) also note that the overapplication of organic fertilisers may also result in eutrophication (an excess of nutrients in the soil), which results in water contamination. Therefore, there is a need to follow the guidelines on using organic fertilisers, such as those discussed by the (Namibian Organic Association [NOA], 2020), to avoid environmental and soil ecosystem degradation.

4. Conclusion

Many research activities have been done around the globe on applying soil amendments (soil conditioners and organic fertilisers) in crop production. However, these efforts are lacking in Namibia, making it challenging to acquire crucial information to improve crop productivity locally. Therefore, research studies are needed in Namibia to scientifically determine the effectiveness and optimal application ratios of locally available soil amendments for crop production. Global research indicates that the use of soil amendments positively impacts soil health (physical, chemical and biological health). Soil conditioners, such as biochar, zeolites and hydrogel polymers, primarily can improve the soils' structures, water and nutrient dynamics and microbial activities. However, they must be supplemented with synthetic or organic fertilisers due to limited macro elements. The knowledge of the classification of soil amendments is also valuable for crop growers, especially those venturing into organic farming where only applying organic soil amendments (conditioners and fertilisers) is acceptable. Organic soil amendments are those derived explicitly from living organisms (e.g. compost, bone meal, manure). Materials from mining activities and manufacturing by-products are inorganic (e.g. zeolite, lime, gypsum). Organic soil amendments are abundant in nutritional content and positively impact the soils' structure, water dynamics and microbial activities; however, over-application can harm humans and the environment, including eutrophication. Therefore, there is a need to follow the guidelines for using organic fertilisers, as with synthetic fertilisers, to avoid environmental and soil ecosystem degradation.

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