

REVIEW

Open Access



The role of organic and inorganic soil amendments on soil physicochemical properties and wheat (*Triticum aestivum* L.) agronomic performance in Semi-arid North-Central Namibia: A Review

Anna Maria Haufiku^{1*}, Petrus Ausiku Ausiku¹ and Sanna Huttunen²

*Correspondence:

Anna Maria Haufiku
annamariahaufiku5@gmail.com
¹Department of Crop Production & Agricultural Technologies, University of Namibia, Windhoek, Namibia
²Biodiversity Unit, University of Turku, Turku, Finland

Abstract

Poor soil fertility in semi-arid and arid regions has been identified as a major challenge affecting agricultural productivity, leading to poverty and low food security among smallholder farmers. Soil amendments, especially organic, have gained popularity in recent years because they improve soil fertility, reduce greenhouse gas emissions and improve crop production. In Namibia, wheat is an important cereal crop that substantially contributes to developing the agricultural sector and improving farm household food security, particularly. The literature review was undertaken to assess the effects of soil amendments on soil physical and chemical properties, wheat growth, and yield across various agro-climatic conditions, with a particular emphasis on evaluating the potential of biochar and compost to enhance wheat production in the semi-arid Namibia. Most of the literature search with keywords "soil amendments, biochar, compost, soil fertility, soil management, sustainable agriculture, wheat, semi-arid" was conducted on online databases such as Google Scholar, Wiley, Scopus, and Science Direct (mostly with the range of years from 2010 to 2024). The selection of scientific articles was based on title, abstract and content. Based on published research articles, the conversion of locally available feedstocks, such as crop residues, forest biomass, and kitchen and animal wastes, into organic soil amendments like biochar, compost and vermicompost may also be necessary in smallholder farming systems. Additionally, biochar use may have applications in tree nursery production and speciality-crop management. Thus, biochar can make a substantial contribution to sustainable agriculture. The review concluded that organic soil amendments can be effective components of chemical fertilizers, contributing to lower nutrient losses in the soil and reducing environmental impacts in a sustainable manner.

Keywords Semi-arid, Food security, Sustainable agriculture, Soil amendments, Biochar, Compost



© The Author(s) 2025. **Open Access** This article is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License, which permits any non-commercial use, sharing, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if you modified the licensed material. You do not have permission under this licence to share adapted material derived from this article or parts of it. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by-nc-nd/4.0/>.

1 Introduction

Soil degradation is recognized as one of the factors contributing to stagnant productivity growth and low crop yields, often linked to continuous cultivation, nutrient depletion, decline of soil organic matter, and imbalances, and the overuse of chemical fertilizers [1, 2]. In addition, changes in climatic patterns significantly challenge agricultural productivity particularly in semi-arid and arid zones [3–5]. Poor land practice leads to high soil nutrient depletion, a major issue that affects food security while increasing production costs and lowering farm income [5–7].

Small holder farmers across Sub-Saharan Africa, often experience low productivity due to low and erratic rainfall, reliance on traditional cultivation methods, insufficient nutrient application and low input use [8]. Many tropical and sub-tropical soils depend heavily on nutrient recycling through organic matter inputs to maintain fertility, but this is often inadequate. Overuse of chemical fertilizers without proper soil management has led to long-term soil quality decline in several regions [9]. As a result, there is growing interest in sustainable soil fertility management practices, such as the use of compost, manure, and biochar, which offer promising alternatives to improve soil health, restore fertility, and enhance crop yields in a more resilient and environmentally friendly manner [7, 10].

In many parts of Africa, the adoption of inorganic fertilizer is considered low in Africa [11] due to high costs, limited or untimely availability of the input and inadequate farmer agronomic knowledge [11]. Inorganic fertilizers have played a significant role in increasing crop production since the Green Revolution. However, long-term overuse of mineral fertilizers may accelerate soil acidification, causing soil erosion at some points affecting both the soil biota and biochemical processes, thus posing environmental risk and decreasing crop production [12]. There is a need for more sustainable solutions to sustain crop yields. In order to address these challenges, it is essential to transition from the reliance on chemical fertilizers to the incorporation of organic fertilizers [13, 14].

Maintaining sufficient soil organic matter and ensuring efficient nutrient cycling in the soil are fundamental to sustainable soil management and agricultural production. The techniques for incorporating soil amendments into the soil are designed to enhance the agronomic use efficiency of the given nutrients and boost crop yield [15]. Soil amendments involve the application of both organic and inorganic fertilizers and knowing how to tailor these practices to local conditions. The natural mineralization of organic matter limits the use of organic fertilizer in tropical regions. Co-composed biochar products have gained attention and being recognized for their role in the carbon sequestration, soil fertility improvement and mitigation of greenhouse gas emissions, especially in acidic or saline soils [4].

Agronomic yield is greatly affected by the quality of the soil. The increase in population, limited agricultural resources and climate variability threatens food and nutritional security in the world, particularly in developing countries. Therefore, ensuring sustainable agronomic methods and enhancing production is essential for increasing the food supply. This article aims to review the potential for increasing wheat production in arid and semi-arid regions of Namibia and Africa by using compost and biochar as amendments. Soil organic matter is crucial in maintaining soil productivity and mitigating the effects of uncertain climate conditions. Adding organic wastes can enhance soil organic

carbon, which helps retain water and nutrients, improves soil structure, and supports soil biota [3, 16].

1.1 Global wheat importance

Wheat species are believed to have originated in various localities in the area adjoining southern Turkey, Iraq, and in some areas of Iran and Syria [17, 18]. From its original domestication, wheat cultivation spread to eastward into Asia and westwards across the Mediterranean countries and European [19]. Globally, wheat is one of the key staple crops for food security [19, 20]. Currently, wheat cultivation is widespread due to its economic value and nutritional importance, especially in the world’s drought-prone and semi-arid tropical regions [21]. On average, wheat provides roughly 21% of the daily dietary protein intake making it the leading protein source among cereal crops [22, 23]. Wheat contributes to total cereal consumption, and constitutes approximately 41% of the caloric intake and 50% of the proteins [19]. Wheat grains are nutritionally rich consisting mainly 70% carbohydrate, 11.5%, 1.5% ash, protein 8–15%, 2% fat, 2% fibre, and 13% water [24–26]. In milling wheat flour, the pericarp and germ, which are rich in protein, are removed from the grain, and the resulting flour is less nutritious than the whole grain. Unlike other cereal crops, wheat is mainly a food rather than a feed crop. After processing, it is usually consumed directly in the form of a flour product [27].

Wheat grows in temperate regions worldwide, which are climatically more suitable for cultivation. It requires specific climatic conditions for successful cultivation. In the tropics, wheat is grown at higher altitudes or in areas with suitable conditions in the lowlands. It is grown only during the winter season in the tropics and subtropics. Wheat can be grown successfully under various rainfall conditions with an optimum temperature of 4–35 °C [28].

1.1.1 Global wheat production

As a central food crop, wheat plays a vital role in sustaining global food and nutrition security [29]. Its production spans vast agricultural landscapes, from the plains of North America to the steppes of Russia and the fertile fields of India and China. On the production front (Fig. 1), the global wheat production volume reached almost 785

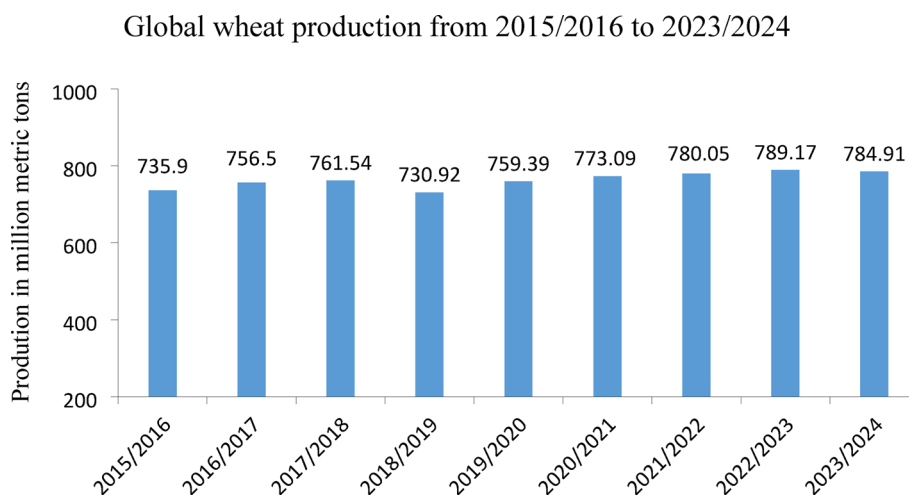


Fig. 1 Global wheat production from 2015–2024. (Source: fas.usda.gov/data/production)

million metric tons, with an estimated production area of 220.7 million hectares [30, 31]. Major wheat producers include China, which contributes 134.3 million tons per year; India, with 109.6 million tons; Russia, contributing 76.1 million tons; and countries in the North America and European Union, which together account for most of the global output. Other producers, such as Ukraine, Australia, Pakistan, Argentina, and several European countries, contribute substantially to global wheat production [31]. These countries have advanced agricultural techniques, including mechanization, irrigation, and improved seed varieties, to enhance yields and meet increasing demand.

1.1.2 Wheat consumption worldwide

Regarding consumption (Fig. 2), it forms a substantial part in diets worldwide, particularly in areas where it serves as a staple food crop. Wheat consumption has increased gradually globally from 2018/2019 to 2023/2024, rising from 735.31 to 796.44 million metric tons. Population growth, and urbanization trends, and dietary shifts towards processed foods are the primary drivers of increasing global wheat demand. The top consumers remain China, Europe, India, Russia, and the United States [32].

1.1.3 Global wheat trade

Global trade in wheat further underscores its importance, with surplus-producing countries exporting to deficit regions, ensuring food security and price stability on international markets [30]. As populations grow and incomes rise, particularly in developing countries, the demand for wheat is expected to continue its upward trajectory, necessitating sustained investment in agricultural infrastructure and research to meet future needs in a sustainable manner. Thus, the future of global wheat production and consumption hinges on innovation, resilience, and strategic international cooperation to ensure food security and economic stability worldwide.

1.2 Status of wheat production in Africa

During the 2020/2021 season, wheat was cultivated on an estimated area of 10.1 million hectares, producing approximately 25.7 million metric tons [33, 34]. The majority of wheat production in Africa comes from northern regions, which contribute over 60%

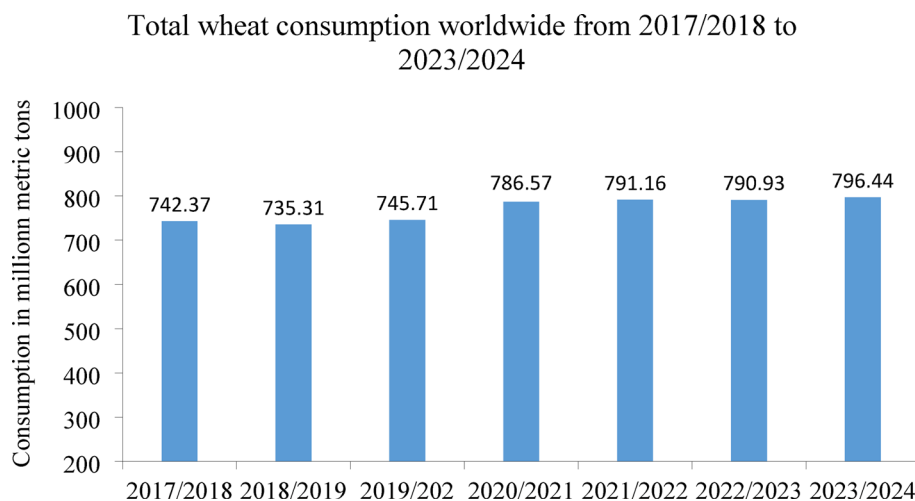


Fig. 2 Total wheat consumption worldwide from 2017–2024. (Source: Statista)

of African wheat production [35]. Countries such as Ethiopia, Kenya, Tanzania, South Africa, and Uganda are among the leading wheat producers in Africa. These nations benefit from varying degrees of suitable climatic conditions, irrigation infrastructure, and government support for agriculture [35]. Wheat is a significant dietary staple in many African countries, particularly in North Africa and those with urbanized populations. It ranks first in terms of per capita consumption and accounts for approximately 30% of cereal consumption on the continent [35, 36]. The crop cultivation in Africa varies significantly depending on climate, soil conditions, and agricultural practices in different regions. Wheat is consumed in various forms, including bread, pasta, couscous, and other traditional dishes. The demand for wheat in Africa is growing at a rate of 2.6% per annum [27, 35]. Despite the importance of wheat in addressing food insecurity issues and serving as an input for agro-industries, the continent imports a high amount of wheat each year to bridge the widening gap between consumption and production [35, 37]. In 2021, Africa imported close to 46.5 million tons, which decreased to 44.0 million tons in 2022 [38].

1.3 Current wheat production and consumption in Sub-Saharan Africa

Sub-Saharan Africa (SSA) contributes nearly 30% of Africa's wheat cultivation area and production [20]. In SSA, Ethiopia is the largest wheat producer [20], with an average annual production of 5.2 million tons on an average area of 1.8 million hectares from 2018 to 2021 [39, 40]. South Africa is the second-largest producer, with an average annual wheat production of 1.9 million tonnes per hectare from 2018 to 2021 [20], covering an area of 519,000 hectares [41]. In Sudan during 2018–2021, about 0.70 tons were produced annually on an average production area of 292,991 hectares [38]. Kenya has grown wheat on 134,689 hectares, achieving an average production level of 2.5 to 3.2 tons per hectare [42, 43]. The total wheat production countries, such as Zambia, Uganda, Mozambique, Rwanda, Namibia, Niger, Lesotho, Angola, Botswana, Malawi, and Cameroon, for the period of 2018–2021 is minimal, ranging from 165,954 tons in Zambia to 567 tons in Cameroon [35]. Wheat consumption has been highest in Northern Africa and lowest in West and Central Africa. However, the gap between production and consumption has widened in all African regions over the past years [35].

1.4 Wheat production and consumption in Namibia

In Namibia, wheat is the main winter cereal grain and ranks second after maize in terms of consumption [44]. The crop is planted during winter (May to mid-June) and harvested annually from October to January [45]. It is mainly produced under irrigation in Kavango, Karstland, Central, and South production areas. Small portions are produced at irrigation farms in the Maize Triangle [45, 46]. During the 2020/2021 planting season, a total area of 1,806 hectares was cultivated, with Hardap distinguishing itself as the leader in total hectares planted, at 1,200 hectares. Kavango followed this with 402 hectares, Karst with 168 hectares, and Central with 37 hectares [47, 48]. The average yield per hectare of wheat in the country is 3.8 metric tons per hectare [45]. The most significant portion of wheat production occurs at the commercial level under irrigation, primarily in the Hardap and Kavango regions, with an estimated cultivation area of approximately 4,286 hectares and a corresponding yield of 5.7 tonnes per hectare [48]. In 2022/2023, Namibia produced 24,696 metric tons per hectare from 19,117 metric tons in 2021 [49].

The growth of the plant depends on temperature, as it needs a certain amount of heat to progress through different stages of development [50]. The optimum temperature range for wheat growth and development ranges from 17 to 25 °C with a minimum and maximum of 0 and 37 °C [51, 52]. In North-Central Namibia, where most of smallholder farmers reside [53], the adoption of wheat cultivation remains low despite the favourable agronomic conditions. The areas experience moderate winter temperatures during May–August, ranging from 7 to 25 °C, which are suitable for growing winter wheat. These cooler months provide an ideal thermal environment for wheat growth and development, particularly during the vegetative and reproductive stages. Moreover, the mean monthly temperatures in northern central Namibia range from about 11 °C in winter to 25 °C in summer [54], for grain development, the optimal temperature ranges between 12 °C and 22 °C [55] which is ideal for wheat. The high temperature affects the phenology, growth, development, and productivity of wheat in tropical, subtropical, arid, and semi-arid regions worldwide [56]. Furthermore, seasonal rainfall and the increasing availability of supplementary irrigation from small-scale water infrastructures could support wheat production.

Soil chemical properties in northern central Namibia varied widely from sandy to loamy sand [57]. The characteristics of the sandy soils in the area are supported by others [58–62], which, with proper soil fertility management, can provide suitable drainage and fertility conditions required for wheat. These soils are generally low in organic matter but can be improved through integrated soil fertility practices like the addition of compost, manure, biochar and many others. Numerous methods have been devised to improve the retention of moisture and nutrients in these soils, thereby ensuring optimal wheat productivity in sandy soils [63, 64]. The application of biochar has been demonstrated to enhance the hydro-physical characteristics of sandy soil, thereby supporting water conservation efforts in arid and semi-arid regions [65]. Most of the soils in these regions are slightly alkaline, with a pH ranging from 7.1 to 8.5 [60] and well drained, which aligns well with wheat tolerance. There are fewer studies about the relationship between wheat yield and soil properties [66]. Therefore, with appropriate agronomic support, wheat cultivation holds significant potential for diversification and food security in North-Central Namibia.

Because domestic production is insufficient; Namibia relies heavily on wheat imports to meet its national demand [67]. Only 10% of domestic production is done commercially in irrigation schemes. Thus, Namibia remains a net importer of wheat grain from countries such as Russia, Poland, and its neighbouring South Africa, and imports cover approximately 90% of its wheat requirement annually [45]. The country imports raw grains and processed wheat products such as flour, pasta, snacks, and cereals. The imports are essential for Namibia's food security, ensuring a steady supply of wheat-based products. From 2010 to 2021, Namibia imported 1,090,409 tons of wheat valued at N\$ 6,172,227,432.23. A total of 112,020 tons of wheat were produced locally during the review period from 2010 to 2021 (Fig. 3). The most significant wheat production was recorded during the 2012/2013 season at 14,819 tons [47, 68], and production has declined significantly over the years. Therefore, this presents an opportunity for increased local wheat production in Namibia. Factors attributed to low wheat production in Namibia include high production costs, poor, infertile sandy soils, and unfavourable climatic conditions.

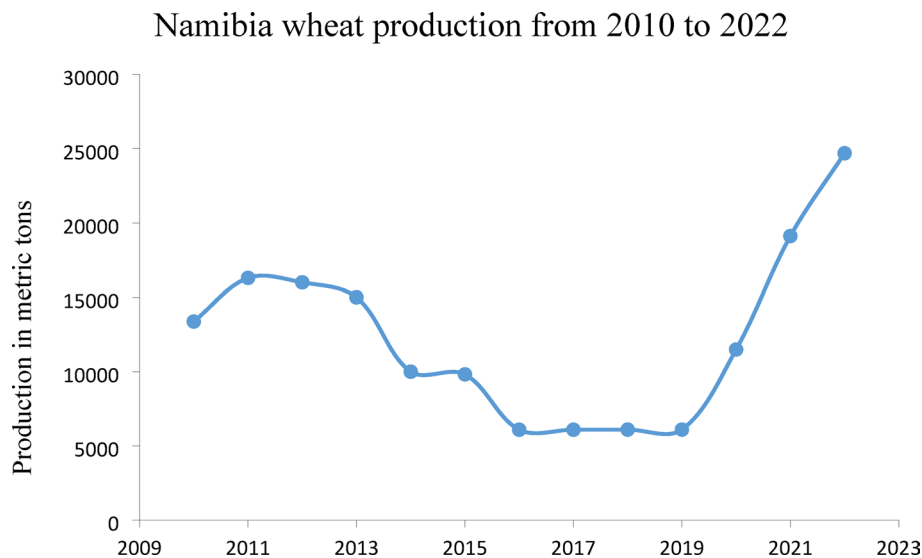


Fig. 3 Namibia wheat production from 2010–2023. (Source: FAOSTAT)

In Namibia, wheat consumption is exceedingly high, nearly matching that of pearl millet, which serves as a staple food for over 60% of the population [69]. Recent figures indicate that Namibia's total domestic wheat demand is 137,000 tonnes per annum, with 90–92% of this being imported [47]. Figure 3 indicates a huge deficit and the opportunity to increase locally produced wheat volumes, thereby enhancing household and national food security. According to the production and statistics for the 2019/2020 financial year, the total domestic demand for wheat grain amounts to 118,824 tonnes per annum [68]. Although Namibia has a potential to produce more wheat, yields are limited by several factors, including insufficient soil fertility, drought, inefficient application of organic and mineral fertilizers, and inadequate agronomic practices. Addressing the low adoption of wheat cultivation, particularly in small-scale agricultural communities, is essential to unlocking Namibia's potential for fully increasing wheat output. Therefore, improved seeds that are better suited to semi-arid and arid regions, along with fertilizers, water availability, and training, are essential for enhancing local wheat production.

Farmers should adopt wheat cultivation which is far less dependent on rainfall and thus more resilient in the face of severe drought. Climate variability represents one of the predominant factors influencing wheat production on a global scale, and Namibia exemplifies this phenomenon. Namibia should engage in research trials involving various wheat varieties to identify those that exhibit superior performance in the Namibian climate [46]. However, there is a notable lack of peer-reviewed scientific literature on these topics in the Namibian context, which underscores the urgent need for locally driven research. These studies would support the development of sustainable agronomic practices tailored to Namibia's environmental conditions, thereby enhancing productivity and long-term soil health.

2 Challenges to wheat production in the semi-arid regions

2.1 Abiotic and biotic stresses

Numerous abiotic and biotic stresses at different levels in rainfed and irrigation environments worldwide limit wheat production. Climate change is making sustainable food

production more challenging, and its consequences are predicted to be comparatively greater in semi-arid and arid regions than in any other areas [69]. The increasing incidence of rising temperatures (heat) and low and irregular dry periods increases the risk of drought stress on crops, which also affects wheat yield and quality. When associated with highly infectious pests and diseases, climate change also reduces the predictability of agriculture. In rain-fed environments, the most significant abiotic stresses are drought, soil acidity, erosion, low soil fertility, waterlogging, and pre-harvest sprouting. High temperatures during wheat's reproductive stages are linked to climate change and significantly reduce grain quality and yield. These effects are primarily caused by shorter developmental stages, lower biomass, early leaf senescence, and unfavourable physiological and biochemical changes [70].

Weeds, insects, and diseases are the three main biotic constraints affecting wheat production in the SSA, causing a significant loss. As evidenced by the recent epidemics, new diseases and pests are expected to arise due to the current effects of climate change. Russian wheat aphids and wheat stem sawflies are the two insects that harm wheat crops the most economically in Sub-Saharan Africa [20].

2.2 Limited availability of resources and other inputs

Subsistence farmers in Sub-Saharan Africa, facing low productivity due to limited availability and affordability of agricultural inputs including fertilizers, pesticides, improved seeds, water, and equipment [71–73]. Many regions have poor soil quality, which limits wheat productivity unless proper soil management practices are implemented. The cost of fertilizer is increasing over time in farming communities. In addition, indirect increases in transportation costs are contributing to this trend. The inability of farmers to obtain financing, roads, and transportation further limits their access to fertilizers, seeds, and agrochemicals at the right moment. The cost of installing irrigation and water availability restrict the potential to increase wheat production in irrigated areas.

3 Organic soil amendments in improving soil productivity and fertility

Organic farming is one of the fastest-growing agricultural sectors in the world driven in part by the increased use of organic amendments like compost, biochar, and vermicompost which improve soil health and long-term agroecosystem sustainability [74, 75]. A variety of organic amendments are applied to agricultural soils, including animal-based inputs such as manure, plant-based materials like compost and vermicompost, microbial-based products such as compost teas, and carbon-rich substances like biochar [5]. These organic amendments provide nutrients for sustainable agricultural production, and when combined with soil microorganisms, they may help to enhance the soil's structure and, consequently, the plant's environment. Applications of compost-derived materials are attracting research interest, although they are not widely adopted in cropping systems. However, most organic soil amendment formulations have received relatively less scientific scrutiny compared to inorganic fertilizers [76]. Organic amendments such as biochar and compost could serve as a sustainable way to enhance growth and productivity in drought-stressed environments [77]. Compared to inorganic amendments,

organic amendments have been shown in numerous studies to offer several benefits. The application of organic amendments in the highlands of central Ethiopia has significantly enhanced soil fertility and barley yield [78]. In order to increase SOC levels and improve soil fertility, compost and biochar have been suggested as the best soil amendments [78].

3.1 Biochar technology in wheat production

Biochar is a soil amendment produced from organic feedstocks that has recently attracted considerable attention due to its unique properties compared to other organic soil conditioners [5, 79]. It is a carbon-rich product obtained by heating agricultural residues, green waste, seaweed, animal manure, and woody biomass in an oxygen-limited conditions [16, 80–83]. Biochar is an organic material characterised by its resistance to decomposition [32] and stabilises through chemical interactions, thereby limiting its spatial accessibility to soil microorganisms [5]. This thermal process, which produces biochar, removes a significant amount of oxygen, resulting in a blackened material primarily composed of carbon. Studies indicated that biochar remains more stable in soils than amendments such as compost or manure, sometimes up to several centuries [78]. Evidence from the literature also reported that animal-sourced biochar, such as manure, can supply nutrients to plants more than agricultural residue and forest biomass-derived biochar [84, 85].

Current research highlights biochar as a promising soil amendment capable of improving agricultural productivity and contributing to long-term soil sustainability [83]. Due to its stability and carbon sequestration potential, biochar has increasingly been recognized as a tool for mitigating greenhouse gas emissions [79, 86–88]. Incorporated biochar can sequester carbon from the atmosphere–biosphere pool and transfer it to the soil. Biochar is an effective tool to combat climate change. Organic materials release greenhouse gases, including carbon dioxide, into the atmosphere during decomposition. A significant portion of carbon is converted into a more stable form through heating of the organic material, and the carbon is effectively sequestered when biochar is applied to soils, because biochar is highly stable. Accordingly, this process is estimated to lower global carbon emissions by over 10% [88]. Thus, biochar can be applied as a stand-alone amendment or in blended products, such as biochar–compost blends, serving as a strategy for greenhouse gas mitigation [3].

When incorporated into soils, biochar positively impacts both physical and chemical characteristics, by improving porosity, water retention, aeration and nutrient retention due to its high cation exchange capacity and surface area [89, 90]. Furthermore, its alkaline nature contributes to pH buffering, mitigating soil acidity and influencing microbial activity and nutrient availability [91, 92]. Although biochar is responsible for altering soil physical, biological and chemical properties, the extent of its impact depends on various factors such as soil texture, moisture content, biochar rate, and particle size [93].

One of the promising uses of biochar is as an additive to organic composting [94]. The benefits of biochar addition in composting processes have been documented by different studies [95, 96]. Adding biochar into the composting pile provides a habitat for microorganisms and enhances the environmental conditions for microbial growth. In addition,

adding biochar to composting has been reported to increase the abundance of bacterial communities colonizing the composting matrix [96]. Similarly, the change in compost microbiology has a crucial impact on the overall composting process by reducing its length and interacting with critical nutrient cycles that lead to an enhanced product [94].

Biochar could be an alternative soil amendment for improving soil fertility and crop productivity [5]. Despite the growing number of biochar scientific studies, there is still a need for field experiments to confirm the results from lab and pot trial experiments [86]. Little scientific literature exists on the effect of biochar on biological, physical, and chemical properties in semi-arid regions like Namibia, where it remains a relatively new concept for smallholder farmers. Moreover, studies conducted in labs and greenhouses are typically short-term; however, long-term data are vital to facilitate a more comprehensive understanding of the ultimate impact of biochar within cropping system conditions.

3.1.1 Influence of Biochar on soil properties

Application of biochar into soil has received positive attention for its beneficial contributions to the agroecosystem from both agricultural and environmental perspectives [94]. Evidence from multiple studies suggests that biochar improves soil quality by enhancing nutrient retention and reducing nutrient loss [10, 90, 97–99]. Different soil types and management systems have shown different reactions to the effects of biochar on crop productivity and soil health. The kind of feedstock and the production process also affect the quality of biochar [100].

Biochar application can neutralize soil acidity, increasing cation exchange capacity [90], and thereby enhance nutrient availability [101, 102]. Compared to other soil amendments, the application of biochar to soils reduces fertilizer leaching into the surface and groundwater, thereby increasing soil fertility management. Biochar has a large surface area and porosity, which allows it to absorb water and nutrients, making them available for plants [3], increase water holding capacity [78, 103, 104], increase soil bulk density and soil organic carbon content [90, 104], and some nutrient content (total N, P, K, Mg, Cu and Zn) [83, 105, 106].

Dong et al. [90] found that the SOC contents of the 0 to 10 cm and 10 to 20 cm soil layers treated with biochar were significantly higher than those without biochar. Additionally, increasing the application of biochar was more conducive to the improvement of SOC. Similar findings are reported by Zhang et al. [107], Zhao et al. [105], Bian et al. [99], El-Naggar et al. [108], and Rombolà et al. [109], who found an increase in soil organic carbon after biochar application.

A study evaluated the beneficial impact of compost and biochar on the nutritional profile of the soil and maize productivity. The results indicated that biochar application showed no-significant effect on the pH of the soil [110]. These results are in line with those of Tammeorg et al. [104], who found that biochar had no effect on soil pH and moisture content. On the contrary, Zhang et al. [111] and Rombolà et al. [109] observed

increased soil pH after biochar application. Unlike all the aforementioned observations, Nelissen et al. [86] investigated the effect of biochar on a temperate agricultural soil on soil chemical, physical and biological properties, and crop growth and nutrient uptake. The authors reported that biochar application had no significant effects on soil chemical and physical properties except for an increase in organic carbon content. However, a meta-analysis by Dai et al. [112], highlighted that biochar properties must be selected based on the needs of the targeted soils and specific issues to maximize its effective use in agriculture.

3.1.2 Impact of Biochar on crop growth and productivity

One of the main reasons for biochar application is its potential to enhance crop biomass and yield [113–116]. Over the past years, investigations on the effects of biochar amendment on crop growth and yield have increased in agro-climatic conditions [117]. Both positive and negative yield responses have been reported for various crops due to biochar application to soils, provided in Appendix A (Table 1). However, meta-analyses reported that biochar application typically increases crop yields ranging between 10% and 13%, although outcomes vary with soil characteristics, application rates and biochar properties [118–121]. The authors added that this yield increase suggests that biochar acts as a matrix to increase fertilizer use efficiency to a greater extent. Yang et al. [122] reported that increasing the biochar application rate from 10 to 40 t ha⁻¹ resulted in a significant reduction in total rice yield. Tammeorg et al. [104] revealed that biochar application had no significant effects on leaf area index (LAI), Soil Plant Analysis Development (SPAD), above-ground biomass (AGB), grain yield, or wheat quality, possibly due to its high organic matter content and low nutrient availability in the soil. These results are similar with other findings that the addition of biochar to soil does not affect crop yield [86]. The results of an experiment by Enguwa et al. [58] showed that biochar produced the highest marketable cabbage heads (24, 884 heads ha⁻¹), largest head girth, and water use efficiency.

Yield responses to biochar differ by crop type, with strong benefits reported on vegetables, legumes, and grasses [123]. With the application of biochar, the globally crucial commercial cereal crops such as rice, wheat, and maize increased productivity by approximately 16, 19, and 22% [119]. Biochar made from different feedstock had a significant effect on the yield. Dai [112] indicates that biochar from crop residues, straws, manure, and sewage sludge increased yield effects than biochar from woody biomass when not integrated with fertilizers. Additionally, the relatively poor performance of woody biochar could be attributed to its high lignin content and inherently low nutrient profile. High lignin slows down decomposition, limiting microbial activity in the soil, while low levels of essential nutrients, such as nitrogen and phosphorus, reduce its immediate benefit as a soil amendment [74, 124].

3.2 Compost as a soil amendment on wheat production

Composting is an aerobic process in which organic materials are broken down by microorganisms into a humus-like end product under controlled conditions [2, 76,

[125]. Feedstock for composting include agricultural wastes (e.g., crop residues, animal manure), municipal and urban wastes (e.g., food scraps, municipal solid waste, garden trimmings), and industrial organic-products [79]. Composting proceeds through three key microbial phases: the mesophilic phase, where microorganisms initiate the breakdown of readily degradable organic matter; the thermophilic phase, dominated by heat-tolerant microbes that accelerate the decomposition of complex compounds and eliminate pathogens; and the maturation phase, during which mesophilic organisms further stabilize the material into a humified and biologically stable compost [126–128]. Similar to biochar, composting contributes to circular economy practices by converting organic wastes into valuable soil amendments that support sustainable agriculture [125, 129].

Compost can be mature but the quality may vary depending on nutrient composition and feedstock type [130]. However, the type of material or feedstock utilized affects the nutrient value. Because of this, compost cannot be used as an organic fertilizer until it is mature. Plants may burn, grow stunted, or even die if applied too soon. Immature compost smells poorly and has a wide range of carbon and nitrogen ration [131]. However, the decomposition process continues after it is absorbed into the soil. Compost has been shown to positively affect the environment, fertility, and soil quality [132].

3.2.1 The influence of compost on soil properties

Adding compost to the soil helps improve physical properties, increases aggregate stability, stimulates microbial activities, enhances nutrient cycling and support crop growth [5, 133]. A review by Viaene et al. [132] found that compost incorporation generally reduced bulk density, enhanced infiltration and hydraulic conductivity, and increased water content and plant available water compared to unamended controls. The improvement in infiltration following compost addition is generally linked to reduced bulk density and increase porosity and [134].

Field experiments were conducted, and the results showed that compost and vermicomposting treatments significantly influenced soil physical and chemical properties, such as electrical conductivity (EC), pH, organic matter, as well as macro and micro-nutrient content [135]. Liu et al. [136] studied biochar and compost's short-term effect on soil fertility and water status under field conditions. The results indicated that high rates of compost application (e.g. 32.5 Mg ha⁻¹) had minimal short-term impact on soil organic carbon and that a high quantity of mature compost is required for a long-term increase in SOC. Kranz et al. [133] reviewed twenty-five papers where compost was incorporated in urban soils. Compared to unamended controls, compost incorporation reduced bulk density, enhanced water infiltration and hydraulic conductivity, and increased water content and plant available water. Research indicates that higher compost application rate are associated with significant increases in soil porosity [137]. Both positive and negative soil properties responses have been reported for various crops due to compost application to soils, provided in Appendix A (Table 2).

3.2.2 Effect of compost on crop growth and productivity

Farmers' adoption of soil amendments is strongly influenced by their potential to enhance crop yields. However, most research to date has focused on the effects of compost on soil physical properties in agricultural systems rather than on crop establishment and yields [133]. However, improving soil physical and chemical properties can improve crop productivity. Application of compost from different feedstock such as date-palm, stover compost, straw compost, composted pineapple residues, and some combinations of compost increased yield and yield components of rice, sorghum, melons, and maize, respectively [5, 123, 138, 139]. By improving soil structure and aeration, compost enhances root penetration and plant growth compared to unfertilized soils. Additionally, humic compounds in compost act as natural growth stimulants, encouraging root elongation and development [138, 140]. Bezabeh et al. [137] found that compost with effective microorganisms and vermicompost significantly increased wheat grain yield compared to traditional compost and mineral fertilizer in year one.

Integrating compost and mineral fertilizers or biochar often produces synergistic effects, leading to greater yield improvements than sole application [113]. Compost, when applied alone, causes modest increases in yields, primarily due to the slow release of nutrients and low availability of nitrogen and phosphorus [141]. However, when compost is combined with mineral fertilizers, crop yields often improve substantially. This is due to the fact that mineral fertilizers provide immediate nutrient availability to the crops, while compost enhances nutrient retention and uptake, which has a synergistic effect on plant growth and productivity [142, 143]. Combined application of compost and inorganic fertilizers is better than the sole application of organic manure or inorganic chemical fertilizers in terms of improve soil health, crop growth and yield [144]. Shah et al. [143] observed an increase in grain weight of wheat through combined application of compost and mineral fertilizer.

Similarly, combining compost with biochar can also lead to yield improvement, though often more gradually compared with their sole application [4, 113, 141, 145]. Biochar increases water retention and nutrient holding capacity, and compost provides organic nutrients and microbial stimulation. The combined application of biochar and compost yield response tends to be moderate in the short term but increases with successive growing seasons, especially where soils are degraded or low in nutrients [141].

3.3 Vermicompost as a soil amendment on wheat production

Vermicompost is an amendment generated through the biological activity of earthworms, which decompose organic wastes into a nutrient-rich, humus-like substance [146–148]. The most commonly used Epigenic species include *Eisenia fetida*, *E. andrei*, *Eudrilus eugeniae*, and *Perionyx excavates*. Furthermore, there are a few species; however, they exhibit limited potential for vermicomposting. These include Anaemic species such as *Lumbricus terrestris*, *L. polyphemus*, *Lampito mauritii*, *Apporrectodea trap-ezoids*, and *A. longac*; Endogenic species such as *Octochaetona thurstoni*, *Apporrectodea*

caliginosa, *Allolobophora rosea*, and *A. caliginosa* [146, 147, 149]. Vermicompost is produced by preparing a suitable substrate, such as crop residues, animal manure, kitchen waste, or other biodegradable materials. Earthworms are then introduced into a substrate under controlled conditions of moisture (60–70%), aeration, and temperature (20–30 °C), to decompose the organic matter [150]. The end product is a dark-coloured and stable organic fertilizer with essential macro- and micronutrients, plant growth regulators, and advantageous microbial populations [151]. Although the technology is economically viable, environmentally sustainable, and socially acceptable, this practice in Namibia remains at its initial stage, with only a few businesses venturing into vermicomposting and limited unpublished research work [152].

3.3.1 Influence of vermicompost on soil properties, growth and yield

Vermicompost plays a crucial role in sustainable agriculture by enhancing soil fertility and crop growth without dependence on chemical fertilizers [153]. It provides essential nutrients such as nitrogen, phosphorus, potassium, and trace elements, in forms that plants can readily absorb along with trace elements [146, 151, 154]. Furthermore, vermicompost includes humic substances and phytohormones such as auxins and gibberellins, which stimulate root growth and plant development [153, 155]. Its application has been demonstrated to enhance germination rates [156, 157], improve crop quality, and increase the resistance of plants to pests and diseases, thereby decreasing input costs and promoting environmentally sustainable farming practices [158–160].

It enhances soil properties by improving structure, porosity, and water retention, increasing drought resistance. Furthermore, it enhances the cation exchange capacity (CEC), organic matter content, nutrient retention, and soil pH buffering capacity [16–162]. It boosts microbial diversity and activity, supporting beneficial organisms that suppress soil-borne pathogens, enhance nutrient cycling, and reduce heavy metals in the soil [151]. These combined effects enhance soil health and long-term productivity, making vermicomposting a crucial practice in sustainable agriculture and land management. The results from research review have been reported for various crops as affected by vermicompost application to soils, provided in Appendix A (Table 3).

3.3.2 Impacts of combined application of organic fertilizers on soil properties, crop growth, and yield

Combining biochar and compost as a soil amendment is a promising approach to benefit crop growth and nutrient cycling [16]. There is an increasing interest in the combined application of biochar and compost within the agricultural sector [125]. Together, the two components could synergistically enhance each other's properties [16]. Combined application of the two soil amendments increased maize grain yield by 2% more than sole applications. The combined application of the two amendments increased yield by 26% in a maize field trial [163].

Compared with the sole application, the combined application of biochar and compost improved all growth and yield characteristics in maize. Soil organic carbon, total N, available P, and available K increased. However, soil pH decreased with biochar and

compost application [113]. Different studies in showed that the combination of biochar and compost application on soil showed a synergistic effect on soil nutrient contents under field conditions, enhanced soil quality, increased plant growth, and improved water retention capacity [12]. Applying biochar with compost can enhance compost properties, leading to a higher added value and a much better carbon sequestration potential than mixing biochar and compost with soil [8]. Agegnehu et al. [97] concluded their findings on biochar and biochar-compost effects on peanut, soil properties, and greenhouse gas emissions. The application positively impacts soil fertility through its effect on SOC, CEC, and plant-available nutrients.

3.4 Inorganic/chemical fertilizer on crop production

Fertilizers like urea, NPK, potassium chloride, ammonium nitrate, and others are examples of inorganic fertilizers that are widely used. In agriculture, they are applied to increase soil fertility. The benefits of using inorganic fertilizers include faster plant development, increased yield, and quickly accessible crop nutrients. Despite their many advantages, chemical fertilizers are known for being expensive. Conversely, the extensive use of inorganic fertilizers results in numerous health issues and degrades soil. Furthermore, the fact that inorganic fertilizers are made up of simple chemical compounds with known compositions sets them apart from organic fertilizers. Farmers combine organic and artificial fertilizers for their crops due to the issue above [164].

Nitrogen is crucial for vegetative growth, chlorophyll production and protein synthesis. It is fast acting and results in vigorous crop growth, making it suitable for crops like maize, rice and wheat [165]. It is a major element that boosts the potential of yield and quality components of crops [165, 166]. Phosphorus is the second most important macronutrient after nitrogen, responsible for energy transfer and root development [167, 168]. Despite its significance, phosphorus availability in tropical soils is frequently restricted due to the presence of iron and aluminium oxides, a characteristic feature in numerous regions of sub-Saharan Africa, including certain areas of Namibia. This circumstance highlights the need for meticulous phosphorus management and the potential inclusion of organic amendments to improve bioavailability. Abera [24] found that the combined use of nitrogen and phosphorus increased the yield of bread wheat while maintaining acceptable economic benefits. Meanwhile, potassium regulates enzyme activation and assimilate translocation. This nutrient is vital for stress tolerance, especially under drought and salinity conditions, and improves crop quality traits like grain filling [169, 170]. El-Mageed [170] reported that wheat yield and yield characters improved with higher potassium fertilizer rates. Potassium deficiency can limit crop productivity in poor, sandy soils, which are common in Namibia's northern regions [171, 172].

3.4.1 Organic amendments and nitrogen fertilizer effects on soil properties and crop productivity

The effects of organic amendments and nitrogen fertilizer on yield and nitrogen use efficiency on barley were investigated by Agegnehu et al. [141] in central Ethiopian highlands. The experiment showed high uptake, agronomic, and apparent recovery efficiency

of applied N with biochar, compost, and their combination. The highest yield (60%) was obtained using organic amendments with moderate rates of N fertilizer. Organic amendments and N fertilizer significantly increased grain and straw N content. Thus, biochar can be mixed with inorganic fertilizer and yield well. Khan et al. [21] studied how biochar optimizes wheat quality, yield, and nitrogen acquisition in low fertile calcareous soil treated with organic and mineral nitrogen fertilizers for two years and found that grain yield showed significant differences ($P < 0.05$) in response to the application of biochar. Wang et al. [173] displayed that the combination of organic and nitrogen fertilizer reduced root (39.3%), shoot (31.3%), and total biomass (31.6%) compared to control with fertilizer.

A meta-analysis by Ye et al. [174] observed decreased crop productivity on biochar sole application. However, biochar increased crop productivity by 15% compared to inorganic fertilizer when combined with inorganic fertilizer. A study by Elfeel and Abouhassan [175] revealed that the combined application of compost and NPK increased the leaf area of the leguminous trees. However, the increase was more significant with NPK fertilizer only. Basir et al. [142] reported that the application of compost and NPK significantly increased plant height and improved wheat grain yield. They further explained that one of the reasons for influencing plant height by enriching the compost applied as an organic source of nutrients is the slow release of nutrients that may have supported crop growth throughout the growing season.

Zhang et al. [111] reported a decrease in soil bulk density at 40 t ha⁻¹ of biochar by 0.1 g cm⁻³ and by 0.12 g cm⁻³ and an increase in soil pH by 0.24 and 0.46 with and without N fertilization, as compared to the treatment with no biochar. In another study by Zhang et al. [107], biochar reduced soil bulk density and boosted soil total N contents but did not affect soil mineral N.

4 Conclusion

Wheat production in the semi-arid conditions of Namibia faces considerable challenges due to nutrient depletion and soil degradation. Both organic and inorganic soil amendments such as biochar and compost, present promising strategies to restore soil health, increase crop production, and contribute to climate change mitigation as carbon sinks. Even with extensive global studies, considerable knowledge gaps remain, particularly regarding field-level trials on cereal crops in developing countries, including Namibia. Critical factors such as optimum incorporation rates, depth of application, and particle size, particularly for biochar, are either irregularly reported or poorly studied.

The combination of organic and inorganic amendments can provide a more affordable and sustainable alternative for resource-constrained farmers. However, it needs to be confirmed by locally relevant field studies. To fully exploit the potential offered by these amendments to wheat farming under semi-arid conditions in Namibia, long-term field trials that resolve such pragmatic uncertainties must be prioritized in future research. This will offer empirical guidance to agricultural stakeholders and policymakers seeking to optimize productivity, soil fertility, and environmental sustainability under challenging environments.

Appendix 1

See Tables 1, 2 and 3

Table 1 The summary of the review results on the effects of Biochar on soil properties and crop productivity

Feedstock type	Application rate	Soil type & Crop	Effect on soil properties	Effect on crop productivity	Reference
	0, 10, 20 t ha ⁻¹	Haplic Luvisol soil,	The concentration of NO ₃ - and NH ₄ ⁺ increases at 20 t ha ⁻¹ when biochar was applied at high rate of 20 t ha ⁻¹ , the SOC content increase, it also led to a significant rise in pH (5.0 to 6.1).		[176]
Vineyard prunings and wood chips	0%, 2% rate (w/w)	Sandy-loam, Swiss chard (<i>Beta vulgaris</i> L. var. <i>cycla</i>)	The P2O43-, Na+, K + and total N contents were significantly higher in the soil amended with the biochar from vineyard prunings. EC significantly decreased both in Bw- and Bv-treated soil by about 23 and 26%, respectively	Biochar from vineyard prunings showed a 20% lower fresh leaf weight value than the soil not amended (80).	[125]
<i>Acacia</i> spp.	0, 10 t ha ⁻¹	Nitisol soils, Barley (<i>Hordeum vulgare</i> L.)	Soil organic carbon (SOC) increased by 23–27% at Holetta, 26–34% at Robgebeya over initial values. Cation exchange capacity (CEC) increased by 20–24% (Holetta) and 19–23% (Robgebeya). Soil pH increased from 5.0 to 5.6 at Holetta, from 4.8 to 5.4 at Robgebeya		[177]
Hardwood biochar (<i>Prosopis africana</i> , <i>Terminalia glaucescens</i>)	0, 25, 50 t ha ⁻¹	Sandy loam soil, Radish (<i>Raphanus sativus</i> L. cv. French Breakfast)	Biochar at 50 t ha ⁻¹ increased soil Ph, decreased bulk density, moisture content and increased porosity. Also, it significantly increased soil N, P, K, Ca, Mg, OM and pH	Biochar application only increased leaf nutrient concentrations. High application rate of biochar increased leaf weight (26.8 g), root length (18.20 g), root weight (0.98 kg m ²) and root girth (8.41 g) in the second year.	[80]
Wood biochar	0, 20 t ha ⁻¹	Sandy loam soil, Barley (<i>Hordeum vulgare</i> L.)	Over two years, biochar addition to soil did not affect soil chemical properties, except for organic carbon content and C: N ratios. Effects on bulk density, porosity and soil water retention. Potassium concentration was increased just after biochar application. Bulk density decreased in biochar treatment.	No significant differences were found between the control and biochar treatments regarding dry matter straw and grain yield, P and N concentrations in grain and straw and grain weight, in both of the two growing seasons	[86]
Wood biochar	0, 11, 22, 44, 88 Mg ha ⁻¹	Silt loam, Wheat (<i>Triticum aestivum</i> L.)	Biochar rates below 22.4 Mg ha ⁻¹ increased nitrate levels. pH, P, K, and S concentration. The soil NO ₃ -N and NH ₄ -N contents decreased with increasing biochar rates in fertilized treatments	Biochar increased wheat shoot biomass by 15% to 20% when applied at the rate of 11.2 and 22.4 Mg ha ⁻¹ .	[102]
Wheat straw biochar	0, 15, 30 t ha ⁻¹	Sand soil, Wheat (<i>Triticum aestivum</i> L.)	SOC content increased with increasing amount of biochar application rate. Total Nitrogen content in the soil increased with biochar application. Biochar decreases soil Ph from 8.05 to 7.98	Increase in biochar application rate, increased wheat yield.	[90]
Lump charcoal - oak (<i>Quercus</i> spp.) and hickory (<i>Carya</i> spp.)	0.5, 10, and 20 kg ha ⁻¹	Fine-loamy soil	20 g kg ⁻¹ biochar treatments reduced total N and total dissolved P leaching by 11% and 69%. The pH of the biochar was 7.6 when first placed in deionized water but increased to 8.2 after 7 days.		[103]

Table 1 (continued)

Feedstock type	Application rate	Soil type & Crop	Effect on soil properties	Effect on crop productivity	Reference
Chips of debarked spruce (Picea abies (L.) H. Karst.)	0, 5, 10, 20 and 30 t ha ⁻¹	Loamy sand, Wheat (<i>Triticum aestivum</i> L.)	B30 treatments increased the soil pH over the B5 treatments (0.2 and 0.1 units for 2011 and 2012, respectively). The B5 treatment resulted in a significant decrease in easily soluble Ca and Mg below control values in both years. The B10 and B30 treatments had no significant ($p > 0.1$) effects on the soil moisture content in comparison to the control.	Biochar addition had no significant ($p > 0.05$) effect on the plant stand density, grain number per plant, HI, grain yield or grain quality.	[104]
Wheat straw	0, 20, 40 t ha ⁻¹	Loamy soil, Maize (<i>Zea mays</i> L.)	Biochar amendment at 40 t ha ⁻¹ caused a significant decrease in soil bulk density by 0.17 gcm ⁻³ . SOC was found to increase by 57.8% under biochar amendment at 40 t ha ⁻¹ .	Maize yield was increased by 15.8%. Total N ₂ O emission was decreased by 10.7% and by 41.8% under biochar amendment at 20 t ha ⁻¹ and 40 t ha ⁻¹ .	[107]

Table 2 The summary of the review results on the effects of compost on soil properties and crop productivity

Feedstock type	Application rate	Soil type & Crop	Effect on soil properties	Effect on crop productivity	Reference
Food waste and cattle manure	25, 50, 75, 100%	Maize (<i>Zea mays</i> L.)	The EC did not show statistically significant difference among treatments. In all cases, it was between 0.04 and 0.06 ds/m. 100% of compost decreased Ph from 6.28 to 6.22	Compost application rate at 50% increased grain yield of maize (6 761.90 kg/ha)	[178]
40% cactus and crop residue, 10% vegetable and fruit peels, 20% animal manure, 10% ash, 5% soil	0, 4, 6, 8 t ha ⁻¹	Clay, Wheat (<i>Triticum aestivum</i> L.)	At 8 t compost ha ⁻¹ , SOM increased 108 and 104%; available P 1.62 and 1.73%; exchangeable Ca 16.7 and 17.4%; and CEC 15.4 and 17.1%, respectively	The highest significant straw and grain yield recorded with the application of 8 t compost ha ⁻¹ .	[179]
Municipal solid waste	0, 50, and 100 ha ⁻¹	Clay-loam, Tomato (<i>Solanum lycopersicum</i>), Lettuce (<i>Lactuca sativa</i>)	Soil organic carbon decreased gradually from 1.7 to 1.4% at 100 t/ha compost. A slighter decline in SOC from 0.9 to 0.7% was assessed in pots treated with 50 t/ha compost. Rate from 50 to 100 t/ha resulted in a slow increase of the available P in the soil. 50 t/ha increased soil Ni from 0.022 to 0.12 mg/kg and Cr content from 0.09 to 0.18 mg/kg.	Tomato plants amended with 50 and 100 t/ha compost produced 48 and 35% lower biomass, respectively.	[180]
H. verticillata, cow dung, sawdust and biochar	0, 10, 20, 30% w/w	viz. laterite (alfisols) and alluvial (fluvisols) soils,	Increased pH of soil from 5.9 to 6.9 to 7.0 and 7.2 in both soils respectively. All pots amended with composts showed significantly higher cation exchange capacity and water holding capacity. The bulk density decreased for all treated soil samples and recorded as 1.67, 1.58, 1.34 and 1.21 in 0%–30% and 1.36, 1.21, 1.05, 0.987 g cm ⁻³ in 0%–30%, respectively		[181]
Cow manure	0, 5 t ha ⁻¹	Loam, Maize (<i>Zea mays</i> L.)	Application of compost increased soil organic carbon (SOC) from 0.8 to 1.2% and eventually made the soil structure porous. An increase in concentration of soil phosphorus by the application of organic amendments enhanced the availability of phosphorus due	Compost increased plant height by 28.6%, increase in 1000 grain weight by 26.21. Compost had the highest amount in shoot Nitrogen level, Phosphorus level and Potassium.	[110]
Peanut shell	0%, 1.5%, 3%, and 5% (w/w)	Crown daisy (<i>Chrysanthemum coronarium</i> L.) and Lettuce (<i>Lactuca sativa</i> var <i>longifolia</i> L.)	Improved water holding capacity, increased soil organic matter, increased electrical conductivity (as more nutrients / soluble salts), also increased available macronutrients (P, K) and some micronutrients (B, Zn, Mn) for low to moderate amendment rates. However, the highest rate (5%) caused high EC, which in some cases reduced yield (due to possibly salt effects)	Compost at < 3%) significantly increased yields by 15.8% — 107%. Compost at 5% decreased yields due to excessive nutrient and high electrical conductivity	[182]

Table 2 (continued)

Feedstock type	Application rate	Soil type & Crop	Effect on soil properties	Effect on crop productivity	Reference
Macademia husks	0, 15, 30 t ha ⁻¹	Sandy loam soil, Chinese cabbage (<i>Brassica rapa</i> L. <i>Chinensis</i>)	Compost application decreased bulk density by 20–40% (season 1) and 20–30% (season 2) in MHC treatments; increased potential available water (i.e. water holding capacity) significantly. Soil pH increased modestly (by 0.1–0.5 units depending on treatment). Other improvements: organic carbon, total N, available P, K, Ca, Mg, exchangeable cations and some micronutrients increased under MHC treatments; no significant effect on EC in most cases.	Application of compost had a significant increase on growth and yield components. 15, 30 t ha ⁻¹ increased leaf number by 43% and 77%, fresh and dry biomass, root growth, leaf area in compost-treated plots compared to control	[129]

Table 3 The summary of the review results on the effects of vermicompost on soil properties and crop productivity

Substrate used and earthworm species	Rate	Soil type & Crop	Effects on soil properties	Effects on crop productivity	Reference
This vermicompost is an organic fertilizer produced by <i>Eisenia fetida</i> earthworm species which are fed with 70% farm manure + 30% vegetable wastes	0, 5 kg	Clay-loam, olives (<i>Olea europaea</i> L. cv. <i>Merneck</i>)	After vermicompost application the average pH and lime content of soil applied with worm castings was reduced while organic matter amounts increased. Vermicompost decreased EC value of soil. Total N values in both depths following the application of vermicompost increased. Phosphorus level at both depths (0–30, 30–60 cm) has increased, respectively by 41.6–64.07%	Nutrient content levels of olive leaves increased with vermicompost application	[153]
	0, 2, 8 16 t ha ⁻¹	Silty loam, Mung bean (<i>Vigna radiata</i> L.	The addition of vermicompost significantly reduce soil pH to 7.20. High application resulted in a reduction of soil salinity (EC). An increase in the ratio of organic matter, total nitrogen, available phosphorus and potassium in the soil after planting as a result of adding vermicompost.	High-rate application of vermicompost (16 t ha ⁻¹) gave the best characteristics of the yield components, including the number of pods plant ⁻¹ , weight of pods plant ⁻¹ , weight 1000 seeds (g), total yield and was 51.0 pods plant ⁻¹ , 92.4 g plant ⁻¹ , 49.8 g plant ⁻¹ , 1216.95 kg ha ⁻¹ respectively.	[183]
	0%, 2.5%, and 5% w/w	Clay-loam, Lettuce (<i>Lactuca sativa</i> var. <i>crispa</i>)	5% V had an increase in the organic matter content of soils (2.19%). 5% VC treatment increased the total N (0.099%), and the lowest (0.016%) was obtained from the control. The greatest available P (34.7 mg kg ⁻¹ in soil), CEC value was found to be higher in 5% VC treatment (28.05 meq 100 g ⁻¹). Significant increases were observed in bulk density, field capacity, available water capacity, saturated hydraulic conductivity and total porosity of soils with 5%.	The highest lettuce yield (178.7 g plant ⁻¹) was observed in 5% VC treatment.	[161]
	0, 8, 16 t ha ⁻¹	Broccoli (<i>Brassica oleracea</i> var. <i>italica</i>)	8 t ha ⁻¹ of vermicompost shows significant differences compared to other treatments in pH, EC, CEC, O.M, microbial density, and available N, P, K with values of 7.30, 2.18, 46.7, 2.96, 4.4, 174.5, 21.6, and 188.5, respectively.	Application of 8 t ha ⁻¹ increased plant height (52.8 cm), number of leaves (32.4), dry weight (190.2 gm) and weight of the main flower disc (865.8 gm). The same application rate gave a higher rate for each protein %, fat %, N%, P%, and K% to be (23.37, 2.81, 3.74, 0.79, and 2.93), respectively.	[148]

Table 3 (continued)

Substrate used and earthworm species	Rate	Soil type & Crop	Effects on soil properties	Effects on crop productivity	Reference
	10.0, 4.3 and 17.0 t ha ⁻¹	Saline-sodic soil, (<i>Triticum aestivum</i> L., cv <i>Misir 2</i>)	Application of vermicompost decreased EC, BD and PR by 28.0%, 4.5% and 17.0% respectively, whereas it significantly increased SOC, HC, MWD and AI by 51.7%, 25.6%, 50.0% and 38.8%, respectively.	The highest SPAD values (45) were obtained from wheat grown in soil treated with vermicompost. Application of high rates (17.0) of vermicompost resulted in higher values of heading date, flag leaf area, and relative water content.	[155]
Cow manure-wastepaper with fly ash and biochar. Worms used species <i>Eisenia fetida</i>	0, 25, 50, 75, 100%	Tomato (<i>Lycopersicon esculentum</i> Mill. var. Heinz), and Swiss Chard (<i>Beta vulgaris</i> L. var. <i>Ford hook Giant</i>)		Relative seedling growth was observed in the CM + Fly ash treatment with a range of 104.65% (tomato) to 31.59% (beetroot). For the Swiss chard, as the vermicompost percentage decreased, the germination increased from 38.9%, 62.5%, 66.6%, 73.6% and 83.3% for 100VC, 75VC, 50VC, 25VC and the control, for the tomato, the as vermicompost level decreased, the germination increased from 76.4%, 69.4%, 75%, 94.4% and 95.8% for the 100VC, 75VC, 50VC, 25VC and control, respectively.	[156]
	0.5, 1, 2, 4% w/w	Sandy-loam, loam, Clay	The increasing rates in organic matter content were 14.0%, 23.8%, 42.0% and 90.2% for 0.5%, 1%, 2% and 4% vermicompost application doses, respectively. Wet aggregate stability increased to 52.2% at 4% vermicompost application rate. The highest application dose (4%) decreased MWD from 4.2 to 2.7 mm in sandy loam soil. Organic matter content increased from 1.43% (control) to 1.63%, 1.77%, 2.03% and 2.72% with 0.5%, 1%, 2% and 4% application rate, respectively		[162]
Fly ash vermicompost (FA) with pine bark (PB) mixture earthworms (<i>Eisenia fetida</i>)	0, 25, 50, 75, 100%	Marigold (<i>Tagetes spp.</i>)	FA compost at 100% increased bulk density (0.630), particle density (92.333), and water-holding capacity (70.017), while the PB at 100% compost increased total porosity (83.804) and air-filled porosity (31.553) of the growth media. The pine bark compost pH was acidic (pH 4.51), while that of the flyash vermicompost was highly alkaline (pH 11.14). Substitution with fly ash vermicompost from 25% up to 75% resulted in a final media pH ranging from 8.33 to 6.68. A significant difference was observed between treatments on EC with the pine bark compost having an EC of 0.36 dS/m while the fly ash vermicompost had an EC of 1.47 dS/m.	The lowest germination percentage of 22.5% was observed in the pinebark compost followed by the 100% fly ash vermicompost with 61.2%. It was important to note that substituting pinebark compost with fly ash vermicompost within the range of 75 to 25% resulted in a significant average 4.2 times (319%) increase in percentage germination compared to the pine bark alone. The 25% FA treatment resulted in significantly higher number of flowers and buds compared to the 50 and 75%.	[157]

Author contributions

A.H. wrote the whole manuscript text and prepared the figures. A.P. and S.H. reviewed the manuscript. All authors of this paper have read and approved the final version submitted.

Funding

Not applicable.

Data availability

No datasets were generated or analysed during the current study.

Declarations**Ethics approval and consent to participate**

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

Received: 10 March 2025 / Accepted: 3 October 2025

Published online: 20 October 2025

References

1. Agegnehu G, Bass AM, Nelson PN, Bird MI. Benefits of biochar, compost and biochar–compost for soil quality, maize yield and greenhouse gas emissions in a tropical agricultural soil. *Sci Total Environ*. 2016;543:295–306. <https://doi.org/10.1016/j.scitotenv.2015.11.054>.
2. Libutti A, Rivelli AR. Quantitative response of Swiss Chard (*Beta vulgaris* L. var. *cycla*) to soil amendment with Biochar-Compost mixtures. *Agronomy*. 2021;11:307. <https://doi.org/10.3390/agronomy11020307>.
3. Agegnehu G, Srivastava AK, Bird MI. The role of Biochar and Biochar-compost in improving soil quality and crop performance: A review. *Appl Soil Ecol*. 2017;119:156–70. <https://doi.org/10.1016/j.apsoil.2017.06.008>.
4. Agegnehu G, Bass AM, Bird MI, Nelson PN. The ameliorating effects of Biochar and compost on soil quality and plant growth on a ferralsol. *Soil Res*. 2015;53:1. <https://doi.org/10.1071/SR14118>.
5. Barus J. Utilization of crops residues as compost and Biochar for improving soil physical properties and upland rice productivity. *J Degrad Min Lands Manag*. 2016;3:631–7. <https://doi.org/10.15243/jdmlm.2016.034.631>.
6. Tumawu AF, Kafu GY, Kangah A, et al. Combating land degradation for sustainable smallholder agriculture and food sovereignty in Ghana's Volta region. *Front Sustain Food Syst*. 2025;9:1–11. <https://doi.org/10.3389/fsufs.2025.1455515>.
7. Diatta AA, Bassène C, Manga AGB, et al. Integrated use of organic amendments increased Mungbean (*Vigna radiata* (L.) Wilczek) yield and its components compared to inorganic fertilizers. *Urban Agric Reg Food Syst*. 2023;8:1–15. <https://doi.org/10.1002/uar2.20048>.
8. Mensah AK, Frimpong KA. Biochar and/or compost applications improve soil properties, growth, and yield of maize grown in acidic rainforest and coastal Savannah soils in Ghana. *Int J Agron*. 2018;2018:1–8. <https://doi.org/10.1155/2018/6837404>.
9. Mugwe J, Otieno EO. Integrated soil fertility management approaches for climate change adaptation, mitigation, and enhanced crop productivity. *Handbook of climate change management*. Cham: Springer International Publishing; 2021. pp. 1–22.
10. Hu W, Zhang Y, Rong X, et al. Biochar and organic fertilizer applications enhance soil functional microbial abundance and agroecosystem multifunctionality. *Biochar*. 2024;6:3. <https://doi.org/10.1007/s42773-023-00296-w>.
11. Liverpool-Tasie LSO, Omonona BT, Sanou A, Ogunleye WO. Is increasing inorganic fertilizer use for maize production in SSA a profitable proposition? Evidence from Nigeria. *Food Policy*. 2017;67:41–51. <https://doi.org/10.1016/j.foodpol.2016.09.011>.
12. Trupiano D, Coccozza C, Baronti S, et al. The effects of Biochar and its combination with compost on lettuce (*Lactuca sativa* L.) Growth, soil Properties, and soil microbial activity and abundance. *Int J Agron*. 2017;2017:1–12. <https://doi.org/10.1155/2017/3158207>.
13. Adhikari T, Gowda RC, Wanjari RH, Singh M. Impact of continuous fertilization on heavy metals content in soil and food grains under 25 years of long-term fertilizer experiment. *Commun Soil Sci Plant Anal*. 2021;52:389–405. <https://doi.org/10.1080/00103624.2020.1854290>.
14. Gourav, Sankhyan NK, Sharma RP, Sharma GD. Long term effect of fertilizers and amendments on the properties of an acid Alfisol and uptake of primary nutrients and sulfur in maize-wheat rotation in North Western Himalayas. *J Plant Nutr*. 2019;42:1770–88. <https://doi.org/10.1080/01904167.2019.1643372>.
15. Vanlauwe B, Kihara J, Chivenge P, et al. Agronomic use efficiency of N fertilizer in maize-based systems in sub-Saharan Africa within the context of integrated soil fertility management. *Plant Soil*. 2011;339:35–50. <https://doi.org/10.1007/s11104-010-0462-7>.
16. Wang Y, Villamil MB, Davidson PC, Akdeniz N. A quantitative Understanding of the role of co-composted Biochar in plant growth using meta-analysis. *Sci Total Environ*. 2019;685:741–52. <https://doi.org/10.1016/j.scitotenv.2019.06.244>.
17. Sall AT, Chiari T, Legesse W, et al. Durum wheat (*Triticum durum* Desf.) cultivation and potential expansion in Sub-Saharan Africa. *Agronomy*. 2019;9:1–20. <https://doi.org/10.3390/agronomy9050263>.
18. Yen C, Yang J, Yuan Z, et al. Geographic and historical origin of wheat BT - Biosystematics of triticeae: volume I. *Triticum-Aegilops* complex. In: Yen C, Yang J, editors. *Biosystematic of triticeae*. Singapore: Springer Singapore; 2020. pp. 173–80.
19. Ghahremannejad F, Hoseini E, Jalali S. The cultivation and domestication of wheat and barley in Iran, brief review of a long history. *Bot Rev*. 2021;87:1–22. <https://doi.org/10.1007/s12229-020-09244-w>.

20. Tadesse W, Bishaw Z, Assefa S. Wheat production and breeding in Sub-Saharan Africa. *Int J Clim Chang Strateg Manag*. 2019;11:696–715. <https://doi.org/10.1108/IJCCSM-02-2018-0015>.
21. Khan MA, Basir A, Fahad S, et al. Biochar optimizes wheat quality, yield, and nitrogen acquisition in low fertile calcareous soil treated with organic and mineral nitrogen fertilizers. *Front Plant Sci*. 2022;13:1–13. <https://doi.org/10.3389/fpls.2022.879788>.
22. Shewry PR, Hey SJ. The contribution of wheat to human diet and health. *Food Energy Secur*. 2015;4:178–202. <https://doi.org/10.1002/fes3.64>.
23. Gorissen SHM, Horstman AMH, Franssen R, et al. Ingestion of wheat protein increases in vivo muscle protein synthesis rates in healthy older men in a randomized trial 1–3. *Nutrition*. 2016;146:1651–9. <https://doi.org/10.3945/jn.116.231340>.
24. Abera T. Effect of nitrogen and phosphorus fertilizers on yield components and yield of bread wheat (*Triticum aestivum* L.) in Lemo district, Hadiya Zone, Southern. *J Adv Agron Crop Sci*. 2022;1:1–8.
25. Hager AS, Wolter A, Jacob F, et al. Nutritional properties and ultra-structure of commercial gluten free flours from different botanical sources compared to wheat flours. *J Cereal Sci*. 2012;56:239–47. <https://doi.org/10.1016/j.jcs.2012.06.005>.
26. Chaudhary N, Dangli P, Mishra ML, Kumar V. Wheat: contribution to healthy diet and health. *Handbook of Cereals, Pulses, Roots, and tubers*. Boca Raton: CRC; 2021. pp. 3–34.
27. Shiferaw B, Smale M, Braun H-J, et al. Crops that feed the world 10. Past successes and future challenges to the role played by wheat in global food security. *Food Secur*. 2013;5:291–317. <https://doi.org/10.1007/s12571-013-0263-y>.
28. adaptive-wheat-management.
29. He X, Gahtyari NC, Roy C, et al. Globally important non-rust diseases of wheat. *Wheat improvement*. Cham: Springer International Publishing; 2022. pp. 143–58.
30. Erenstein O, Jaleta M, Mottaleb KA, et al. Global trends in wheat production, consumption and trade. In: Reynolds MP, Braun H-J, editors. *Wheat improvement*. Cham: Springer International Publishing; 2022. pp. 47–66.
31. Statista. (2024) Production of wheat worldwide. In: Online Database. <https://www.statista.com/statistics/267268/production-of-wheat-worldwide-since-1990/>. Accessed 20 Jun 2024.
32. Erenstein O, Jaleta M, Mottaleb KA, et al. Global trends in wheat production, consumption and trade. *Wheat improvement: food security in a changing climate*. Springer International Publishing Cham; 2022. pp. 47–66.
33. Alemayehu S, Olago D, Opere A, et al. Evaluating wheat cultivation potential in Ethiopia under the current and future climate change scenarios. *Land*. 2024;13:1915. <https://doi.org/10.3390/land13111915>.
34. Claude SJ, Ngigi MW, Majiwa E. Determinants of market participation and its effect on profit margins among smallholder wheat producing farmers in Rwanda. *Discov Agric*. 2025;3:38. <https://doi.org/10.1007/s44279-025-00184-w>.
35. Silva JV, Jaleta M, Tesfaye K, et al. Pathways to wheat self-sufficiency in Africa. *Glob Food Sect*. 2023;37:100684. <https://doi.org/10.1016/j.gfs.2023.100684>.
36. Wright B, Cafiero C. Grain reserves and food security in the middle East and North Africa. *Food Secur*. 2011;3:61–76. <https://doi.org/10.1007/s12571-010-0094-z>.
37. Zegeye F, Alamirew B, Tolossa D. Analysis of wheat yield gap and variability in Ethiopia. *Int J Agric Econ*. 2020;5:89. <https://doi.org/10.11648/j.ijae.20200504.11>.
38. FAOSTAT (2020) FAOSTAT Online Database. <https://www.fao.org/faostat/en/#data/QCL>. Accessed 19 Jun 2020.
39. Tadesse W, Zegeye H, Debele T, Kassa D. Wheat production and breeding in Ethiopia: retrospect and prospects. *Crop Breed Genet Genomics*. 2022;4:1–22. <https://doi.org/10.20900/cbagg20220003>.
40. Geleta Ayana N, Geleti D. Revitalizing the Ethiopian wheat sector: progresses and challenges of wheat research and seed production revitalizing the Ethiopian wheat sector. *Progresses and Challenges of Wheat*; 2023.
41. Swapi A, Akande J, Hosu YS. Wheat value chains and vertical price transmission in South Africa: A nonlinear autoregressive diagnostic lag bound approach. *Economies*. 2024;12:1–21. <https://doi.org/10.3390/economies12120340>.
42. Mwangi V, Owuor S, Kiteme B, Giger M. Assessing smallholder farmer's participation in the wheat value chain in North-West Mt. Kenya. *Front Sustain Food Syst*. 2021;5:1–13. <https://doi.org/10.3389/fsufs.2021.657744>.
43. Ahmed AM. (2024) Factors affecting wheat production (evidence from smallholders farmers in case of Honkolo Wabe woreda, Arsi zone).
44. Raheem D, Dayoub M, Birech R, Nakiyemba A. The contribution of cereal grains to food security and sustainability in Africa: potential application of UAV in Ghana, Nigeria, Uganda, and Namibia. *Urban Sci*. 2021;5:8. <https://doi.org/10.3390/urbansci5010008>.
45. NAB (2022) Agronomy and horticulture market development division.
46. Lilemon L. (2021) Wheat production forecast report for the 2020/2021 marketing season.
47. Namibia Agronomic Board. The impact of the Russia-Ukraine. war on Namibia's crop industry; 2022.
48. NAB NAB. (2021) Market intelligence report - Wheat grain.
49. FAOSTAT (2020) FAOSTAT Online Database. In: FAOSTAT Online Database. <https://www.fao.org/faostat/en/#data/QCL>. Accessed 23 Aug 2020.
50. Cleland EE, Chuine I, Menzel A, et al. Shifting plant phenology in response to global change. *Trends Ecol Evol*. 2007;22:357–65.
51. Chakrabarti B, Bhatia A, Pramanik P, et al. Changes in thermal requirements, growth and yield of wheat under the elevated temperature. *Indian J Agric Sci*. 2021;91:435–9. <https://doi.org/10.56093/ijas.v91i3.112527>.
52. Mondal S, Singh RP, Mason ER, et al. Grain yield, adaptation and progress in breeding for early-maturing and heat-tolerant wheat lines in South Asia. *F Crop Res*. 2016;192:78–85. <https://doi.org/10.1016/j.fcr.2016.04.017>.
53. Awala SK, Hove K, Wanga MA, et al. Rainfall trend and variability in semi-arid Northern Namibia: implications for smallholder agricultural production. *Wijas*. 2019;1:5.
54. Vlieghe K, Picker M. Do high soil temperatures on Namibian Fairy circle discs explain the absence of vegetation? *PLoS ONE*. 2019;14:1–12. <https://doi.org/10.1371/journal.pone.0217153>.
55. Farooq M, Bramley H, Palta JA, Siddique KHM. Heat stress in wheat during reproductive and grain-filling phases. *CRC Crit Rev Plant Sci*. 2011;30:491–507. <https://doi.org/10.1080/07352689.2011.615687>.
56. Khan A, Ahmad M, Ahmed M, Iftikhar Hussain M. Rising atmospheric temperature impact on wheat and thermotolerance strategies. *Plants*. 2021;10:1–24. <https://doi.org/10.3390/plants10010043>.
57. Yoshinori W, Fisseha I, Yuichiro F, et al. Characteristics of soils under seasonally flooded wetlands (oshanas) in north-central Namibia. *Afr J Agric Res*. 2016;11:4786–95. <https://doi.org/10.5897/ajar2016.11758>.

58. Enguwa KBP, Horn LN, Awala SK. Comparative effect of different irrigation levels and soil amendments on cabbage productivity in semi-arid central Namibia. *Irrig Drain*. 2024;73:538–56. <https://doi.org/10.1002/ird.2906>.
59. Awala SK, Yamane K, Izumi Y, et al. Field evaluation of mixed-seedlings with rice to alleviate flood stress for semi-arid cereals. *Eur J Agron*. 2016;80:105–12. <https://doi.org/10.1016/j.eja.2016.07.003>.
60. Prudat B, Bloemertz L, Kuhn NJ. Local soil quality assessment of north-central Namibia: integrating farmers' and technical knowledge. *SOIL*. 2018;4:47–62. <https://doi.org/10.5194/soil-4-47-2018>.
61. Awala SK, Hove K, Valombola JS, et al. Co-Cultivation and matching of early- and late-maturing Pearl millet varieties to sowing windows can enhance climate-change adaptation in Semi-Arid Sub-Saharan agroecosystems. *Climate*. 2023;11:227. <https://doi.org/10.3390/cli11110227>.
62. Hove K, Johannes J, Hatutale G, et al. Growth and yield response of Swiss Chard (*Beta vulgaris* (L.) to media mixture ratios of sand, acacia soil, and goat manure. *Magna Sci Adv Biol Pharm*. 2020;1:018–24. <https://doi.org/10.30574/msabp.2020.1.1.0015>.
63. Siltecho S, Suvannang N, Kaiphoem J, et al. Characterization of pterocarpus macrocarpus (pradoo wood) Biochar and its effect on the retention properties of sandy soils in Northeast Thailand. *Soil Use Manag*. 2022;38:1293–306. <https://doi.org/10.1111/sum.12774>.
64. El-Akhdar I, Shabana MMA, El-Khateeb NMM, et al. Sustainable wheat cultivation in sandy soils: impact of organic and biofertilizer use on soil health and crop yield. *Plants*. 2024;13:3156. <https://doi.org/10.3390/plants13223156>.
65. Alkhasha A, Al-Omran A, Aly A. Effects of Biochar and synthetic polymer on the hydro-physical properties of sandy soils. *Sustain*. 2018;10:1–18. <https://doi.org/10.3390/su10124642>.
66. Vilček J, Torma S. Winter wheat (*Triticum aestivum* L.) growth potential in the Slovak rural landscape. *Arch Agron Soil Sci*. 2016;62:235–45. <https://doi.org/10.1080/03650340.2015.1043899>.
67. Fortunato A, VALDIVIA SE. Food for growth. A Diagnostics of Namibia's Agriculture Sector; 2023.
68. HEI (2021) Wheat Grain Report.
69. Hirooka Y, Awala SK, Hove K et al. (2021) Effects of cultivation management on Pearl millet yield and growth differed with rainfall conditions in a seasonal wetland of sub-saharan Africa. *Agronomy* 11:1. <https://doi.org/10.3390/agronomy11091767>
70. Chand UJ, Bohra A, Singh NP. Heat stress in crop plants: its nature, impacts and integrated breeding strategies to improve heat tolerance. *Plant Breed*. 2014;133:679–701. <https://doi.org/10.1111/pbr.12217>.
71. Agegnehu G, Ashagrie AK, Yirga C. Farming systems characterization and analysis in East Gojjam zone. Implications for research and Research Report No; 2020. p. 127.
72. Boulanger P, Dudu H, Ferrari E, et al. Effectiveness of fertilizer policy reforms to enhance food security in Kenya: a macro-micro simulation analysis. *Appl Econ*. 2022;54:841–61.
73. Woomer L, Zozo PM, Lewis R, Roobroeck S. D (2023) Technology promotion and scaling in support of commodity value chain development in Africa. In: *Agricultural Value Chains*. pp 1–28.
74. Shyam S, Ahmed S, Joshi SJ, Sarma H. Biochar as a soil amendment: implications for soil health, carbon sequestration, and climate resilience. *Discov Soil*. 2025;2:18. <https://doi.org/10.1007/s44378-025-00041-8>.
75. Gao S, Medina M, Gonzalez-Ospina L, et al. Boosting soil health and crop nutrients with locally sourced Biochar and compost in Sacramento urban agriculture. *Front Sustain Food Syst*. 2025;9:1–13. <https://doi.org/10.3389/fsufs.2025.1546426>.
76. Abbott LK, Macdonald LM, Wong MTF, et al. Potential roles of biological amendments for profitable grain production – A review. *Agric Ecosyst Environ*. 2018;256:34–50. <https://doi.org/10.1016/j.agee.2017.12.021>.
77. Ullah N, Ditta A, Imtiaz M, et al. Appraisal for organic amendments and plant growth-promoting rhizobacteria to enhance crop productivity under drought stress: A review. *J Agron Crop Sci*. 2021;207:783–802. <https://doi.org/10.1111/jac.12502>.
78. Agegnehu G, Nelson PN, Bird MI. Crop yield, plant nutrient uptake and soil physicochemical properties under organic soil amendments and nitrogen fertilization on Nitisols. *Soil Tillage Res*. 2016;160:1–13. <https://doi.org/10.1016/j.still.2016.02.003>.
79. Katakula AAN, Gawanab W, Itanna F, Mupambwa HA. The potential fertilizer value of Namibian beach-cast seaweed (*Laminaria pallida* and *Gracilariaopsis funicularis*) Biochar as a nutrient source in organic agriculture. *Sci Afr*. 2020;10:e00592. <https://doi.org/10.1016/j.sciaf.2020.e00592>.
80. Adekiya AO, Agbede TM, Aboyeji CM, et al. Effects of Biochar and poultry manure on soil characteristics and the yield of radish. *Sci Hortic (Amsterdam)*. 2019;243:457–63. <https://doi.org/10.1016/j.scienta.2018.08.048>.
81. Lehmann J, Joseph S. Biochar for environmental management: an introduction. *Biochar for environmental management*. Routledge; 2015. pp. 1–13.
82. Tripathi M, Sahu JN, Ganesan P. Effect of process parameters on production of Biochar from biomass waste through pyrolysis: A review. *Renew Sustain Energy Rev*. 2016;55:467–81. <https://doi.org/10.1016/j.rser.2015.10.122>.
83. Salim BBM. Influence of Biochar and seaweed extract applications on growth, yield and mineral composition of wheat (*Triticum aestivum* L.) under sandy soil conditions. *Ann Agric Sci*. 2016;61:257–65. <https://doi.org/10.1016/j.a0as.2016.06.001>.
84. Spokas KA, Cantrell KB, Novak JM, et al. Biochar: A synthesis of its agronomic impact beyond carbon sequestration. *J Environ Qual*. 2012;41:973–89. <https://doi.org/10.2134/jeq2011.0069>.
85. Gaskin JW, Steiner C, Harris K, et al. Effect of low-temperature pyrolysis conditions on Biochar for agricultural use. *Trans ASABE*. 2008;51:2061–9. <https://doi.org/10.13031/2013.25409>.
86. Nelissen V, Ruyschaert G, Manka'Abusi D, et al. Impact of a Woody Biochar on properties of a sandy loam soil and spring barley during a two-year field experiment. *Eur J Agron*. 2015;62:65–78. <https://doi.org/10.1016/j.eja.2014.09.006>.
87. Kammann C, Ratering S, Eckhard C, Müller C. Biochar and hydrochar effects on greenhouse gas (Carbon dioxide, nitrous oxide, and methane) fluxes from soils. *J Environ Qual*. 2012;41:1052–66. <https://doi.org/10.2134/jeq2011.0132>.
88. Woolf D, Amonette JE, Street-Perrott FA, et al. Sustainable Biochar to mitigate global climate change. *Nat Commun*. 2010;1:56. <https://doi.org/10.1038/ncomms1053>.
89. Yang L, Bian X, Yang R, et al. Assessment of organic amendments for improving coastal saline soil. *L Degrad Dev*. 2018;29:3204–11. <https://doi.org/10.1002/ldr.3027>.
90. Dong L, Wang J, Shen M, et al. Biochar combined with nitrogen fertilizer affects soil properties and wheat yield in medium-low-yield farmland. *Soil Use Manag*. 2021;38:584–95. <https://doi.org/10.1111/sum.12712>.
91. Tammeorg P, Bastos AC, Jeffery S, et al. Biochars in soils: towards the required level of scientific understanding. *J Environ Eng Landsc Manag*. 2016;25:192–207. <https://doi.org/10.3846/16486897.2016.1239582>.

92. Pituya P, Sriburi T, Wijitkosum S. Properties of Biochar prepared from acacia wood and coconut shell for soil amendment. *Eng J*. 2017;21:63–75. <https://doi.org/10.4186/ej.2017.21.3.63>.
93. Zhang Y, Wang J, Feng Y. The effects of Biochar addition on soil physicochemical properties: A review. *CATENA*. 2021;202:105284. <https://doi.org/10.1016/j.catena.2021.105284>.
94. Jindo K, Sánchez-Monedero MA, Mastrolonardo G, et al. Role of Biochar in promoting circular economy in the agriculture sector. Part 2: A review of the Biochar roles in growing media, composting and as soil amendment. *Chem Biol Technol Agric*. 2020;7:1–10. <https://doi.org/10.1186/s40538-020-00179-3>.
95. Li J, Xing W, Bao H, et al. Impact of pine leaf Biochar amendment on bacterial dynamics and correlation of environmental factors during pig manure composting. *Bioresour Technol*. 2019;293:122031. <https://doi.org/10.1016/j.biortech.2019.122031>.
96. Dias BO, Silva CA, Higashikawa FS, et al. Use of Biochar as bulking agent for the composting of poultry manure: effect on organic matter degradation and humification. *Bioresour Technol*. 2010;101:1239–46. <https://doi.org/10.1016/j.biortech.2009.09.024>.
97. Agegnehu G, Bass AM, Nelson PN, et al. Biochar and biochar-compost as soil amendments: effects on peanut yield, soil properties and greenhouse gas emissions in tropical North Queensland, Australia. *Agric Ecosyst Environ*. 2015;213:72–85. <https://doi.org/10.1016/j.agee.2015.07.027>.
98. Laghari M, Saffar M, Hu Z, et al. Catena effects of Biochar application rate on sandy desert soil properties and sorghum growth. *CATENA*. 2015;135:313–20. <https://doi.org/10.1016/j.catena.2015.08.013>.
99. Bian R, Zhang A, Li L, et al. Effect of municipal Biowaste Biochar on greenhouse gas emissions and metal bioaccumulation in a slightly acidic clay rice paddy. *BioResources*. 2014;9:685–703. <https://doi.org/10.15376/biores.9.1.685-703>.
100. Elbasiouny H, Elbehiry F, El-Ramady H, Hasanuzzaman M. Contradictory results of soil greenhouse gas emissions as affected by Biochar application: special focus on alkaline soils. *Int J Environ Res*. 2021;15:903–20. <https://doi.org/10.1007/s41742-021-00358-6>.
101. Monlau F, Francavilla M, Sambusiti C, et al. Toward a functional integration of anaerobic digestion and pyrolysis for a sustainable resource management. Comparison between solid-digestate and its derived pyrochar as soil amendment. *Appl Energy*. 2016;169:652–62. <https://doi.org/10.1016/j.apenergy.2016.02.084>.
102. Bista P, Ghimire R, Machado S, Pritchett L. Biochar effects on soil properties and wheat biomass vary with fertility management. *Agronomy*. 2019;9:623. <https://doi.org/10.3390/agronomy9100623>.
103. Laird D, Fleming P, Wang B, et al. Biochar impact on nutrient leaching from a Midwestern agricultural soil. *Geoderma*. 2010;158:436–42. <https://doi.org/10.1016/j.geoderma.2010.05.012>.
104. Tammeorg P, Simojoki A, Mäkelä P, et al. Short-term effects of Biochar on soil properties and wheat yield formation with meat bone meal and inorganic fertiliser on a boreal loamy sand. *Agric Ecosyst Environ*. 2014;191:108–16. <https://doi.org/10.1016/j.agee.2014.01.007>.
105. Zhao P, Shen Y, Ge S, et al. Clean solid biofuel production from high moisture content waste biomass employing hydrothermal treatment. *Appl Energy*. 2014;131:345–67. <https://doi.org/10.1016/j.apenergy.2014.06.038>.
106. Borchard N, Wolf A, Laabs V, et al. Physical activation of Biochar and its meaning for soil fertility and nutrient leaching—a greenhouse experiment. *Soil Use Manag*. 2012;28:177–84.
107. Zhang A, Liu Y, Pan G, et al. Effect of Biochar amendment on maize yield and greenhouse gas emissions from a soil organic carbon poor calcareous loamy soil from central China plain. *Plant Soil*. 2012;351:263–75. <https://doi.org/10.1007/s11104-011-0957-x>.
108. El-Naggar A, Awad YM, Tang X, et al. Biochar influences soil carbon pools and facilitates interactions with soil: A field investigation. *L Degrad Dev*. 2018;29:2162–71.
109. Rombolà AG, Fabbri D, Baronti S, et al. Changes in the pattern of polycyclic aromatic hydrocarbons in soil treated with Biochar from a multiyear field experiment. *Chemosphere*. 2019;219:662–70. <https://doi.org/10.1016/j.chemosphere.2018.11.178>.
110. Zahra MB, Aftab Z, Akhter A, Haider MS. Cumulative effect of Biochar and compost on nutritional profile of soil and maize productivity. *J Plant Nutr*. 2021;44:1664–76. <https://doi.org/10.1080/01904167.2021.1871743>.
111. Zhang A, Cui L, Pan G, et al. Effect of Biochar amendment on yield and methane and nitrous oxide emissions from a rice paddy from Tai lake plain, China. *Agric Ecosyst Environ*. 2010;139:469–75. <https://doi.org/10.1016/j.agee.2010.09.003>.
112. Dai Y, Zheng H, Jiang Z, Xing B. Combined effects of Biochar properties and soil conditions on plant growth: A meta-analysis. *Sci Total Environ*. 2020;713:136635. <https://doi.org/10.1016/j.scitotenv.2020.136635>.
113. Naeem MA, Khalid M, Aon M, et al. Combined application of Biochar with compost and fertilizer improves soil properties and grain yield of maize. *J Plant Nutr*. 2018;41:112–22. <https://doi.org/10.1080/01904167.2017.1381734>.
114. Gilardi G, Pugliese M, Gullino ML, Garibaldi A. Effect of different organic amendments on lettuce fusarium wilt and on selected soilborne microorganisms. *Plant Pathol*. 2016;65:704–12. <https://doi.org/10.1111/ppa.12460>.
115. Jeffery S, van der Verheijen FGA, Bastos AC. A quantitative review of the effects of Biochar application to soils on crop productivity using meta-analysis. *Agric Ecosyst Environ*. 2011;144:175–87. <https://doi.org/10.1016/j.agee.2011.08.015>.
116. Hussain M, Farooq M, Nawaz A, et al. Biochar for crop production: potential benefits and risks. *J Soils Sediments*. 2017;17:685–716. <https://doi.org/10.1007/s11368-016-1360-2>.
117. Ahmed HP, Schoenau JJ. Effects of Biochar on Yield, nutrient Recovery, and soil properties in a Canola (*Brassica Napus L*)-Wheat (*Triticum aestivum L*) rotation grown under controlled environmental conditions. *BioEnergy Res*. 2015;8:1183–96. <https://doi.org/10.1007/s12155-014-9574-x>.
118. Crane-Droesch A, Abiven S, Jeffery S, Torn MS. Heterogeneous global crop yield response to biochar: a meta-regression analysis. *Environ Res Lett*. 2013;8:044049. <https://doi.org/10.1088/1748-9326/8/4/044049>.
119. Jeffery S, Abalos D, Prodana M, et al. Biochar boosts tropical but not temperate crop yields. *Environ Res Lett*. 2017;12:053001. <https://doi.org/10.1088/1748-9326/aa67bd>.
120. Liu X, Zhang A, Ji C, et al. Biochar's effect on crop productivity and the dependence on experimental conditions—a meta-analysis of literature data. *Plant Soil*. 2013;373:583–94. <https://doi.org/10.1007/s11104-013-1806-x>.
121. Melo LCA, Lehmann J, Carneiro JSdaS, Camps-Arbestain M. Biochar-based fertilizer effects on crop productivity: a meta-analysis. *Plant Soil*. 2022;472:45–58. <https://doi.org/10.1007/s11104-021-05276-2>.
122. Yang X, Vancov T, Penuelas J, et al. Optimal Biochar application rates for mitigating global warming and increasing rice yield in a subtropical paddy field. *Exp Agric*. 2021;57:283–99.

123. Liu CH, Liu Y, Fan C, Kuang SZ. The effects of composted pineapple residue return on soil properties and the growth and yield of pineapple. *J Soil Sci Plant Nutr.* 2013;13:433–44. <https://doi.org/10.4067/S0718-95162013005000034>.
124. Antonangelo JA, Bigatao Souza JL, Zhang H. Fertilizer potential of Biochar and ryegrass productivity in metal-contaminated soil. *Front Plant Sci.* 2025;15:1–12. <https://doi.org/10.3389/fpls.2024.1475939>.
125. Rivelli AR, Libutti A. (2022) Effect of biochar and inorganic or organic fertilizer co-application on soil properties, plant growth and nutrient content in Swiss Chard. *Agronomy* 12:2089. <https://doi.org/10.3390/agronomy12092089>
126. Yin J, Xie M, Yu X, et al. A review of the definition, influencing factors, and mechanisms of rapid composting of organic waste. *Environ Pollut.* 2024;342:123125. <https://doi.org/10.1016/j.envpol.2023.123125>.
127. Mengistu T, Gebrekidan H, Kibret K, et al. Comparative effectiveness of different composting methods on the stabilization, maturation and sanitization of municipal organic solid wastes and dried faecal sludge mixtures. *Environ Syst Res.* 2018;6:5. <https://doi.org/10.1186/s40068-017-0079-4>.
128. Finore I, Feola A, Russo L, et al. Thermophilic bacteria and their thermostases in composting processes: a review. *Chem Biol Technol Agric.* 2023;10:7. <https://doi.org/10.1186/s40538-023-00381-z>.
129. Maselesele D. (2020) Effects of macademia husk compost on physicochemical soil properties, growth and yield of chinees cabbage (*Brassica Rapa L. Chinensis*) on sandy soil.
130. Fuchs JG, Cuijpers WJM. (2016) Compost types, feedstocks and composting methods. In: Handbook for composting and compost use in organic horticulture. BioGreenhouse COST (European Cooperation in Science and Technology), pp 29–43.
131. Farrell M, Jones DL. Critical evaluation of municipal solid waste composting and potential compost markets. *Bioresour Technol.* 2009;100:4301–10. <https://doi.org/10.1016/j.biortech.2009.04.029>.
132. Viaene J, Van Lancker J, Vandecasteele B, et al. Opportunities and barriers to on-farm composting and compost application: A case study from Northwestern Europe. *Waste Manag.* 2016;48:181–92. <https://doi.org/10.1016/j.wasman.2015.09.021>.
133. Kranz CN, McLaughlin RA, Johnson A, et al. The effects of compost incorporation on soil physical properties in urban soils – A concise review. *J Environ Manage.* 2020;261:110209. <https://doi.org/10.1016/j.jenvman.2020.110209>.
134. Angelova VR, Akova VI, Artinova NS, Ivanov KI. The effect of organic amendments on soil chemical characteristics. *Bulg J Agric Sci.* 2013;19:958–71.
135. Ananthi K, Parasuraman P. Effect of Panchagavya foliar spray on the plant metabolism and grain yield of Tenai under rainfed condition. *Int J Agric Sci.* 2020;16:265–9. <https://doi.org/10.15740/HAS/IJAS/16.2/265-269>.
136. Liu J, Schulz H, Brandl S, et al. Short-term effect of Biochar and compost on soil fertility and water status of a dystic Cambisol in NE Germany under field conditions. *J Plant Nutr Soil Sci.* 2012;175:698–707. <https://doi.org/10.1002/jpln.201100172>.
137. Bezabeh MW, Haile M, Sogn TA, Eich-Greatorex S. Wheat (*Triticum aestivum*) production and grain quality resulting from compost application and rotation with Faba bean. *J Agric Food Res.* 2022;10:100425. <https://doi.org/10.1016/j.jafr.2022.10.0425>.
138. Aydi S, Sassi Aydi S, Rahmani R, et al. Date-Palm compost as soilless substrate improves plant growth, photosynthesis, yield and phytochemical quality of greenhouse Melon (*Cucumis Melo L.*). *Agronomy.* 2023;13:212. <https://doi.org/10.3390/agronomy13010212>.
139. Liang Y, Al-kaisi M, Yuan J, et al. Agriculture, ecosystems and environment effect of chemical fertilizer and straw-derived organic amendments on continuous maize yield, soil carbon sequestration and soil quality in a Chinese Mollisol. *Agric Ecosyst Environ.* 2021;314:107403. <https://doi.org/10.1016/j.agee.2021.107403>.
140. Piccolo A, Drosos M. The essential role of humified organic matter in preserving soil health. *Chem Biol Technol Agric.* 2025;12:21. <https://doi.org/10.1186/s40538-025-00730-0>.
141. Agegnehu G, Nelson PN, Bird MI. The effects of biochar, compost and their mixture and nitrogen fertilizer on yield and nitrogen use efficiency of barley grown on a Nitisol in the highlands of Ethiopia. *Sci Total Environ.* 2016;569–570:869–79. <https://doi.org/10.1016/j.scitotenv.2016.05.033>.
142. Basir A, Iqbal S, Adnan M, et al. Integration of compost with mineral NPK fertilizers for improving wheat yield and soil health. *Pakistan J Bot.* 2025;57:981–9. [https://doi.org/10.30848/PJB2025-3\(19\)](https://doi.org/10.30848/PJB2025-3(19)).
143. Madani H, Gomarian M, Hosseini SRM. Effect of organic and chemical nitrogen fertilizers on grain yield and yield components of wheat and soil fertility. *J Crop Nutr Sci.* 2018;4:1–14.
144. Iqbal MA, Rahim J, Hassan S, et al. Rainfed winter wheat (*Triticum aestivum L.*) cultivars respond differently to integrated fertilization in Pakistan. *Pakistan Fresenius Environ Bull.* 2021;30:3115–21.
145. Mohan D, Preetiva B, Chaubey AK, et al. Eggplant growth in wheat straw-, wheat straw biochar- and compost-amended soils: a field study of CO₂ emission dynamics, soil physicochemical, microbial, and nutrient effects. *Waste Manag Bull.* 2024;1:143–57. <https://doi.org/10.1016/j.wmb.2023.10.004>.
146. Mupambwa HA, Ravindran B, Mkeni PNS. Potential of effective micro-organisms and *Eisenia fetida* in enhancing vermi-degradation and nutrient release of fly Ash incorporated into cow dung–paper waste mixture. *Waste Manag.* 2016;48:165–73. <https://doi.org/10.1016/j.wasman.2015.10.001>.
147. Bhat SA, Singh J, Vig AP. Earthworms as organic waste managers and biofertilizer producers. *Waste Biomass Valoriz.* 2018;9:1073–86. <https://doi.org/10.1007/s12649-017-9899-8>.
148. Alkobaisi JS, Abdel Ghani ET, Mutlag NA, Lafi ASA. Effect of vermicompost and vermicompost tea on the growth and yield of broccoli and some soil properties. *IOP Conf Ser Earth Environ Sci.* 2021;761:012008. <https://doi.org/10.1088/1755-1315/761/1/012008>.
149. Edwards CA, Arancon NQ. The use of earthworms in organic waste management and vermiculture. *Biology and ecology of earthworms.* Springer; 2022. pp. 467–527.
150. Peng W, Wang Y, Cui G, et al. Compost quality, earthworm activities and microbial communities in Biochar-augmented vermicomposting of dewatered activated sludge: the role of Biochar particle size. *Biochar.* 2024;6:73. <https://doi.org/10.1007/s42773-024-00365-8>.
151. Oyege I, Balaji Bhaskar MS. Effects of vermicompost on soil and plant health and promoting sustainable agriculture. *Soil Syst.* 2023;7:101. <https://doi.org/10.3390/soilsystems7040101>.

152. Nghituwamhata SN, Horn LN, Ashipala SN. Vermicompost as a possible solution to soil fertility problems and enrichment in the semiarid zones of Namibia BT - Vermicomposting for sustainable food systems in Africa. In: Mupambwa HA, Horn LN, Mnkeni PNS, editors. Sustainability sciences in Asia and Africa. Singapore: Springer Nature Singapore; 2023. pp. 203–12.
153. Bellitürk K, Çelik A, Baran MF. The effect of vermicompost application on soil properties in Olive (*Olea Europaea* L. cv. Memecik) plant. *Erwerbs-Obstbau*. 2022;64:107–13. <https://doi.org/10.1007/s10341-021-00623-0>.
154. Abdel-Lattif H, Abbas M. Influence of partial vermicompost tea substitution for mineral nitrogen fertilizers on yield and nutrient content of wheat cultivars. *Crops*. 2025;5:51. <https://doi.org/10.3390/crops5040051>.
155. Ding Z, Kheir AMS, Ali OAM, et al. A vermicompost and deep tillage system to improve saline-sodic soil quality and wheat productivity. *J Environ Manage*. 2021;277:111388. <https://doi.org/10.1016/j.jenvman.2020.111388>.
156. Mupambwa HA, Gawanab W, Lilungwe E, et al. The potential of seaweed Biochar and fly Ash amendments in enhancing vermi-degradation and the fertilizer value of cow manure, wastepaper-based vermicompost. *Bioresour Technol Rep*. 2024;28:101968. <https://doi.org/10.1016/j.biteb.2024.101968>.
157. Mupambwa HA, Lukashe NS, Mnkeni PNS. Suitability of fly Ash vermicompost as a component of pine bark growing media: effects on media physicochemical properties and ornamental marigold (*Tagetes* spp.) growth and flowering. *Compost Sci Util*. 2017;25:48–61. <https://doi.org/10.1080/1065657X.2016.1180270>.
158. Liang C, Yang D, Dong F, et al. Biocontrol potential of bacteria isolated from vermicompost against meloidogyne incognita on tomato and cucumber crops. *Horticulturae*. 2024;10:407. <https://doi.org/10.3390/horticulturae10040407>.
159. Oyege I, Balaji Bhaskar MS. Evaluation of vermicompost and vermicompost tea application on corn (*Zea mays*) growth and physiology using optical plant sensors. *J Plant Nutr*. 2025;48:1275–93. <https://doi.org/10.1080/01904167.2024.2434583>.
160. Wonglom P, Ruangwong O-U, Poncheewin W, et al. Trichoderma-Bioenriched vermicompost Vnduces defense response and promotes plant growth in Thai rice variety Chor Khing. *J Fungi*. 2024;10:582. <https://doi.org/10.3390/jof10080582>.
161. Demir Z. Effects of vermicompost on soil physicochemical properties and lettuce (*Lactuca sativa* Var. Crispa) yield in greenhouse under different soil water regimes. *Commun Soil Sci Plant Anal*. 2019;50:2151–68. <https://doi.org/10.1080/00103624.2019.1654508>.
162. Aksakal EL, Sari S, Angin I. Effects of vermicompost application on soil aggregation and certain physical properties. *L Degrad Dev*. 2016;27:983–95. <https://doi.org/10.1002/ldr.2350>.
163. Glaser B, Wiedner K, Seelig S, et al. Biochar organic fertilizers from natural resources as substitute for mineral fertilizers. *Agron Sustain Dev*. 2015;35:667–78. <https://doi.org/10.1007/s13593-014-0251-4>.
164. Sharma A. A review on the effect of organic and chemical fertilizers on plants. *Int J Res Appl Sci Eng Technol V*. 2017;6:77–80. <https://doi.org/10.22214/ijraset.2017.2103>.
165. Yu X, Keitel C, Zhang Y, et al. Global meta-analysis of nitrogen fertilizer use efficiency in rice, wheat and maize. *Agric Ecosyst Environ*. 2022;338:108089. <https://doi.org/10.1016/j.agee.2022.108089>.
166. Palchetti E, Moretta M, Calamai A, et al. Effects of nitrogen fertilization and plant density on proso millet (*Panicum miliaceum* L.) growth and yield under mediterranean pedoclimatic conditions. *Agriculture*. 2023;13:1657. <https://doi.org/10.3390/agriculture13091657>.
167. Arif M, Ali S, Ilyas M, et al. Enhancing phosphorus availability, soil organic carbon, maize productivity and farm profitability through Biochar and organic–inorganic fertilizers in an irrigated maize agroecosystem under semi-arid climate. *Soil Use Manag*. 2021;37:104–19. <https://doi.org/10.1111/sum.12661>.
168. Wang Y, Chen YF, Wu WH. Potassium and phosphorus transport and signaling in plants. *J Integr Plant Biol*. 2021;63:34–52. <https://doi.org/10.1111/jipb.13053>.
169. Xu Q, Fu H, Zhu B, et al. Potassium improves drought stress tolerance in plants by affecting root morphology, root exudates and microbial diversity. *Metabolites*. 2021;11:1–17. <https://doi.org/10.3390/metabo11030131>.
170. El-Mageed TAA, Semida WM, Abdou NM, El-Mageed SAA. Coupling effects of potassium fertilization rate and application time on growth and grain yield of wheat (*Triticum aestivum* L.) plants grown under cd-contaminated saline soil. *J Soil Sci Plant Nutr*. 2023;23:1070–84. <https://doi.org/10.1007/s42729-022-01104-3>.
171. Philp JNM, Cornish PS, Te KSH, et al. Insufficient potassium and sulfur supply threaten the productivity of perennial forage grasses in smallholder farms on tropical sandy soils. *Plant Soil*. 2021;461:617–30.
172. Sidhu SK, Zotarelli L, Sharma LK. A review of potassium significance and management approaches in potato production under sandy soils. *J Sustain Agric Environ*. 2024;3. <https://doi.org/10.1002/sae2.12106>.
173. Wang H, Zheng H, Jiang Z, et al. Efficacies of Biochar and Biochar-based amendment on vegetable yield and nitrogen utilization in four consecutive planting seasons. *Sci Total Environ*. 2017;593–594:124–33. <https://doi.org/10.1016/j.scitotenv.2017.03.096>.
174. Ye L, Camps-Arbestain M, Shen Q, et al. Biochar effects on crop yields with and without fertilizer: A meta-analysis of field studies using separate controls. *Soil Use Manag*. 2020;36:2–18. <https://doi.org/10.1111/sum.12546>.
175. Elfeel AA, Abohassan RA. Compost effects on leaf area index and seed production enhancement in an important arid land leguminous tree (*Acacia tortilis* subsp. *Raddiana*). *Legum Res*. 2016;39:748–54. <https://doi.org/10.18805/lrv0iOF.3546>.
176. Hematimatin N, Igaz D, Aydın E, Horák J. Biochar application regulating soil inorganic nitrogen and organic carbon content in cropland in the central europe: a seven-year field study. *Biochar*. 2024;6:14. <https://doi.org/10.1007/s42773-024-00307-4>.
177. Agegnehu G, Nelson PN, Bird MI. The effects of biochar, compost and their mixture and nitrogen fertilizer on yield and nitrogen use efficiency of barley grown on a Nitisol in the highlands of Ethiopia. *Sci Total Environ*. 2016;569–570:869–79. <https://doi.org/10.1016/j.scitotenv.2016.05.033>.
178. Wolka K, Melaku B. Exploring selected plant nutrient in compost prepared from food waste and cattle manure and its effect on soil properties and maize yield at Wondo Genet, Ethiopia. *Environ Syst Res*. 2015;4:9. <https://doi.org/10.1186/s40068-015-0035-0>.
179. Demelash N, Bayu W, Tesfaye S, et al. Current and residual effects of compost and inorganic fertilizer on wheat and soil chemical properties. *Nutr Cycl Agroecosystems*. 2014;100:357–67. <https://doi.org/10.1007/s10705-014-9654-5>.
180. Giannakis GV, Kourgiyalas NN, Paranychianakis NV, et al. Effects of municipal solid waste compost on soil properties and vegetables growth. *Compost Sci Util*. 2014;22:116–31. <https://doi.org/10.1080/1065657X.2014.899938>.

181. Jain MS, Kalamdhad AS. Soil revitalization via waste utilization: compost effects on soil organic properties, nutritional, sorption and physical properties. *Environ Technol Innov*. 2020;18:100668. <https://doi.org/10.1016/j.eti.2020.100668>.
182. Liu B, Cai Z, Zhang Y, et al. Comparison of efficacies of peanut shell Biochar and Biochar-based compost on two leafy vegetable productivity in an infertile land. *Chemosphere*. 2019;224:151–61. <https://doi.org/10.1016/j.chemosphere.2019.02.100>.
183. Alkobaisy JS, Mutlag NA. Effect of the use of vermicompost and rhizobial inoculation on some soil characteristics, growth and yield of mung bean vigni radiate L. *Iraqi J Agric Sci*. 2021;52:163–9. <https://doi.org/10.36103/jjas.v52i1.1248>.

Publisher's note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.