

Sustainable Soil Management: A Challenge for Sustainable Agriculture in Tropical Regions

Ruth Adenike KOREDE, Oluwakorede Ipoola SALAWU, and Henry Olalekan IBIRONKE

Department of Crop and Horticultural Sciences, Faculty of Agriculture, University of Ibadan, Ibadan, Oyo State, Nigeria.

Abstract: Soil degradation caused by poor management has become a major global issue, especially in tropical areas where high temperatures and heavy rainfall are the norm. This degradation takes a toll on agricultural productivity, food security, and the overall quality of the environment. Tropical soils often lack organic matter and essential nutrients due to severe weathering, leading to problems like nutrient leaching and erosion. These challenges are made worse by practices such as slash-and-burn agriculture, which not only strip the soil of nutrients but also lead to deforestation and increased greenhouse gas emissions. To counter these negative effects, it's vital to implement effective soil management strategies that enhance soil fertility and support agricultural productivity. Integrated nutrient management (INM) strategies are key to maintaining soil health, as they blend organic and inorganic fertilization methods with conservation techniques. Using compost, manure, and green manure can boost organic matter levels, while careful application of inorganic fertilisers provides the necessary nutrients for crops to thrive. Even with the natural limitations of tropical soils, sustainable practices like no-tillage, cover cropping, and crop rotation can greatly enhance soil quality and promote eco-friendly farming. Identifying nutrient deficiencies and employing advanced fertiliser application techniques are crucial for increasing crop yields and ensuring agricultural productivity. By embracing these methods, farmers can achieve lasting agricultural sustainability in tropical regions, ultimately supporting food security and environmental resilience.

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INTRODUCTION

Soil degradation resulting from inappropriate management of the available soil resources has been a global concern in the 20th century and continues to be a critical issue in the 21st century, impacting the environment, agricultural productivity, food security, and overall quality of life (Scholten and Seitz, 2019; Abdulkadir et al., 2021). This phenomenon is a major subject in the Tropics where soils develop in regions characterised by high annual temperatures and rainfall. While the climates of savannas and tropical rainforests both contribute to the formation of deep, highly weathered soils, the ecosystems and conditions in these areas vary significantly. These soils tend to have low levels of organic matter and nutrients due to the intense weathering processes they undergo. The unconsolidated surface material, which consists of mineral or organic matter, is influenced by genetic and environmental factors such as climate (temperature and water), as well as macro and microorganisms. These factors, along with relief, act on the parent material over time. Soils differ in their physical, chemical, biological, and morphological properties due to the materials from which they are derived (Olusola *et al.*, 2018). The composition of soil varies by location, and for optimal crop growth, soil fertility is essential (Kamalu *et al.*, 2018). Most tropical soils

are rich in oxides, which are present as concretions or lateritic crusts. When absent as concretions, iron oxides are found in the clay fraction, influencing the soil's physical properties (Li *et al.*, 2023).

In tropical soils, iron and aluminium oxides dominate the clay complex. For crops to reach their full potential, the soil must be fertile, which refers to its ability to retain, cycle, and supply essential nutrients for long-term plant growth. Soil fertility depends on not only nutrient content but also the activity of soil organisms (such as earthworms and microbes), the types and amounts of clay minerals, air exchange rates, and other biological, chemical, and physical factors. These elements, together with temperature, rainfall, or irrigation, impact the nutrients available for plant growth. Soil fertility is a significant challenge in the tropics due to the inherent limitations of tropical soils. Poor soil fertility results in low agricultural productivity, as agricultural success depends largely on the land's productivity. Mismanagement of soil and the vulnerability of soils contribute to significant nutrient losses through erosion and leaching (Scholten and Seitz 2019). The dry season helps retain more nutrients in these soils. In contrast, the tropical rainforest experiences year-round rainfall, often daily, which leads to nutrient leaching (Haider *et al.*, 2017). Soils in this region are often oxisols and ultisols. In

oxisols, the clay content has been leached out, leaving behind aluminium oxides, while ultisols still contain clays. Both soil types have been heavily weathered over thousands of years, resulting in the distinctive red and yellow soils found in regions like Africa, Australia, South America, and Southeast Asia (Abdulkadir *et al.*, 2021). Fertility decline is widespread in tropical regions due to insufficient nutrient replenishment and high losses compared to natural ecosystems. This issue has been recognised for decades, underscoring the need for research on soil charge dynamics and nutrient management strategies to improve agriculture and develop appropriate cropping systems.

Slash and burn agriculture is prevalent in this region. A woodland is cleared to provide fuel for cooking fires. The remaining vegetation is subsequently burnt out. This procedure extracts nutrients from trees, which plants require to grow. The area is cultivated for a few years until the nutrients run out, at which point it will be abandoned to allow vegetation to grow. After around 20-25 years, the landowners return. However, due to an increase in food demand, farmers are obliged to return to their lands before they are ready (van Leeuwen *et al.*, 2019). This can deplete soil nutrients to a very poor point. This is known as deforestation. Despite receiving plenty of rain, the soils dry out and become desert-like. This can result in severe erosion (Meselhy *et al.*, 2014).

Tropical soils have been farmed intensively without restoring their fertility, due in part to limited use of fertilisers and soil management practices. Additionally, much of the newly cultivated land is of lower quality than existing agricultural land. Despite these challenges, some tropical soils are naturally productive, supporting large amounts of vegetation (Han, 2016). According to Abdulkadir *et al.* (2021), tropical rainforests are among the most biodiverse regions in the world. Despite abundant vegetation, the soils contain few nutrients, with most of them locked in the plants and trees. The warm climate ensures rapid decomposition of plant and animal matter, which then feeds new growth. Some species never interact with the soil, and many fruits, such as bananas, mangoes, and papayas, come from these regions. Proper soil conservation is crucial for improving soil fertility in the tropics, as agriculture is deeply connected to the livelihoods of many people in these regions (Anozie and Chukwumati 2019). Sustainable agriculture aims to increase output and income without depleting natural resources. Effective soil management can conserve nutrients and help rehabilitate degraded or inherently infertile soils, particularly in tropical Africa.

Managing soil in tropical regions

The management of soils is essential for agricultural productivity, climate regulation, and the environmental cycling of energy, carbon and nutrients, as well as the sustainment of biodiversity (van Leeuwen *et al.*, 2019). Increasing agronomic productivity and improving the quality of the environment are among the important goals of soil management in the tropics. Soil management (soil fertility) is critical for plant growth, serving as a medium for nutrients, water, and oxygen. However, soil degradation, driven by nutrient depletion, erosion, salinisation, acidification, and organic matter loss, poses significant challenges, affecting 16% of global agricultural land (Scholten and Seitz 2019). Integrated nutrient management (INM) combines organic and inorganic fertilisation methods with soil and water conservation techniques to maintain fertility, especially in tropical regions where soils are heavily reliant on organic matter for nutrient release. Strategies include maximising organic material use (Olugbemi and Akinrinola, 2020; Akinrinola, 2023), balancing inorganic fertiliser application (Akinrinola and Fagbola, 2018), and minimising nutrient losses through erosion control and crop rotation. INM is adaptable to local conditions, addressing variability in resources and socio-economic factors. Policies promoting infrastructure, credit access, and sustainable practices are essential, alongside composting efforts to enhance organic matter, reduce toxic elements, and mitigate climate impacts. Overall, effective soil fertility management supports sustainable agriculture, improved productivity, and environmental conservation (Roba, 2018).

The history of agriculture is filled with examples of failed attempts to grow tropical crops using "modern" methods developed for cooler climates. While some methods have been successfully adapted, achieving success typically requires extensive experimentation and adjustment to local conditions. Although the basic principles of soil science and plant nutrition are universal, their practical application varies significantly across different climates. Soil conditions in the tropics are highly diverse, with notable differences between the wet and dry tropics, savannah belts, and paddy soils. Wet tropics often feature leached, acidic soils deficient in nutrients, but this is not universally true, especially in dry tropical regions or savannahs, where soil fertility varies widely. Consequently, the effectiveness of fertilisers in tropical agriculture also varies considerably. In the tropical zone, fertiliser responses are often disappointingly small, influenced by multiple factors still under investigation. Even when soils appear nutrient-deficient, a large response to fertilisers is not guaranteed, as crop growth can be limited by issues

like water supply, light intensity, day length, poor crop yield potential, low plant density, suboptimal farming practices, or pest and disease pressures—often more severe than in temperate regions. Tropical soils can surprisingly mobilise plant nutrients from their limited reserves. Perennial plantation crops, with extensive root systems and longer lifespans, respond differently to nutrient supplies compared to annual peasant-grown crops. Beyond the major nutrients (NPK), deficiencies in trace elements are significant in some tropical areas, such as West Africa, where their absence can hinder crop growth and reduce fertiliser efficacy. Adding these missing elements often boosts yields and fertiliser effectiveness. However, most tropical soils have adequate minor elements for common crops, making standard fertilisers generally sufficient, though trace element deficiencies remain an important factor affecting soil fertility.

The critical role of adequate plant nutrients in achieving efficient crop production is increasingly recognised (Toor *et al.* 2021). Farmers are actively addressing nutrient deficiencies and adopting enhanced management strategies to boost yields and profitability (Babajide *et al.*, 2022). Advances in fertiliser technology and a deeper understanding of plant and soil chemistry have significantly improved fertilisation techniques and farming practices, leading to increased crop yields globally (Toor *et al.*, 2021). However, Excessive use of commercial fertilisers can diminish farm profitability, degrade soil quality, and contribute to environmental pollution (Toor *et al.*, 2021). The convenience of synthetic fertilisers plus lack of knowledge on the best way to coincide fertiliser treatments with crop nutrient requirements makes this problem worse. Tropical soils have consistently been challenged by low pH, high aluminium, calcium deficiencies and low organic matter (Diatte *et al.*, 2020). Strong phosphate fixation in many tropical soils also renders phosphorus unavailable to plants and makes these soils highly unproductive. Phosphate fertiliser applications are required in substantial amounts to counteract its effects in soils prone to this phenomenon. Freiling *et al.* (2022) show that combining rock phosphate with organic manure increases rock phosphate dissolution and thereby enhances phosphorus availability to plants. Organic acids released during organic manure decomposition facilitate this process, providing the protons used to dissolve rock phosphate (Shepherd *et al.*, 2017). In tropical soils, organic matter additions are essential for economic productivity, as they enhance the soil's cation-exchange and buffering capacities (Assefa, 2019). Nitrogen is a critical nutrient limiting crop yields in the tropics, with its availability fluctuating seasonally (Sanches, 1976). Fertiliser planning and farming systems must consider

these fluctuations. Gross and Glaser (2021) found that nitrogen from organic fertilisers becomes more available in the second season due to mineralisation. Additionally, the use of aerobically composted organic waste improves mineral NUE and mitigates environmental concerns like nitrate leaching, offering both nutrient value and ecological benefits.

Sustainable soil management practices such as zero tillage, cover cropping, crop rotation, and mulching enhance soil quality, conserve resources, and promote eco-friendly agriculture in tropical regions. Among soil management practices, tillage is one of the most influential practices that change the condition of the soil surface where erosion processes take place (Wang *et al.*, 2024).

Uses of Fertiliser on Tropical Soil.

Understanding fertiliser efficiency is particularly crucial for developing countries especially West Africa, as it is essential to increase crop yields while minimising costs. Tropical regions face unique challenges due to soil, plant, and climatic factors that influence fertiliser effectiveness. Many tropical soils are acidic, which reduces fertiliser efficiency because plant roots struggle to grow and utilise the available nutrients. Enhancing yield potential requires a deeper understanding of the interactions between crop species, soil conditions, and climate. Adopting appropriate application timings, such as optimising the use of urea-based nitrogen, can significantly improve efficiency. Research has shown that an initial broadcast application of phosphorus (P) followed by band placement is more effective than using either method alone (Freiling *et al.*, 2022). Despite known yield potentials, current crop yields in tropical countries remain low, primarily due to the absence of suitable crop germplasm and a lack of knowledge about advanced agronomic practices. Therefore, increasing research into fertiliser use efficiency in tropical regions is strongly recommended to address these issues (Akinrinola and Fagbola, 2019).

Fertilisers have become one of the key factors in sustainable and modern agriculture today. The quality and yield of agricultural products is now considerably improved, by taking advantage of the advances in scientific research, technical methods and different types of fertilisers (Wenqi *et al.*, 2022). Tropical soils, with their high temperatures, intense rainfall, and varying fertility, present special challenges for agricultural productivity, and as such, fertilisers are a crucial tool for improving soil fertility and raising production. They are typically low in nutrients due to recurrent cropping and leaching due to heavy rainfall, which exacerbates deficits in crucial macronutrients such as nitrogen, phosphorus, and potassium. fertilisers replace these nutrients, enabling plants to

grow and produce optimally; nitrogenous fertilisers promote growth, phosphorus aids root development and flowering, and potassium improves resistance and fruit quality. In addition, tropical soils, such as Oxisols and Ultisols, are highly acidic, which restricts nutrient uptake and root development; lime-containing fertilisers, like calcium carbonate or dolomite, neutralize acidity, increasing overall nutrient availability. Application of organic fertilisers like compost and manure to the soil facilitates improving the structure of soil, water retention, as well as aeration and thereby address the problems caused by compaction and poor water infiltration (Oshunsanya and Akinrinola, 2013). Fertilisers can also be tailored to meet the specific nutrient needs of various crops; cereals benefit from nitrogen during vegetative stages, legumes require phosphorus and potassium to enhance growth, and cash crops like cocoa and coffee demand balanced nutrient management for better yield and quality. High rainfall in tropical regions leads to significant nutrient losses through leaching and runoff, but controlled-release fertilisers and techniques like band placement or split application can minimise these losses, ensuring nutrients are available over time (Akinrinola and Babajide, 2023). Fertilisers also support sustainable farming practices by increasing productivity on existing farmland, reducing the need for deforestation and expansion into fragile ecosystems, especially when combined with soil conservation techniques and crop rotation. Enhancing crop yields and quality through efficient fertiliser use directly contributes to food security in tropical regions, addressing the challenges of a growing population. However, effective fertiliser application requires soil testing to determine the right quantities and proportions, precise timing and methods of application, integration with organic amendments for improved efficiency, and consideration of climatic factors such as high temperatures and rainfall patterns (Akinrinola and Babajide, 2023; Olugbemi and Akinrinola, 2020). By optimising fertiliser use to address nutrient deficiencies, enhance soil fertility, and improve crop productivity, tropical regions can achieve sustainable agricultural development and ensure food security for future generations.

Research shows that planting in nutrient-deficient soils not only hampers plant growth but also impacts human and animal health through the consumption of such crops (Montgomery and Biklé, 2021). Looking ahead, it is anticipated that chemical fertilisers will be increasingly utilised in agricultural production to grow higher-quality crops and meet the rising food demands driven by the growing global population. The use of fertilisers is crucial for achieving large-scale sustainable improvements in crop productivity across tropical Africa. However, smallholder farmers often

face significant financial constraints, necessitating high profit-to-cost ratios with manageable risks to gradually alleviate poverty. When fertiliser application rates are carefully tailored to the farmer's financial and agronomic circumstances, it can yield substantial profitability. Ensuring access to commonly used fertilisers is typically essential for maximising the profit-to-cost ratio. (Ewulo, and Sanni, 2015)

Inorganic Fertiliser and Organic Fertiliser

Both organic and inorganic fertilisers supply essential nutrients required for healthy and robust plant growth. However, they differ in composition and the manner in which they deliver these nutrients. Organic fertilisers gradually enhance the growing environment over time, while inorganic fertilisers offer a quick source of nutrition (Roba, 2018). Organic fertilisers are derived exclusively from plant or animal-based materials, often as by-products or end-products of natural processes, such as manure, compost, or decomposed leaves. In contrast, inorganic fertilisers, also known as synthetic fertilisers, are artificially produced and consist of minerals or chemically synthesised substances.

It is crucial to understand that fertiliser alone is not a solution to all the challenges facing Nigerian agriculture. Promoting its use without addressing other necessary interventions will have minimal long-term impact (ALnaass *et al.*, 2021). It is essential to acknowledge that fertiliser, by itself, cannot resolve all the issues affecting Nigerian agriculture. Its promotion, without incorporating other critical measures, is unlikely to yield sustainable results.

Organic fertiliser, when available, should be an integral part of soil fertility management strategies (Akande *et al.*, 2018). However, relying solely on organic fertiliser will not suffice to sustain the high levels of productivity required to feed Nigeria's rapidly growing population. This limitation arises from spatial and temporal variability in the production and use of organic fertilisers. Key challenges in Nigerian agriculture include diminishing fallow periods, deforestation, and land degradation—the latter being the temporary or permanent decline in land productivity due to continuous cultivation without adequate soil fertility replenishment. As a renewable resource, organic manure interacts synergistically with the soil to enhance fertility sustainably (Akinpelu *et al.*, 2019). It also supports soil biological activity, improves water retention, and enhances aeration, recognising that soil is a living system.

Inorganic fertilisers, also known as mineral, chemical, or synthetic fertilisers, provide either a single nutrient—such as nitrogen, phosphorus, or potassium—or a combination of these macronutrients along with trace

elements in compound or mixed formulations. Organic sources, on the other hand, include animal manure, household waste, plant materials like crop residues, and compost (Akinrinola, 2018; Akinrinola and Ojo, 2024). Both types of fertilisers play significant roles in the development of Nigerian agriculture. According to Abdulkadir *et al.* (2021), Nigerian soils are generally low in productivity due to poor moisture retention, low organic carbon, and insufficient organic matter, as no soil type in Nigeria inherently supports high productivity. This has put farmers in a predicament of needing to continue to use and conserving soils effectively in order to keep from degrading further. Based on the 1990 Global Assessment of Soil Degradation (GLASOD), the percentage of land surface estimated to have been degraded was 27 % (Montgomery *et al.*, 2021).

As highlighted by Randolph *et al.* (2017), some of these unsustainable agriculture practices include burning plant residues for disposal, overuse of agrochemicals manufactured from non-renewable materials, and disruption of complex soil processes through practices such as unnecessary tilling and unbalanced applications of chemicals for fertiliser and pest control. These practices also cause the food chain to become contaminated with harmful pesticides and over-irrigation, leading to soil salinisation and groundwater resource depletion (Dhankhar and Kumar, 2023).

To enhance soil fertility and produce healthy crops with high output, the application of organic fertilisers as part of sustainable agriculture not only supplies fundamental minerals but also makes the soil better through enhancing its structure, chemical, and biological makeup (Oshunsanya and Akinrinola, 2013; Akinrinola and Fagbola, 2019). This practice contributes to the overall health of agricultural soils. An added benefit of organic fertilisers is the gradual release of nutrients and the reuse of soil organic matter. Based primarily on locally sourced materials with minimal reliance on external inputs, it aligns with the eco-supportive strategies for sustainable rural development advocated by Montgomery *et al.* (2021). However, a drawback is that rapid decomposition of organic matter can release nutrients quickly, while slower decomposition, which favours the release of soil organic matter, depends on moisture and temperature—factors beyond human control. Consequently, nutrients may become available when plants do not require them. Moreover, the limited availability of organic matter in many regional soils makes it insufficient to meet crop nutrient demands on its own.

The advantages of inorganic fertilisers include their known nutrient content and the rapid release of nutrients, as they do not require the decomposition of other materials. This allows for precise prediction of nutrient uptake timing. However, the disadvantages include their high cost and the long-term environmental damage they cause, which may outweigh their benefits, especially given the poverty levels among Nigerian farmers and the fragility of the farming ecosystem. According to Adesina (2012), fertiliser use per hectare in sub-Saharan Africa is the lowest globally. Additionally, while it is relatively straightforward to measure yield increases from inputs such as agrochemicals, irrigation, mechanisation, labour, and the adoption of modern high-yielding varieties, the impact of sustainable inputs often goes unquantified.

Improving soil biology primarily depends on enhancing soil organic matter levels. The most cost-effective approach involves the bulk application of animal manures, green manures (such as straw and hay), and farm-produced composts, where available. The effectiveness of specialised products "rich in beneficial organisms" depends on the presence of adequate organic matter in the soil. Heavy applications of manures and composts gradually enhance the indigenous and introduced populations of soil organisms, improving soil fertility over time. As soil is a living system, its health and productivity will improve with these practices. However, while the application of manures and composts can raise soil organic matter and support soil biology (assuming organic inputs exceed outputs), they must be supplemented with inorganic fertilisers to meet the annual nutritional demands of crops (Adeola *et al.*, 2023). This also indirectly supports the nutritional needs of some soil organisms. Inorganic fertilisers, particularly for nitrogen and potassium, remain essential. For phosphorus, an annual application of chicken litter may suffice, as it provides both phosphorus and a substantial amount of organic matter. Farmers typically apply organic products to their soils either to enhance crop yields by improving soil health or to prioritise soil health, with improved yields as a secondary goal. Optimal soil health begins with sufficient soil organic matter, which serves as the primary food source for soil organisms (Akinrinola *et al.*, 2022). Applying specialised products that promote microorganism populations and related soil activities may provide limited benefits in soils with low organic matter levels. Organic manures often require large quantities to achieve the desired effects, and additional labour is needed for harvesting green manures or preparing cattle manure. A lack of seeds for green manures is a significant limitation, and the effectiveness of most organic materials must often be

enhanced with costly mineral fertilisers. Moreover, green manures take up land that could otherwise be used for growing food crops.

Biochar and its Effects on Soil Properties

Biochar is a carbon-rich solid material produced by the pyrolysis of biomass in an oxygen-limited environment (García *et al.*, 2021). Pyrolysis, as described by Osayi *et al.* (2014), is the thermal decomposition of organic materials within an oxygen-deprived setting, leading to biochar production, syngas, and bio-oil.

Factors that affect the yield of biochar include heating rate, residence time and lignin content in the feedstock. According to Diatta *et al.* (2020) and Laghari *et al.* (2015), biochar produced under low temperature ≤ 300 °C had higher nutrient content than that at high temperature ≥ 600 °C. Generally, properties of biochar such as pH, surface area, water-holding capacity, electrical conductivity and pore size distribution, usually depend on type of feedstock and pyrolysis temperature and conditions (Shepherd *et al.*, 2017).

Feedstock composition of biochar production is important and determines the final product characteristics and quality (Tomczyk *et al.*, 2023). Crop residues have high ash content, compared to woody and organic sources such as manure, which also have high calorific values with few voids (Ji *et al.*, 2022). Many feedstocks may be utilised including corn cob and corn stalk, rice straw, cotton stalk, wheat straw, sugar cane straw, and maize husk (Zubairu *et al.*, 2023).

Biochar derived from biomass has received considerable attention from the scientific community due to its tremendous potential for promoting long period carbon sequestration, its recalcitrance in nature and its various applications (Das *et al.*, 2021). Use of the amendment has been shown to enhance soil physical, chemical, hydrological and biological properties by enhancing soil fertility through minimizing leaching of nitrogen to the groundwater, raising the cation exchange capacity, lowering soil acidity, as well as enhancing the water retention capacity (Scholten and Seitz 2019).

Biochar acts as an organic fertiliser by adding nutrients from the feedstocks to the soil (Gul *et al.*, 2016). Advantages of applying biochar include increased nutrient utilisation and decreased nutrient leaching in the soil (Randolph *et al.*, 2017), Enhanced nutrient retention and natural nutrient richness (Shepherd *et al.*, 2017). It is particularly known for its capacity to directly retain macronutrients such as nitrogen (N) (Randolph *et al.*, 2017). Laghari *et al.* (2015) study reports that the addition of biochar to sandy soils of low fertility increased nutrient levels significantly. In addition, biochar addition increased levels of total carbon (C) by 7–11%, potassium (K) by

37–42%, phosphorus (P) by 68–70%, and calcium (Ca) by 69–75%.

The pH of the soil may be affected by different biochar amendments, depending on the type of soil or biochar used. For instance, alkaline biochar can be added to acidic soils to raise the pH of the soil. This pH change, according to Zhang *et al.* (2017) can then affect the availability of nutrients in the soil matrix. As a result, biochar can serve as a soil amendment and used to provide a liming effect, lower soil acidity, and improve soil quality by improving soil nutritional availability (Zubairu *et al.*, 2023).

However, the addition of acidic or neutralized biochar in order to decrease the alkalinity of alkaline soils would change the solubility of soil nutrients like phosphorus and trace minerals (Laghari *et al.*, 2015).

The reported retention of ammonium and nitrate following biochar application has been repeatedly noted in field research (Haider *et al.*, 2017), and laboratory and greenhouse experiments (Han *et al.*, 2016) have similarly shown this pattern. The choice of feedstock and pyrolysis temperature are two examples of variables that affect how biochar affects the soil nitrogen cycle (Solaiman and Anawar, 2015). Existing research supports the potential of lowering soil ammonia and nitrate losses by inhibiting nutrient release to plant roots by inorganic N adsorption onto biochar (Haider *et al.*, 2017). Experiments in greenhouse and laboratory settings, field studies, and other relevant research, such as adsorption (Amin *et al.*, 2023), have all supported this occurrence (Haider *et al.*, 2017; Abdulsalam and Akinrinola 2024).

Biochar has become a focus of attention in the global endeavour to reduce the surge in atmospheric CO₂ concentrations (Paustian *et al.*, 2016). Biochar can boost plant productivity and hence increase soil carbon (C) inputs (Gross and Glaser, 2021), it may be especially beneficial for low-fertility soils (García *et al.*, 2021). In contrast to other organic soil fertilisers like compost and manure, which break down more quickly (Akinrinola and Fagbola, 2018; Akinrinola and Tijani-Eniola, 2022), the carbon component of BC exhibits a higher degree of stability and resistance to degradation inside the soil, as noted by Zubairu *et al.* (2023). The longer carbon half-lives, which range from 102 to 107 years for lower and higher temperature biochar, respectively, are responsible for this resistance (Tomczyk *et al.*, 2020).

Biochar exhibits the ability to increase the diversity and activity of soil microbial populations by utilising its special qualities that contribute to the physical and chemical characteristics of soil, such as its porous structure, CEC, and substantial sorption capability (Ji *et al.*, 2022; Abdulsalam and Akinrinola 2024).

The microstructure of biochar, particularly those forms rich in micro-porosity, greatly increases its

usefulness as a habitat for microorganisms by offering ideal pore spaces that enable their proliferation (Diatta *et al.*, 2020). In addition to offering readily degradable carbon sources and vital mineral elements that support microbial growth, biochar also protects microorganisms from problems like desiccation and exploitation, as highlighted by Diatta *et al.* (2020).

Role of fertilisers in soil fertility and crop productivity

Fertilisers constitute a key component of modern agriculture, as they significantly boost soil fertility and crop yields, particularly in nutrient-poor soils. They provide the plant with the essential macronutrients—i.e., phosphorus (P), potassium (K), and nitrogen (N)—in addition to essential micronutrients required for growth, development, and reproduction (Alnaass *et al.*, 2021). In intensive agricultural systems, the nutrients are rapidly depleted from the soil; therefore, in the absence of fertiliser replacement, soil fertility decreases leading to low yields and poor quality crops. Through their replenishment function, fertilisers support important plant metabolic processes such as photosynthesis, root development, and nutrient absorption, which translate into improved crop quality and yield (Asadu *et al.*, 2024).

In particular, nitrogen is vital because it is involved in the synthesis of chlorophyll, a basic ingredient in the process of photosynthesis. The applications of nitrogen are proven to increase chlorophyll concentration leading to accelerated plant growth and biomass accumulation (Fathi, 2022). For instance, He *et al.* (2024) demonstrated that rice yield increased with appropriate nitrogen application rates, with some treatments showing increased rice yield up to 19.38% compared to lower nitrogen applications. Also, phosphorus is essential for root growth and the transfer of energy by ATP synthesis, which are critical for plant resistance and nutrient uptake. Research indicates that phosphorus is crucial for root development, and its deficiency can result in poor root establishment (Malhotra *et al.*, 2018). This inadequate root system limits the plant's capacity to uptake essential nutrients and water, which is critical for overall plant health and productivity (Liu *et al.*, 2024). Additionally, potassium also has a unique role in improving plant stress tolerance. Potassium enables plants to survive drought by regulating water usage in plant cells and strengthening cell walls, which in turn, make plants less susceptible to certain diseases (Xu *et al.*, 2021). The results of a study showed that application of 75 kg ha potassium improved grain yield, biological yield, and water productivity of maize

under drought conditions. This application rate was associated with enhanced drought resilience compared to lower rates, highlighting potassium's role as a stress alleviator (Ul-Allah *et al.*, 2020). In addition, potassium increases fruit and vegetable quality by enhancing sugar accumulation and colour uniformity, both of which are essential to market value. For instance, a study by Valentinuzzi *et al.* (2018) demonstrated that the use of potassium-based fertiliser by foliar spray increased the total content of soluble solids (sugars) by approximately 12% and the sweetness index by approximately 13%.

Significantly, organic fertilisers are also crucial, especially in sustainable agriculture. Organic fertilisers, which are obtained from plant residues, animal manure, and compost, decompose slowly and release nutrients gradually, adding to the long-term fertility of the soil. A meta-analysis conducted by Gross and Glaser (2021) reported that the application of manure on agricultural soils increased the stocks of soil organic carbon by 35.4% on average and corresponded to approximately 10.7 Mg ha⁻¹. Consequently, this implies substantial improved soil organic matter as a result of manure application over time. Organic fertilisers also generate microbial activity in soil. For instance, Gu *et al.* (2019) and Akinrinola *et al.* (2022) describe that organic manure application enhances microbial diversity and alters microbial community composition in agricultural soils. It emphasizes that organic amendment such as manure has a beneficial effect on soil health by increasing the microbial abundance and diversity that promote nutrient cycling and general soil quality. Thus, organic fertilisers not only increase the yields of crops but also reduce the dependency on synthetic fertilisers and therefore encourage sustainable agriculture (Assefa, 2019).

Excessive or imprudent use of fertiliser could contribute to the degradation of the environment. For example, high quantities of inorganic fertilisers containing nitrogen and phosphorus typically lead to large amount of nutrient runoff and subsequently eutrophication of bodies of water, thereby disturbing aquatic ecosystems (US EPA, 2024). Such impacts raise the importance of precision agriculture where the fertilisers are applied according to crop needs and soil conditions. In this context, Dinesh *et al.* (2024) reported that precision nitrogen management in maize lowered the loss of nitrogen by 20% without compromising yields, thereby exemplifying the potential offered by technology-based methods in increasing fertiliser efficiency.

CONCLUSION

Soil degradation caused by poor management practices has become a pressing global concern, especially in tropical areas where high temperatures and heavy rainfall are the norm. This degradation has serious implications for agricultural productivity, food security, and the overall quality of our environment. Tropical soils often struggle with a lack of organic matter and nutrients due to intense weathering, leading to issues like nutrient leaching and erosion, which are exacerbated by methods such as slash-and-burn agriculture. To improve soil fertility and maintain agricultural productivity, effective soil management is crucial. Integrated nutrient management (INM) strategies, which blend organic and inorganic fertilisers with conservation practices, play a key role in keeping soil healthy. Even though tropical soils have their challenges, sustainable practices like zero tillage, cover cropping, and crop rotation can significantly improve soil quality and encourage environmentally friendly farming. Identifying nutrient deficiencies and using advanced fertiliser application techniques are essential for increasing crop yields and ensuring long-term agricultural sustainability in tropical regions. While fertilisers are vital for enhancing soil fertility and boosting crop productivity, their use needs to be managed carefully. A balanced approach that combines organic and inorganic fertilisers can optimize nutrient availability while safeguarding soil health. By employing precise application methods, fertilisers can effectively support high-yield, quality-driven agricultural production. On the flip side, mineral or inorganic fertilisers often require a hefty financial investment, and accessing them can be tough, particularly in remote areas where farmers have limited resources. These fertilisers also need to be applied at specific times, which can be risky in regions that experience either too little or too much rainfall, potentially impacting their effectiveness.

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