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Review Article

Regenerative Horticulture: A Climate Change Strategy for Sustainable Crop Nutrition in Africa

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Abstract

Climate change is causing a need for innovative strategies to ensure sustainability and food security in crop production. This necessitates research in agriculture and horticulture to develop methods for increasing food production and improving access to nutritious food. With a comprehensive evaluation of farming practices, production, distribution and food consumption, "regenerative agriculture" and "regenerative farming" have gained interest as potential solutions. This systematic review evaluates the effectiveness of integrating biofertilizer in regenerative horticulture for sustainable nutrient supply in crop production, focusing on field studies by African farmers and researchers. It also assesses their effectiveness under various environmental conditions, including drought, salinity and temperature fluctuations. A thorough literature search identified relevant field-based studies involving African farmers using various biofertilizers. Criteria for inclusion were studies that examined the impact of biofertilizer on crop yield, soil health and nutrient efficiency. Data extraction and quality assessment were performed on the selected studies, followed by a meta-analysis. The findings suggest that integrating biofertilizer into regenerative horticulture is a viable strategy for sustainable nutrient management in crop production amid climate change. Field studies by African farmers show the practical benefits and growth of these practices, supporting their broader adoption for enhanced agricultural sustainability and food security.

Key words: Farming system, greenhouse gases, horticultural crops, micro-organisms, soil fertility, sustainable agriculture

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Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

The agriculture industry is under a lot of pressure, as the growing population requires more nutritious food to be produced. This requires either expanding the area of cultivated land or increasing the productivity of existing agricultural land. Increasing the productivity of current land is a more viable strategy than expanding cultivation, as it helps mitigate environmental degradation and decreases the need for additional land conversion. The application of chemical agents in farmland has historically increased horticultural crop production significantly; their excessive use and negative effects pose substantial threats to soil ecosystems and contribute to environmental pollution[1]. Several farming systems advocate for low use of synthetic fertilizers or no synthetic fertilizer at all, such as organic farming, permaculture, etc. In more recent times, the concern about GHG emissions led to advocacy for conservation agriculture (CA). However, CA continues to rely heavily on the use of synthetic fertilizers and pesticides, leading to a search for another "suite" of alternatives in the form of regenerative agriculture. When considering the critical nature of the agricultural industry, the centrifugal role it plays within the African continent and the current pressures it faces, developing more efficient, profound and cost-reducing methods for horticulture production becomes crucial. The birth of regenerative agriculture and its history are detailed[2].

Regenerative farming can be defined as a comprehensive, long-term approach designed to maximize food production with minimal resource use, aiming to restore rather than deplete the soil and simultaneously providing a viable solution for carbon sequestration[3]. This is especially important as reducing CO2 emissions to mitigate regional and global climate change is one of the most challenging issues facing humanity[4]. This shift towards regenerative agricultural practices includes the adoption of various organic and conservation farming techniques aimed at preserving and enhancing soil organic matter. These practices include minimum tillage, the cultivation of cover crops and green manures, composting, mulching and crop rotation. Employing these practices in the African agricultural land could be the solution to the degraded soil caused by the use of heavy machinery and misuse of land, which poses a threat to sustainable agriculture. Importantly, regenerative agriculture extends beyond sustainability, characterized by maintaining the existing soil health by using methods that actively restore and regenerate the soil[5]. Whilst there are minor differences that exist amongst proponents of this approach regarding the place of synthetic fertilizers, there is general agreement that bio-fertilizers will drive increased productivity in the future[6]. The use of phosphorus biofertilizer, a key component of regenerative agriculture, influenced the relative abundance of various microbial phyla, classes and orders, enhanced the variety of soil microorganisms and showed that the sampling time also affects the composition of the soil microbiome[7].

Biofertilizers are broadly defined as organic material and/or microorganisms that are utilized to enhance nutrient uptake, stimulate plant growth and improve stress tolerance or crop quality[8]. In the specific context of the African smallholder farmer, if they work and an initial capital layout is affordable, bio-fertilizers may offer a better alternative to use instead of synthetic fertilizers. Available statistics on the use of inorganic fertilizers show that Africa lags far behind other continents in the use of fertilizers[9] mentioned that from 2002-2016, the use of nitrogen-based fertilizers in Africa was 0,3-15 kg/ha. Mainly because of costs that are driven by, among other factors, poor infrastructure and markets. The use of biofertilizers in regenerative agriculture in Africa could be an ideal solution, as this fertilizer contains microbes that assist in the biological soil mineralization; their combination with the principles of regenerative agriculture would sustain the soil health while maintaining the yield of horticulture crops. Application of biofertilizer in saline soil significantly heightened soil nutrient effectiveness, increased microbial biomass, enhanced nitrogen utilization efficiency and increased cotton yield[10]. Horticulture has garnered increasing recognition in many African countries as concern has moved from food security to food and nutrition security. Horticultural commodities, such as vegetables, require substantial amounts of nutrients to achieve the high levels of production and productivity necessary to feed an ever-growing African population, which is projected to reach 1 billion by 2030[11]. This review examines the capacity of biofertilizers to sustainably enhance food production for Africa's increasing population employing regenerative agriculture. The objective is to evaluate the availability, efficacy and adaptability of biofertilizer products in the horticultural sector by examining field-based evidence from African studies.

MATERIALS AND METHODS

Search strategy: To explore the use of biofertilizers in regenerative horticulture for sustainable nutrient supply in crop production amidst climate change in Africa, we followed the PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses) guidelines for a systematic review[12]. Peer-reviewed articles were obtained using Web of Science and Scopus, looking for publications that researched

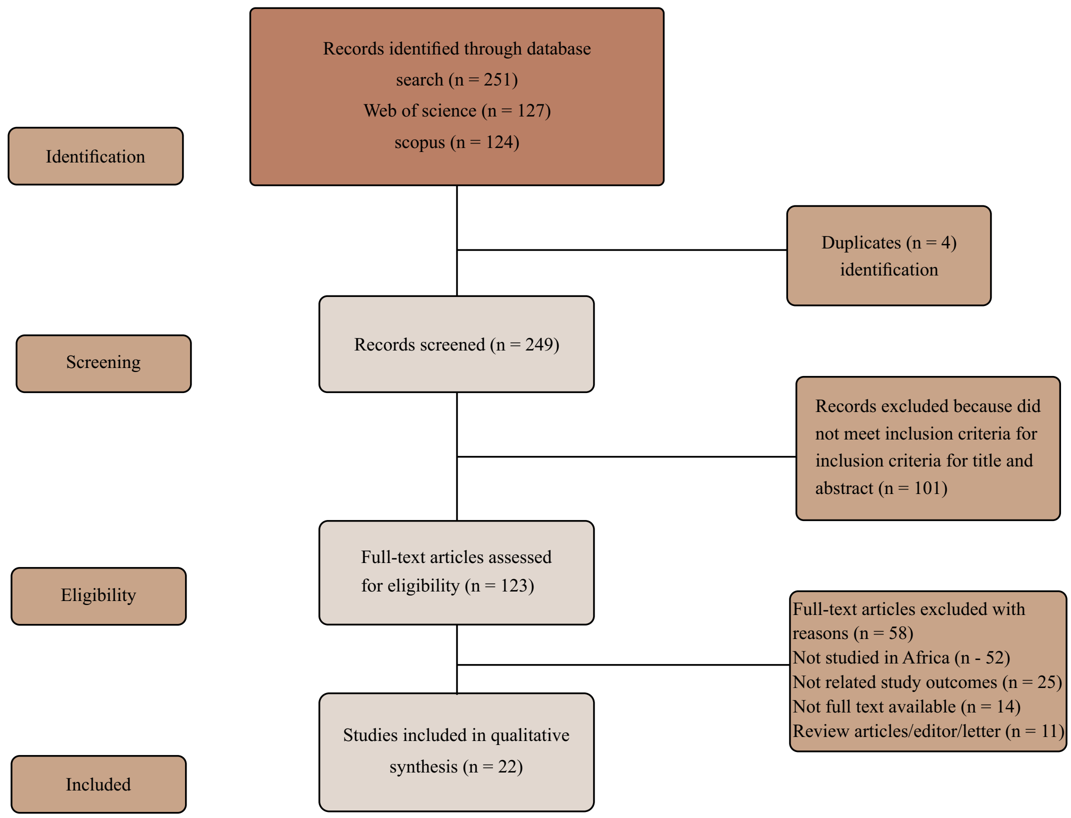

Fig. 1: Flow diagram of the selection process used to identify studies for inclusion in this review based on the PRISMA Statement[12]

bio-fertilizers/bio-stimulants in Africa, regenerative horticulture, nutrient supply, slow nutrient release fertilizer, crop production and climate change. To source information, the following key words and phrases were used, ("biofertilizer" OR "bioeffectors" OR "biostimulants" OR "slow release fertilizer") AND ("organic material") AND ("regenerative farming") AND ("climate change") AND ("Africa") AND ("horticulture crops") AND ("sustainable agriculture") AND ("inoculants") AND ("soil microorganisms") AND ("plant nutrition") AND ("nutrient use efficiency") AND ("nutrient losses") AND ("soil fertility" OR "soil health") AND ("biofertilizer types") AND ("fertilizers in Africa" OR "fertilization in Africa") AND ("greenhouse gases").

INCLUSION AND EXCLUSION CRITERIA

Table 1 outlines the inclusion and exclusion criteria used to select studies for this review. The inclusion criteria focused on field-based experiments evaluating the effects of biofertilizers on either fully grown plants or seedlings. Studies that tested biofertilizers in the field and later analyzed samples in the laboratory were also included, provided they met peer-review and English-language requirements. In contrast, studies conducted exclusively in glasshouses, laboratories, or incubation settings were excluded, along with non-peer-reviewed sources such as conference papers, editorials, letters, commentaries, short surveys, notes and articles not written in English. Only studies specifically examining the effects of biofertilizers were considered eligible.

HAND SEARCH AND DATA MANAGEMENT

To improve sensitivity and find more comparable studies, looked through the published papers' (251) reference lists. The Excel program was used to handle and manage the retrieved references found through database searches. Replications were eliminated and added to a duplicate collection.

Data extraction: Data from the selected articles were independently screened and extracted by a single author (A.M). The search result was obtained by reading the title and abstract of the retrieved papers to determine if the article was relevant to the study. Once determined, the full text of the selected articles was further analysed to extract relevant information. The information that was collected and extracted after full text reading from each article included year, study

Table 1: Inclusion and exclusion criteria of studies

Inclusion criteria	Exclusion criteria
Field experiment studies	Studies conducted in glasshouses only
Studies that involved testing the effect of biofertilizer in the field and were subsequently analyzed in the lab	Studies conducted in the Lab and Incubation studies
Studies that investigated the effect of biofertilizer on both fully grown plants and seedlings	Conference papers, editorials, letters, commentary, short surveys and notes
Articles written in English	Articles not Written in English
Peer-reviewed articles	Non-peer-reviewed articles
Studies from the lab and field	
Studies that investigate biofertilizers only	

area and country, type of biofertilizer studied, soil type that the biofertilizer was used in, type of crop used, main research findings and conclusions. Collected articles were categorised by country and biofertilizer type.

Data analysis: A thorough analysis of regenerative agriculture on African soils was conducted to assess the effect of biofertilizer on horticulture crops in different soil types. The findings were presented through tables, with descriptive statistics presented using bar graphs and figures showing the geography of the included studies. To manage the data, Excel and Mendeley software were utilized for data acquisition and storage from the databases, with duplicate entries systematically removed.

Risk of bias assessment: The methodological quality of eligible studies was ranked and classified using the Jadad scale as part of the quality assessment process. Every study was assigned a value between 0 and 5, considering factors such as blinding and randomization. Research with a Jada score of more than 3 was regarded as of good quality. The Cochrane Collaboration risk of bias evaluation methods, which include the following six domains: Sequence creation, allocation concealment, blinding, incomplete data, selective reporting and additional bias, were used to evaluate the quality of the included studies. The risk of bias evaluation was carried out separately by the first two authors, who discussed any discrepancies with a third author. The author's classification of bias is low risk, high risk, or unclear risk.

Study selection: A total of 251 records were identified through four databases. A total of 249 records remained after duplicates were removed. Of those remaining, 126 records were deemed ineligible based on their titles and abstracts. Of the 123 papers that were qualified for a full-text review, 101 full-text articles were excluded because they did not meet the eligibility criteria for the review, the review covered articles published between 2021 to 2025 (Fig. 1).

RESULTS

The included studies used different types of biofertilizers. Table 1 shows the papers and the type of biofertilizer used in each paper (Table 2). Biofertilizers can be divided into three classes (i) Microbial, which uses bacteria, fungi, viruses, protozoa and nematodes; (ii) Botanical, which uses substances produced by plants; and(iii) Biochemical, which uses natural substances from either source[13].

GENERAL CHARACTERISTICS OF THE INCLUDED STUDIES

Thirty-one peer-reviewed journal articles were included in the use for the analysis and interpretation of the data. All the selected studies included the investigation of biofertilizers and their associated factors as their main findings. These are the general characteristics of the included studies and their study findings summary. Nineteen of the included studies were of Randomised Complete Block Design (RCBD), seven were split-plot design and two were a Complete randomised block design; three studies did not mention the experimental design used. Studies that were conducted in clay loam soils were that of[14,19,29] and Sandy loam[16,26,33,24] and Vertisol and Nitisol[18] and Sandy[25,32,34] and Clay[29,32,21] and Sandy clay loam[20] and Soil type not mentioned[14,17,22]. Ten of the studies were conducted in one season only, eighteen were conducted in two seasons and three were conducted in three seasons; the other eight were not mentioned.

GEOGRAPHY OF THE INCLUDED STUDIES

The most studied microbial-based biofertilizers are rhizobium and bacillus with a mixture of other materials, followed by AMF and trichoderma (Table 1). On the botanical-based biofertilizer, the most studied materials are the seaweed extracts, followed by moringa leaf extracts (MLE), the least are the rice straw and *A. brasilense* and

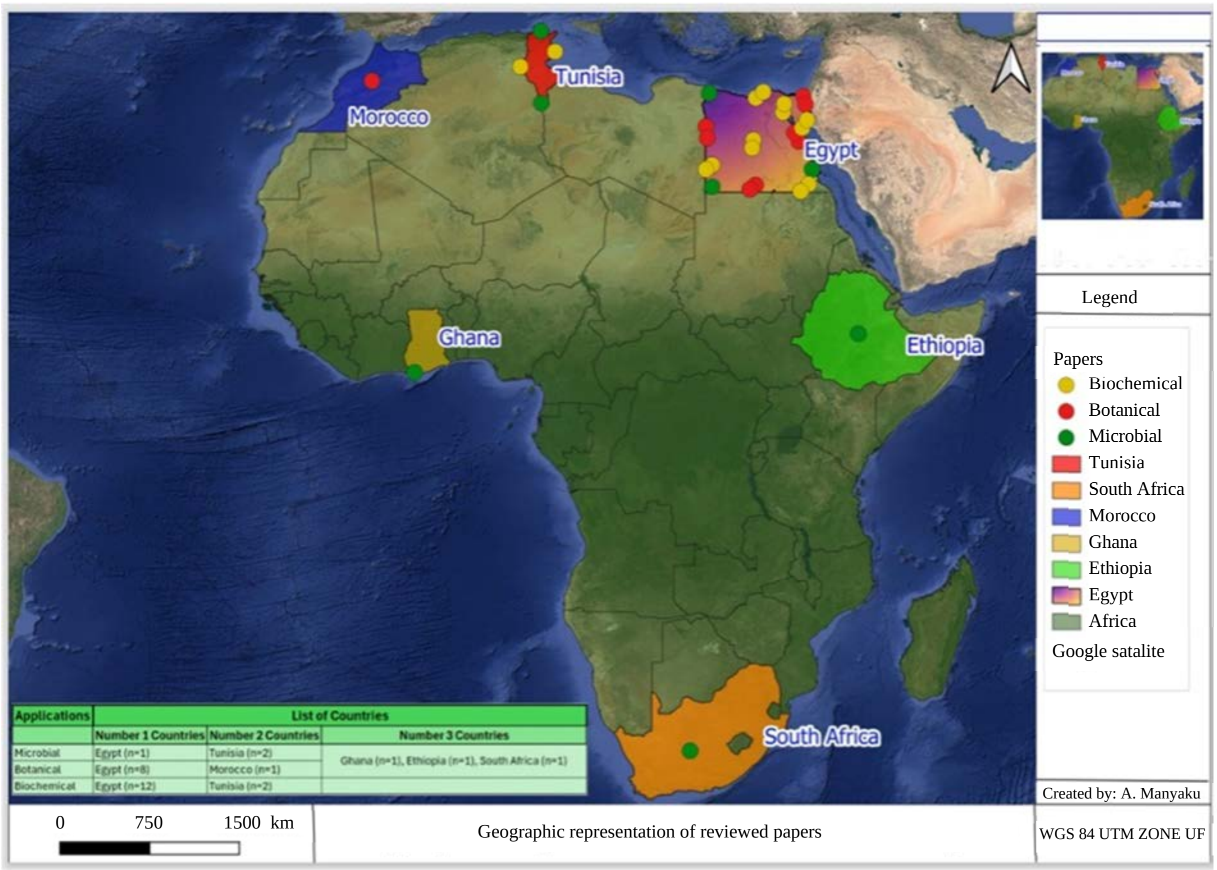

Fig. 2: Geographical distribution of reviewed papers (n = 22)
Picture created from Quantum Geographic Information

Table 2: Summary of included studies and types of biofertilizers applied

Biofertilizer types	Material used	Impact on horticulture	Papers
Microbial	- Mycorrhizae biofertilizer	The application of the microbial biofertilizer increased the yield of the horticultural crops, improved their vegetative growth. It also increased the drought tolerance in potatoes	Abdel Aal *et al.*[14]
	- *Arbuscular mycorrhizal* Fungi and plant growth-promoting Rhizobacteria		Rawaa *et al.*[15]
	- *Arbuscular mycorrhizal* Fungi		Kwashie *et al.*[16]
	- *Bacillus megaterium* and *Trichoderma album*		Fatema *et al.*[17]
	- *Pseudomonas fluorescens, Bacillus subtilis and Rhizobium leguminosarum*		Sileshi *et al.*[18]
	- *Trichoderma harzianum*		Ben-Jabeur *et al.*[19]
	- *Rhizobium tropici* sp.,		Gatabazi *et al.*[20]
	Green and red algae		Galal *et al.*[21]
	- *Bacillus cabrialesii*		Masmoudi *et al.*[22]
	- *Rhizophagus irregularis*		Tahiri *et al.*[23]
	- AMF		Lahbouki *et al.*[24]
Botanical	- Seaweed extracts	The fruit yield and the vegetative growth was increased. The high frost resistance was reported in strawberries	Ashour *et al.*[25]
	- Seaweed extracts		Mosa *et al.*[26]
	- Seaweed extracts		Amer *et al.*[27]
	- Seaweed extracts and moringa leaf extracts		Al-Saif *et al.*[28]
	- Moringa extracts		El Sheikha *et al.*[29]
	- Rice straw		Marzouk *et al.*[30]
Biochemical	- Humic acid	An improvement in shoot and root growth was observed in horticultural crops treated with biochemical biofertilizer. Furthermore, the yield of fruits and vegetables was increased; they were also resistant to salinity and drought	Ennab *et al.*[31]
	- Amino acid		Tekaya *et al.*[32]
	- Humic acid, seaweed extracts and moringa leaf extracts		Almutairi *et al.*[33]
	- Yeast extract, fulvic acid, moringa leaf extract, seaweed extract and nano-potassium		Al-Saif *et al.*[34]
	Amino acid		
	- Amino acid		Ismaiel *et al.*[35]
	- Fulvic acid		Nassar *et al.*[36]

Table 3: Summary of the results of the included studies; the effect of biofertilizer on the soil, plant growth, yield, plant resistance, fruit quality and the production costs

	Results					
Biofertilizer type	Soil	Plant growth	Yield	Plant resistance	Quality	Costs
Microbial	Increased the content of different beneficial microorganisms in the soil and enhanced the soil properties[14] Increased soil properties[18] Improves nutrient availability in soils[17]	Increased onion and potato plant growth[14] Improved growth performance of potato plants[15] Improved the survival of cocoa seedling[16] Increased plant height and number of leaves in an onion plant[17] Improving the studied nodule, root and shoot[18] No significance on bean plant emergence, but plant height, root length and number of nodules increased[20] Enhanced chlorophyll and mineral level on the leaves of Valencia orange[21]	Increased dry matter yield[14] Increased potato yield[15] Sustainable yield were obtained[16] Increase in onion yield[17] Application of biofertilizer had no significant on faba bean yield[18] Higher bean yield were obtained[15]	Decreased environmental stress on onion and potato growth, protecting against climate change[14] Potato plants were resistance to drought[15] Cocoa plants survived in drought[16] Onion plants reduces oxidative burdens in field environments[17]	Increased the quality of the potato tubers and onion bulbs[14] Enhanced the quality of potato tubers[15] Increased onion bulb quality[17] Improved quality potato tubers[18] Improved quality of orange fruits[21]	Reduced onion and production costs by lowering fertilizer and pesticide expenses[14] Reduced cost because the need for higher Nitrogen was reduced[20]
Botanical	Increased bacterial community in the soil[17] Activated soil microorganisms and increasing organic matter[27] Improved soil structure, enhanced nutrient cycling and increased microbial activity[30]	Improved vegetative growth of strawberry plants[19] Increased plant growth in shoot length, diameter, leaf area, chlorophyll[26] Enhanced plant growth of Chia plants[27] Increased plant growth in green bean plant[29] Increased plant height and number of tillers[30]	Increased yield of the strawberry[20] Improved the fruit set and fruit yields per apple tree[26] Enhanced fruit yield of Guava trees[27] Increased yield of green bean[28] Improved yield of corn and wheat[29]	Strawberry plants had high frost resistance[19]	High fruit weight in strawberries were observed[25] Positively influenced on increasing the fruit weight, size, length and diameter as well as fruit firmness of[26] Increased quality of green bean[29]	Reduced costs of fertilizer[19] Reduced the apple fruit drop and saved money[26] Decrease the total amount of fertilizer needed for Chia plants[27] It is cheaper compared to synthetic fertilizer[29] Minimized the use expensive synthetic fertilize[30]
Biochemical	Increased microorganisms content[31] Positively effected microbial community structure[32] Improved the soil characteristics[23] Soil element contents such as Extractable bases (Ca, Mg, Na and K), macronutrients (N, P, K, S, Ca and Mg) and micronutrients (Cu, Mn, Fe, Zn, B and Se) significantly increased[35]	Vegetative growth of Mexican lime tree improved[31] Increased root growth on Olive trees[32] Improvement of the number of leaves in green beans[23] Enhanced shoot length, shoot diameter and total leaf chlorophyll of orange tree[33] Increased in shoot length, number of leaves, leaf area and number of branches on pea plant[35]	Vegetative growth of sugar beet increased[36] Improved total yield of Mexican lime tree[32] Increased yield of green bean[23] Improved Orange fruit yield[33] Increased yield of Pea plant[35] Increased yield of sugar beet[36]	Mexican lime trees tolerance under saline conditions[32] Orange trees survived abiotic stress such as drought, salinity and cold[33] Sugar beet plants were resistance to salinity[36]	Improved fruit quality on Mexican lime fruit[32] Increased pod weight of green bean[23] Increased fruit firmness, fruit carotene and fruit juice percentages[33] Increase in yield components such as number of pods per plant, pod length, number of seeds per pod and dry weight of 100 seeds of Pea plants[35] Increment in root yield, top yield, biological yield, sugar yield, sucrose percentage, root length of sugar beet[36]	Reduced fruit drop in orange[33] Improved the net benefit-cost ratio[36]

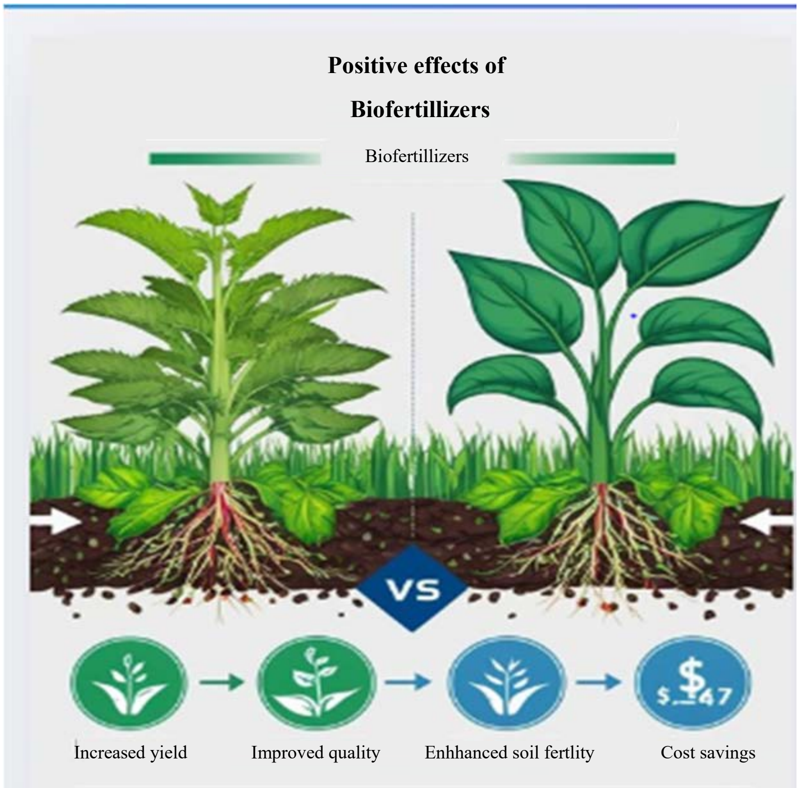

Fig. 3: Positive effect of biofertilizer on yield, yield and plant quality, soil fertility and cost savings
Picture created from Canva

Table 4: Merits and demerits of biofertilizers

Merits	Demerits
It improves plant growth and metabolite production	The manufacturer's ignorance of the product's quality
Enhance nutrient proximity	It takes time for the results to show
It assists in the mineralization of nutrients and the transportation of nutrients from the soil to the plant	It requires special storage conditions
Soil fertility improvement	They cannot be used on any crop
Advocates for sustainable agriculture and the circular economy.	Lack of adequate carrier resources is a limitation.
It reduces the contamination of water bodies	Higher volumes are needed for land application because of the low contents of nutrients
Restore soil structure	
Promotes plant resistance to environmental stress	
Increases the microbial community in the soil	

T. harzianum. Amino acids alone and mixed with other material-based biofertilizers are the most studied in biochemical research, followed by humic acid and fulvic acid alone and mixed with other materials, the least studied are silicon, spirulina platensis, trifolium alexandrinum and calcium-based biofertilizers. Figure 2 shows the Geographical distribution of reviewed papers of the included articles (n = 35). African countries with peer-reviewed articles where the studies were performed from field trials are Egypt with the highest number of publications followed by followed by Tunisia and the countries with the fewest publications are Morocco, Ghana, Ethiopia and South Africa.

IMPACT OF BIOFERTILIZER ON THE SOIL, PLANT GROWTH, YIELD, YIELD QUALITY, PLANT RESISTANCE AND COSTS IN AFRICA

The application of biofertilizers in the study had a positive impact in the included studies; an improvement of soil characteristics was observed in almost all the studies. Even on the vegetative growth of all the vegetables, fruits, grains, etc., was positively influenced by the different types of biofertilizers applied, alone or in combination with chemical fertilizers, depending on the treatments of each study, as well as the increment on the yield of these plants and quality. But in a study conducted[18], the use of biofertilizer had no significant effect on the faba bean yield, even though it had on the study conducted earlier[14]. Some of the plants showed resistance to environmental stressors and reduced the costs in one way or the other. Table 3, summarises the impact of biofertilizers on the soil, plant growth, yield, quality, plant resistance and costs in the included studies.

DISCUSSION

EFFICACY OF BIOFERTILIZER PRODUCTS IN HORTICULTURE CROPS

The findings shed light that the use of biofertilizers can have many positive effects on the sustainable agriculture approach. Biofertilizer is able to enhance the availability and accessibility of plant nutrients uptake through the colonization of the plant root system by the microorganisms. They also promote plant growth, improve plant stress tolerance and pathogen resistance. Biofertilizers also play a significant role in seed germination, as well as stimulating plant growth hormones. It is also found that they increase horticultural crop yield and it is cost-effective. The figure below (Fig. 3) summarizes the effect of using biofertilizer on yield, yield and plant quality, soil fertility and cost savings. Biofertilizer products have their disadvantages, although these disadvantages are no greater danger to the environment as compared to chemical fertilizers (Table 4).

The agriculture industry is the major contributor to Greenhouse gas emissions through gases like nitrous oxide (N_2O), carbon dioxide, methane from the manure management and soil fertilization processes[13]. This has led to the search for an alternative approach to farming that would allow more sustainable production and better protection of the environment. Utilization of biofertilizers in regenerative farming are a promising alternative because they increase the soil organic matter that keeps carbon dioxide[37], thus reducing its release of it to the atmosphere. Moreover, the reduction of released carbon dioxide to the atmosphere reduces climate change by not increasing the temperature. Research findings show that using both inorganic and organic fertilizers can raise soil carbon levels, but analysis indicates that organic fertilizers enhance carbon sequestration more effectively than inorganic fertilizers (0.82 MgC/ha/yr compared to 0.54 MgC/ha/yr)[38]. This finding by Lynch *et al.*[38] is a positive effect on climate change, because raising soil carbon levels using organic fertilisers improves carbon sequestration, lowering atmospheric carbon and reducing global warming.

AVAILABILITY AND ADAPTABILITY OF BIOFERTILIZER PRODUCTS IN AFRICA

According to the literature there are biofertilizer products that are currently used in the horticulture industry, although there is little evidence of their performance at a field scale. Pradhan *et al.*[39] mentioned that there about 15 rhizobacteria biofertilizer products produced in African countries, in the 15 about 13 were from South Africa, 1 from Nigeria and 1 from Kenya. The high number of biofertilizer products from South Africa may be the products of the large-scale waste to energy and biofertilizer facility in Athlone, Cape Town. However, many of the biofertilizer products found on the markets of other African countries had poor quality and were not effective[40]. Tahiri *et al.*[23] also found that the use of biofertilizer in Africa was very low in terms of peer reviewed papers, where African continent showed less than 118 peer reviewed papers publications.

Africa has access to many oceans and seas, which gives it a great opportunity to produce seaweed and microalgae for biofertilizers[41]. The Gedeo zone is also well-suited for biofertilizer production because of its rich organic waste and helpful microorganisms[42]. The countries with articles included in this study also have a potential to produce biofertilizers in high volumes. However, several challenges exist that hinder the development of facilities that could produce biofertilizers. Such challenges in those countries are that there are no proper systems to control biofertilizer quality and production is still too small to meet demand. Other issues include a lack of storage facilities, weak extension services, poor biofertilizer standards and low awareness among farmers[43]. These challenges could be overcome if the following solutions can be implemented depending on each country's challenges, the governments should improve biofertilizer policies and provide financial support. Working with agro-dealers and collaborating with developed countries can also help bring new technology and better distribution. Investing in production facilities, training experts and funding research will also strengthen the sector. If the above-mentioned possible solutions could be applied, Africa has the resources and conditions to grow this industry, create jobs and reduce its dependence on other continents.

CONCLUSION

The integration of biofertilizer in regenerative horticulture presents a promising strategy for sustainable nutrient supply in crop production, particularly in the context of climate change. The systematic review shows that biofertilizer application results in notable enhancements in vegetative growth, yield and yield quality of all vegetables, fruits and grains, along with improved soil fertility and cost savings. This review has discussed the importance of the biofertilizer approach, reviewing two key aspects: Biofertilizer policy and trade and potential advances of material sciences to the development of soil-tailored biofertilizers for Africa. Such advances may contribute to mitigating some of the most urgent problems necessary to decrease yield gaps in the future, including lowering the use of chemical fertilizers and fertilizer costs. The review also highlighted that the quality of biofertilizer available on the market easily deteriorates and the African farmers do not have proper storage to maintain the quality of the biofertilizers. Furthermore, the lack of knowledge about biofertilizers in terms of how to utilize the products properly also contributed to the poor adoption of biofertilizers in Africa. In the longer term, a successful implementation of the strategy outlined in this work that interconnects research in geology, material science and agronomy is hoped to result in restored soil health and an increase in horticulture crop production in Africa.

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