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Review

Bioresources in Organic Farming: Implications for Sustainable Agricultural Systems

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Abstract: Over the years, the practice of agriculture has transformed from the era of traditional to that of intensive agriculture in the bid to boost the production index that will satisfy the food needs of the globally growing population. However, the continuous and exaggerated use of chemical fertilizers and pesticides has resulted in major adverse impacts on food and environmental safety, whereas most traditional techniques for reclamation of natural soil nutrients, including shifting cultivation and polyculture, are no longer attractive measures of land rejuvenation. There is, therefore, the need for urgent evaluation and adoption of innovative methods of replenishing the agricultural soils that conform to the current agricultural systems without exerting undesirable effects on the ecosystem. In this review, we elucidated the use of key bioresources, such as organic fertilizers, biofertilizers, and biopesticides, as alternatives to chemical-based products in attaining a safe and sustainable agricultural system. Bioresources are naturally available, safe, and easily accessible products. The potential of these biological products in fostering soil microbial growth, plants' productivity, and induced host immunity to diseases, alongside the promotion of healthy soil–microbe–plant relationships and preservation of the ecosystem processes without disruption, are aspects that were also explored. Therefore, the productive use of bioresources is considered strategic as it pertains to attaining safe and sustainable food production.

Keywords: soil–microbe–plant relationship; food security; soil health; biofertilizers; biopesticides

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1. Introduction

Continuous land cultivation without commensurate nutrient replacement leads to declining soil performance as a result of the depletion of essential nutrients that support crop growth. This also causes an imbalance in the ecosystem, leading to reduced land productivity and eventually impairing both the quantity and quality of the farm produce obtained at harvest [1]. This becomes critical where non-eco-friendly sources of nutrient additives are applied to make up for the soil nutrient requirements as the natural rejuvenation processes of the farmland are altered. Hence, the importance of healthy soil to the attainment of efficient food production that would support the ever-increasing human population cannot be over-emphasized.

Considering the current global shrinking of agricultural land as a result of urbanization [2], and the trend of large-scale monocropping [3], adequate soil fertility replenishment during or before crop cultivation is highly essential if a successful cropping season would be attained. Some of the traditional farming practices, such as shifting cultivation and mixed cropping, may no longer be methods of choice. In recent times, agriculture depends largely on the use of chemical fertilizers and pesticides to enhance crop yield and quality. Generally, fertilizer and pesticide use has been categorized into chemical, organic, or biofertilizers, with each category possessing distinct characteristics and effects on soil fertility and crop management [4].

Synthetic fertilizers are classified based on their mode of action and their chemical nature. The commonly available types are categorized into nitrate (e.g., sodium nitrate), ammonium (e.g., ammonium nitrate), nitrate and ammonium (e.g., ammonium sulfate), and amide (e.g., urea) fertilizers [5]. They improve soil fertility and provide essential nutrients to plants, which results in noticeable improvements in plants' growth within a short period. Despite their benefits, the use of chemical fertilizers comes with several drawbacks as inappropriate or prolonged use could result in water and environmental pollution, which occurs through leaching, runoff, or volatilization [6].

The recently advocated measures for soil nutrient replenishment with better crop productivity include the use of biological resources, which are naturally available products that could be productively harnessed in sustainable farming [7,8]. Bioresources are natural materials that are degradable and renewable; some of these substances include plant biomass and wastes from some industries and municipalities, agriculture, grasses, weeds, forest, and/or marine resources, such as fishes and aquatic crustaceans [9]. All these bioresources are valuable and may be utilized as raw materials or feedstocks for the manufacturing of a variety of valued goods that are strategically significant both economically and industrially. Hence, bioresources are considered to be a major center of the bioeconomy [10].

On the other hand, over-exploitation and improper use of bioresources have been reported to have detrimental impacts on the environment [11,12]. Most of the associated adverse effects are prevented by the application of bioresources, such as human-modified plant- and/or animal-based products applied to aid soil health and plant performance. Since bioresources are organic materials, they are often used in agriculture as organic fertilizers, biofertilizers, and biopesticides because they hold enormous potential in nurturing plant–soil–microbe relationship by creating a favorable soil environment in which valuable macro- and microflora and fauna thrive. Furthermore, products of bioresources enhance soil's inherent buffer capacity without causing heavy metal contamination in the soil [13,14].

They are, therefore, a suitable alternative to chemical use in agricultural practices. Although an initial agricultural boost could be experienced by the chemical-based formulations, the consequences of their use over a prolonged period could be detrimental to both the soil and the human environment. Hence, this review discusses the inherent potential and implications of adopting the use of bioresources as organic-based solutions to enhance both soil and crop health and productivity.

2. Bioresources as the Principal Components of Soil

Bioresources are non-fossil biogenic materials that can be applied by humans for purposes including food, essential products, and/or energy [15]. Bioresources primarily consist of a wide range of materials, such as plants, animals, microorganisms, and waste products from various industries. The secondary bioresources include residues, byproducts of green areas, or biological organisms, while tertiary bioresources entail parts of virgin materials separated from processing chains, which are naturally available biological-based materials applied by humans in the soil to important functions. However, the optimization of the benefits of soil biotic components towards enhancement in soil integrity has not received considerable attention [16,17]. Soil is a three-phase system, which includes the solid, liquid, and gaseous phases. The solid phase comprises a diverse mixture of inorganic (40–45%) and organic components (5%), while water and air make up about 50% of the volume of soil in the liquid and gaseous phases, respectively.

Although the quantity of vegetation, water availability, and soil compaction vary, each of these factors contributes to the definition of a good and healthy soil that can support and sustain plant growth. Soil is particularly noteworthy because it is a network of pores that serves as the physical and main habitat for all organisms. Soil is also known as the biological engine of life since it is an interior space that houses all below-ground life and functions [18].

The importance of soil is unquestionably vast but needs to be maintained and managed sustainably as a renewable resource. However, the factors that contribute to effective soil fertility are diverse and complex. The soil biota has been known to contribute immensely to effective soil functions, especially in the maintenance of agricultural fertility [19,20]. Moreover, biomass, although a small proportion of total soil mass, has a greater effect on its functions. It constitutes the biological components that fully interact in a series of complex mechanisms for recycling nutrients and ensuring continual soil function. The heterogeneous porous matrix that is produced by the soil's uneven structure acts as a habitat for the soil organisms, which influences the organic input in line with the aggregate dynamic model of Six, et al. [21]. However, the microbiota possesses either a direct or indirect impact on the soil structure, including the movement, alignment, and adherence of primary particles along cell or hyphal surfaces, the adhesive force produced by colony cohesion, metabolites, or exudates, such as extracellular polysaccharides, coating of pore walls with hydrophobic substances, such as fungal mycelium insulating polymers, and enmeshment and binding of growth structures, such as fungal hyphae [22,23].

Different key factors define an ecosystem's service of soil biota: the soil structure integrity, carbon cycling, nutrient cycling, biotic regulations, and so on. The soil itself is composed of several components, including clay, salt, and sand fractions, and was formed as a result of various biogeochemical changes, which include weathering [24]. Both the organic and mineral components of the soil aggregated into larger units bind together to form a larger scale as part of the soil structure on a hierarchical scale [14]. The soil structure can also be enhanced by microorganisms due to their actions on organic materials [25,26]. The organic matter, as potential energy-containing substrates, binds the soil particles together, while the degradation of organic matter by microorganisms alters the soil structure and results in the loss of soil carbon [14]. The profiles or matric of soil are intrinsically linked to the interactions between microbial processes, water, and the pore network in the soil. Furthermore, while microorganisms, such as protozoa and bacteria, require a water film to travel, fungi can spread across wide surfaces through the use of hyphae or mycelium that can penetrate air-filled pores. Thus, microbes have evolved a variety of survival methods, such as aerobic or anaerobic respiration, to survive various soil processes, such as methanogenesis and denitrification [14,27].

The soil organic matter is obtained from primary producers of terrestrial vegetation. This has an adverse influence on soil function and agriculture. The degraded biomass is modified through chemical and biological processes to enrich the soil organic matter, which serves as a major source of energy to soil organisms. To achieve this, soil microorganisms must migrate across the soil matrix to access the organic matter; this movement then leads to the formation of the structural soil and the soil's ability to act as a buffer [13,28,29]. Bioperturbation can be considered the genesis and sustaining mechanism of the soil structure and function [30]. Invertebrate organisms, such as worms, ants, or mollusks, as well as the plants' roots, are often concerned with physical disturbance of the solid soil matrices to gain passage and locomotion, and, by this, they also ensure the mixing and distribution of substantial soil materials. Plants are the primary producers of fixed carbon; microbial respiration balances the net ecosystem carbon flux [31,32].

3. Bioresources Use as an Organic Amendment

Two of the major hindrances to attaining high production in farming operations across the globe are the problems of soil compaction and loss of soil organic matter. These concerns have been effectively addressed with the application of readily available bioresources, such as organic fertilizers. With the applications at an acceptable rate, organic fertilizer has been found to augment plants' growth and enhance productivity [33]. Moreover, organic fertilizers increase the quality and yield of plants and enhance the biological activities, chemistry, structure, and quality of the soil. They are also capable of mitigating the adverse impact of soil-acidifying synthetic fertilizers such as urea that alter the soil pH reaction, thereby affecting soil chemical and biological functions. Furthermore, organic fertilizer creates a conducive environment for soil microorganisms to thrive, and this is essential in harnessing the benefit of services rendered by the associated soil microbes, which entail the provision of key ecosystem services, such as decomposition, and water regulations, including nitrogen and carbon cycling.

Moreover, the addition of organic fertilizer has been recorded to increase organic nitrogen (N) and sulphur (S) content in the soil [16,28], while rhizosphere fungi, nitrogen-fixing rhizobia bacteria, and some other beneficial soil microorganisms have been reported to support plant growth and enhance plants' resistance to diseases [20,22,23,34]. Efficient and continual availability of nutrients is ensured from the gradually released nutrients by organic fertilizer for plant uptake. Varying types of organic fertilizers available include farmyard manure, green manures, vermicompost, oil cakes, biological wastes, compost, and biochar produced from crop waste and other agricultural byproducts. However, the nutrient content of each depends on many factors, including the source of the material used, storage method, and application technique [13,14,35,36]. An instance is the role of biochar, which is a biomass-derived product obtained through pyrolysis; it has been explored as an organic amendment in growth promotion and disease management in plants, which are results of the enhanced soil physicochemical properties and interactions of the beneficial soil microbes with plants [28,37,38]. Although some minerals such as phosphorus and nitrogen may not be readily available for plants' use, such minerals are initially transformed into available forms for plants' uptake. Generally, nutrient absorption is higher in the first year of application of organic fertilizers in the soil [39]. However, the organic manure lasts longer in the soil compared to the commercial fertilizer [40]. Hence, the use of organic manure in organic farming is important to maintain a balance between an interconnected system involving humans, plants, animals, and soil organisms. Organic manure is essential in the biological process of plants, assists in the suppression of the population of plant pests, increases anion and cation exchange potential, and increases the microorganism activity, organic matter, as well as the carbon content of soil [41]. Its action of preventing diseases, supplying nutritional requirements, and enhancing the plants' tolerance to adverse conditions heightens the potential of organic fertilizers to increase the yield and quality of agricultural produce with minor or non-adverse impacts on the environment.

In addition to its potential to stimulate plants' growth, plant disease development can also be halted through the introduction of organic fertilizer under field conditions. The timely application of organic fertilizer has been found to reduce disease occurrence as a result of decreased likelihood of leaching, contributing to sufficient nutrient availability in the soil that could serve the plants for the long term. This, therefore, promotes the high absorption of nutrients by plants [42]. Meanwhile, robust, healthy, and vigorous plants are less susceptible to diseases because such plants can provide vital adaptations, such as thicker cell walls and tissues, which serve as a mechanical barrier against pathogens. This implies that plants' immunity is sustained under a continuous supply of nutrients. However, despite the resistance of some plants to infections, climatic conditions can also affect their susceptibility [43]. Reports in several studies have shown that organic fertilizers support the development of potato dry rot as well as other diverse post-harvest fungal deterioration [44,45]. However, organic fertilizers such as manure, compost, and organic residues may act as an effective alternative strategy in the management of diseases and pests since they increase the activity of beneficial microorganisms that suppress soil-borne diseases and prolific pathogens [46].

Gupta et al. [47] reported the relationship between nutrients and the suppression of several plant diseases, including the clubroot of crucifers, *Verticillium* wilt, *Streptomyces* scab of potatoes, and take-all of wheat. Additionally, the antagonistic *Paenibacillus polymyxa* SQR21 and *Trichoderma harzianum* T37 were reportedly used to ferment mature compost in the production of bio-organic fertilizer that prevented the *Fusarium* wilt disease of watermelons, while the provision of a balanced and timed source of nutrient to plant growth was established via slow decomposition of organic matter by microorganisms, mineralization, and nutrient release [48,49]. Similarly, Sharma and Garg [50] reported that, aside from micronutrients and macronutrients, vermicompost contains plant-growth-promoting substances, such as auxins, humic acids N-fixing, and P-solubilizing bacteria, vitamins, and enzymes. These water-soluble components increase the availability of nutrients to plants, which results in better output and good quality.

Contrary to the immediate positive impacts of organic fertilizers recorded, their long-term use produces inconsistent results. The reason for this has been linked to variations in the quality of organic matter applied as sources with a low C/N ratio constitute a lower trophic level in the soil food web while the labile carbon inputs are increased and more efficiently used by the microbes under the organic fertilizer treatments. In the long term, high-quality labile litter would result in greater formation and accumulation of soil organic matter [51]. Furthermore, in the report of Weithmann et al. [52], organic fertilizers, especially those from composting and biowaste fermentation, were considered the neglected entry path of microplastic particles into the environment. Meanwhile, the resulting challenge of equitable distribution of nutrients through the prevailing organic fertilizer management methods could be addressed through refining the methods used to process large quantities of organic waste [28,53].

4. Indicators of the Effectiveness of Conventional and Organically Derived Bioresources in Farming

It is important to weigh the relevance of bioproducts obtained from refined bioresources compared to that of conventional products in their use as soil treatments. The derived facts from using conventional and alternative bioproducts can be reinforced by some essential indicators. One such aspect is soil health indicators, which include the pH, nutrient content, soil organic matter, soil structure, and soil microbial activities, which directly impart the plant performance and respond differently both in the short term and long term to the input materials to support plant growth, either in conventional or organic products. An instance of this was the study conducted by Kobierski et al. [54], which compared the chemical properties and enzymatic activities of the surface soil horizon of conventional farming and an organically farmed field from 2001 to 2007. The study reported significantly higher activity of catalase, alkaline phosphatase, and dehydrogenases in the soil of organic farm than in the conventional cultivation system. The crop yield and quality is another marker to access the suitability of either conventional or non-conventional bioproducts in improving soil fertility and agricultural production. An earlier comparative study on the yields of some selected tropical vegetables subjected to organic and inorganic nutrient sources indicated that the yields between organic and inorganic sources reflected a significant increase in crop yield under organic nutritional sources [55]. Similarly, environmental sustainability of the soil treatments used also serves as indicator that measures the effectiveness of conventional or organic bioproducts; this is achieved through the efficacy of each method to manage soil erosion, conserve water resources in the soil, and reduce the greenhouse gas emissions [56]. However, organic agricultural practices and an integrated approach have been described to offer proactive measures in ensuring environmental sustainability when compared to the conventional method. This was further validated by other scientists who discussed and researched agricultural sustainability and various soil and crop management techniques, including nutrient management, site-specific nutrient management, integrated nutrient management, integrated soil fertility management, integrated soil–crop system management, ridge–furrow mulching systems, sustainable water management, conservation agriculture, and sustainable land use [55,57]. Furthermore, the economic feasibility of both conventional and alternative bioproducts can be assessed by the cost of production, consumer demand, and profitability. Therefore, these economic viability indicators enable farmers and other stakeholders to evaluate the financial advantages of the type of bioproducts to use in soil treatments. Moreover, user satisfaction is one of the major indicators to assess the efficacy of conventional and alternative bioproducts used. This often serves as a guide to farmers and other stakeholders in terms of the preference regarding soil treatments by the end users [58].

5. Bioresources Uses as Biofertilizers and Biopesticides

As a result of their continuous and incessant application, chemical fertilizers alter the soil characteristics to either become more acidic or alkaline [59], a condition that results in a reduction in the naturally occurring soil microbes, and it also affects the availability of plant nutrients for uptake and use, which in turn decreases yield production. However, the application of beneficial microorganisms as biofertilizers and biopesticides, which is currently gaining attention, serves as an effective alternative to the use of chemical-based products in enhancing soil fertility and managing the associated pest and diseases. Biofertilizers and biopesticides are eco-friendly products and good candidates for integrated nutrient, pest, and disease management techniques [60].

Unlike organic fertilizers, which are constituents of various agricultural wastes that require the intervention of microorganisms for their degradation from a solid state into decomposed and soluble material for easier absorption by plants, biofertilizers and biopesticides are made up of beneficial microorganisms. They are microbial inoculants that consist of living cells of microorganisms, such as bacteria, fungi, alga, or the consortium of the inoculants. They colonize the plant endosphere or the rhizosphere when applied either to seeds, plant surfaces, or soil [61,62]. Biofertilizers, unlike organic fertilizers, employ natural processes of solubilizing phosphorus and nitrogen fixation to increase the available primary nutrients to the host plant. They also stimulate plant growth through the synthesis of growth-promoting substances. On the other hand, biopesticides describe a variety of substances from preparations containing live microorganisms to botanical compounds, plant-incorporated protectants, and semiochemicals, such as pheromones [63] (Figure 1). Hence, the use of biopesticides is not restricted to the applications of microbial pest control agents, i.e., fungi, bacteria, viruses, nematodes, and protozoa.

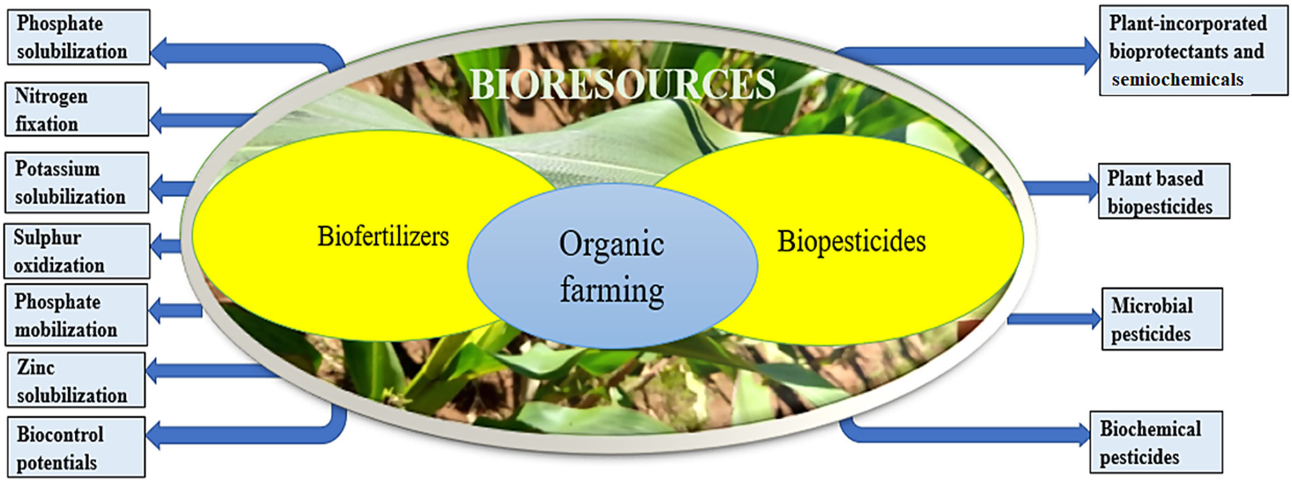

Figure 1. Role of bioresources in organic agriculture.

A further consideration includes using bioactive compounds, such as metabolites produced directly from the microbes that suppress the pest populations, including pathogens, insects, and weeds [64]. Thus, biopesticides are becoming more important in pest management, biological control, cultural techniques, and newer synthetics, as well as in the genetics of plants and animals. They are characterized by their beneficial roles, such as eco-friendliness, being less harmful, specificity in targets, effectiveness at low dosage, biodegradability, and non-persistent nature [65,66].

Many microorganisms have been characterized as of now; they are commonly referred to as plant-growth-promoting rhizobacteria (PGPR) or plant-growth-promoting fungi (PGPF) [19,67]. Their deployment for plant growth and disease management has been widely encouraged by soil scientists [23,68,69]. Thus, the natural soil microflora contain a variety of PGPR or PGPF [70], and they constitute a key element of integrated nutrient management with their application as biofertilizers that could be employed in sustainable agriculture. They can be suitably formulated for application through the seed or soil. These preparations, which include living or latent cells of effective microorganism strains, aid in the nutrient absorption of agricultural plants by interacting with the rhizosphere. They accelerate several microbial activities in the soil that increase the amount of nutrients available in an easy-to-assimilate state for plants. These potential biofertilizers have been classified based on their roles as nitrogen fixers (*Rhizobium, Azospirillum, Azobacter,* blue–green algae, and *Azolla*), phosphate solubilizers (*Pseudomonas*, *Rhizobium, Bacillus, Achromobacter, Burkholderia, Aereobacter, Microccocus, Flavobacterium, Agrobacterium,* and *Erwinia*), phosphate absorbers (Mycorrhiza), and zinc solubilizers (*Bacillus subtilis*, *Thiobacillus thioxidans,* and *Saccharomyces* sp.) (Table 1).

The potentials of soil microbial pesticides have recently been linked with the mechanisms against pathogen attacks, such as systemic acquired resistance (SAR), a system that confers resistance to a plant against a broad spectrum of plant pathogens and a range of secondary infections. A number of bacterial and fungal species have been characterized as microbial pesticides. *Paenibacillus polymyxa* and *Paenibacillus lentimorbus* were affirmed to suppress root-knot nematode and Fusarium wilt fungus in infected plants by Son, Khan [71]. In another study, Ma et al. [72] reported the inhibitory and biocontrol effects of *Bacillus pumilus* strain AR03 against tobacco black shank disease. Similarly, the biostimulatory effects of some strains of rhizosphere fungi, such as *Aspergillus niger*, *Yarrowia lipolytica*, *Talaromyces astroroseus*, *T. harzianum*, *T. purpurogenus*, *Cunnighamella elegans,* among others, have been researched [16,17,73,74], in addition to *Burkholderia cepacian*, *Pseudomonas fluorescens*, *Bacillus subtilis,* and *P. chlororaphis*, *B. firmus* against soil-borne fungi and nematodes, *Agrobacterium radiobacter* K84, K1026 against the crown gall disease caused by *Agrobacterium tumefaciens*, non-pathogenic *Ralstonia solanacearum* against the pathogenic species [75], and *Trichoderma* spp. against the root rot diseases of tomato (Olowe et al., 2022), while the effectiveness of arbuscular mycorrhiza fungi as a biofertilizer and biopesticide have been reported in various crops [76–78].

Table 1. Types and roles of some biofertilizers on selected crops.

Type of Biofertilizers	Mechanisms	Microorganisms	Crop Category	Associated Crops	Rate of Application	References
Rhizobium	Fixes nitrogen in the soil. Forms symbiotic association with the rhizobium bacteria, leading to formation of root nodules, which fixes atmospheric nitrogen	*Rhizobium leguminosarum, R. japonicum, R. lupine orinthopus, R. phaseoli, R. melliloti, R. trifoli*	Legumes	Green pea, Lentil, Soybean, Lupinus, Melilotus, Phaseoli, Trifolium, Moong, Redgram, Cowpea, Groundnut, Bengal gram	As a seed treatment, use *Rhizobium* + Phosphotika at a rate of 200 gm each per 10 kg of seed.	[79]
Azotobacter	Functions as biofertilizer for non-leguminous plants; the lack of soil organic matter is a limiting factor for its proliferation in the soil since it is only present in the rhizosphere region and not on the rhizosplane	*A. chroococcum, A. beijerinchii, A. vinelandii, A. paspali, A. macrocytogenes, A. insignis, A. agilies*	Cereals and other non-leguminous plants	Rice, cotton, vegetables, etc.	As a seed treatment, use *Azotobacter* + Phosphotika at a rate of 200 gm each per 10 kg of seed.	Poorniammal, Prabhu [80]
Azospirillum	Forms associative symbiosis with the higher plant system and cereals	*A. brasilense, A. agricola, A. canadense, A. doebereinerae, A. fermentarium, A. formosense, A. zeae, A. thiophilum, A. griseum, A. halopraeferens, A. humicireducens, A. largimobile, A. lipoferum, A. melinis, A. oryzae, A. palustre, A. picis, A. ramasamyi, A. rugosum, A. soli*	Cereals and other non-leguminous plants	Rice, maize, millets, wheat, sorghum, oat, barley, oilseeds, cotton, millets, fodder grasses	It is recommended during the transplanting of rice to soak the seedling's roots for 8 to 10 h in *Azospirillum* + Phosphotika solution at 5 kg per ha.	[81,82]

Table 1. *Cont.*

Type of Biofertilizers	Mechanisms	Microorganisms	Crop Category	Associated Crops	Rate of Application	References
Nitrogen fixing endophytes	The nitrogen-fixing bacteria occur within the tissues of a host plant that does not show disease symptoms Surface colonization at the site of emergence of root hairs Production of hydrolytic enzymes or endoglucanases during tissue penetration	*Azoarcus sp.*, *Gluconacetobacter*, and *Herbaspirillum*	All plant categories	Sugar cane, *Miscanthus sinensis*		Bhat, Ahmad [83]
Silicate-solulizing bacteria (SSB)	Produce indole acetic acid (IAA), promote plant growth, and encourage silicon (Si) uptake and deposit in plants to enhance resistance against biotic and abiotic stressors.	*Burkholderia*, *Bacillus*, *Proteus*, *Pseudomonas*, *Rhizobia*, and *Enterobacter*	All plant categories	Rice, maize, barley, sorghum, tomato, strawberry, pepper, pumpkin, cucumber.	Application of 3–5 tons of SiO 2 (river sand) per hectare	Raturi, Sharma [84], Geetha Thanuja, Reddy Kiran Kalyan [85]
Phosphate-solubilizing microorganisms	Phosphate-solubilizing microorganisms convert insoluble phosphorus into a plant-available form	*Bacillus*, *Pseudomonas*, *Mycobacterium*, *Pantoea*, *Burkholderia*, *Enterobacterbacteria Pseudomonas*, Mycorrhiza, *Rhizobium*, *Aspergillus*, and *Penicillium*	All plant categories	Wheat, maize, tomato, sorghum, pepper, rice		Anand, Kumari [86], Rawat, Das [87]

Table 1. *Cont.*

Type of Biofertilizers	Mechanisms	Microorganisms	Crop Category	Associated Crops	Rate of Application	References
Blue–Green Algae (BGA) (Cyanobacteria), and *Azolla*	They are abundant in tropical environment. The majority of nitrogen-fixing BGAs are filamenters, which are chains of vegetative cells. Regarding its nitrogen contribution to rice, *Azolla* is regarded as a potential biofertilizer.	*Tolypothrix*, *Nostic*, *Schizothrix*, *Calothrix*, *Anoboenosois*, and *Plectonema*	Cereal	Rice, maize, barley, sorghum, millets, wheat, oat	Range of 6.25–10.0 t/ha and incorporated before transplanting of rice. They fix 20–30 kg N/ha in submerged rice fields as they are abundant in paddy, so also referred to as ‘paddy organisms.	Malyan, Bhatia [88], Adhikari, Bhandari [89], Rajesha and Ray [90]

Many of these bioagents are now available in commercial quantities [7,69]. Furthermore, the botanical pesticides obtained naturally from plant-based products have also been demonstrated as effective alternatives to usual synthetic pesticides [91]. For instance, neem-based pesticides, pyrethrum, and eucalyptus oil have been widely explored for agricultural pest management [92–94]. However, the use of biofertilizers and biopesticides, unlike classical biological control, requires repeated applications to the desired field or pest-infested areas because they are not capable of spreading beyond the applied region, and, more importantly, their population is not self-sustaining beyond one or a few growing seasons [95], except for endophytes, which are delivered in seed or other propagation material, typically through inundate release as spray, drench, granules, or seed coating. They often need to be registered with the appropriate authorities to affirm that they are safe for the environment and the community when mass-produced, manufactured, packed, and sold as a bioprotection product [96,97].

6. Demerits of Organic Farming Practices

The increasing interest in organic agriculture is greatly influenced by the demands and focus placed on environmental preservation, health, and food safety [13,98,99]. However, the organic movement is dominated by the notion that natural products are superior to synthetic ones, and this concept largely justifies the absence of synthetic fertilizers and pesticide use in organic farming strategies [100]. While organic agriculture aims at biodiversity conservation within the agricultural systems, the emphasis of organic farming is on integrated solutions rather than separate management approaches, and such techniques are inclusive of biological control strategies [101]. Hence, the formulated microbial agents are considered alternatives to pesticide use in plant management, especially for their environmental friendliness, but their use is, in most instances, guided by rules and regulations [102]. An instance is the prohibition of the use of genetically modified biological control agents in several countries around the world [103], while organic crop protection strategies have so far been developed and available for only a select few crops [104].

Despite the importance of biological control techniques in protecting organic crops, they also exert adverse effects on humans, including a greater risk of contracting *E. coli* infection when consuming organic food than in non-organic food. This is in line with the report by Dennis Avery of the Hudson Institute in 1998 [105]. Moreover, organic agriculture practices, especially in developing nations, have recorded lower productivity compared to the conventional methods [106]. In addition, organic farming is more labor-intensive than conventional agricultural practices because it involves time-consuming activities, such as manual weed control, crop rotation, and intercropping practices, among others. Hence, the cost of producing organic food is in most cases more expensive for consumers. Furthermore, the reliance of organic farmers on only natural methods in the control of pests and diseases often makes organic farming less effective than when synthetic pesticides and fertilizers are applied. This thereby increases the risk of crop failure, which can be devastating for farmers who rely on their crops for income [107,108]. It has similarly been reported that organic farming only contributes a small fraction to agricultural product needs around the world. Therefore, organic farming may thereby have little chance of mitigating the effects of climate change [109]. Hence, despite acknowledging the regenerative organic farming methods as viable approaches to reduce CO_2 emissions, the benefits obtained from this method are still considered not significant [109,110].

7. Conclusions

Despite being a long-standing practice, interest in organic farming has recently been resuscitated and advocated as it pertains to measures of soil nutrient replenishment aimed at promoting food sustainability and security. Organic farming is also a practice that employs the processing and productive utilization of potentially wasted bioresources generated from a farm in order to generate more useful available forms for plant use. The refined products, such as compost, biochar, beneficial microorganisms, and plant materials, have shown effectiveness in various applications as biofertilizers and biopesticides. Despite the increasing relevance of products of bioresources in sustainable food production and environmental preservation, their use is guided largely by rules and regulations that often discourage their widespread application. However, safety concerns have been expressed by many regarding their use, especially in the case of bioagents, while other researchers have argued that organic farming is more labor-intensive, time-consuming, and produces a more expensive farm output yet only contributes negligibly to food requirements around the world as compared to the conventional farming techniques. Therefore, while organic agricultural practices have been successful in enhancing the biodiversity conservation within agricultural systems, for them to sustainably gain relevance in meeting the current global food needs, there is a need for the emphasis of organic farming to be one of the integrated solutions rather than a separate management approach.

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References

1. Bhardwaj, A.K.; Arya, G.; Kumar, R.; Hamed, L.; Pirasteh-Anosheh, H.; Jasrotia, P.; Kashyap, P.L.; Singh, G.P. Switching to nanonutrients for sustaining agroecosystems and environment: The challenges and benefits in moving up from ionic to particle feeding. *J. Nanobiotechnology* **2022**, *20*, 19. [CrossRef]
2. Gohain, K.J.; Mohammad, P.; Goswami, A. Assessing the impact of land use land cover changes on land surface temperature over Pune city, India. *Quat. Int.* **2021**, *575*, 259–269. [CrossRef]
3. Sunderland, T.; O'Connor, A.; Muir, G.; Nerfa, L.; Nodari, G.; Widmark, C.; Bahar, N.; Ickowitz, A.; Katila, P.; Colfer, C. SDG2: Zero hunger: Challenging the hegmony of monoculture agriculture for forests and people. In *Sustainable Development Goals: Their Impacts on Forests and People*; Pierce Colfer, C.J., Winkel, G., Galloway, G., Pacheco, P., Katila, P., de Jong, W., Eds.; Cambridge University Press: Cambridge, UK, 2019; pp. 48–71.
4. Baweja, P.; Kumar, S.; Kumar, G. Fertilizers and pesticides: Their impact on soil health and environment. In *Soil Health*; Springer: Berlin/Heidelberg, Germany, 2020; pp. 265–285.
5. Li, T.; Wang, Z.; Wang, C.; Huang, J.; Feng, Y.; Shen, W.; Zhou, M.; Yang, L. Ammonia volatilization mitigation in crop farming: A review of fertilizer amendment technologies and mechanisms. *Chemosphere* **2022**, *303*, 134944. [CrossRef]
6. Chaitra, A.; Ahuja, R.; Sidhu, S.; Sikka, R. Importance of Nano Fertilizers in Sustainable Agriculture. *Environ. Sci. Ecol. Curr. Res.* **2021**, *5*, 1029.
7. Dlamini, S.P.; Akanmu, A.O.; Babalola, O.O. Rhizospheric microorganisms: The gateway to a sustainable plant health. *Front. Sustain. Food Syst.* **2022**, *6*, 925802. [CrossRef]
8. Abiala, M.; Akanmu, A.; Oribhaboise, A.; Aroge, T. Combined Effects of Ocimum gratissimum and Soil-borne Phytopathogenic Fungi on Seedling Growth of Quality Protein Maize. *J. Adv. Biol. Biotechnol.* **2020**, *23*, 25–32. [CrossRef]
9. Ingle, A.P.; Philippini, R.R.; Martiniano, S.; Marcelino, P.R.F.; Gupta, I.; Prasad, S.; da Silva, S.S. Bioresources and their Significance: Prospects and obstacles. In *Current Developments in Biotechnology and Bioengineering*; Elsevier: Amsterdam, The Netherlands, 2020; pp. 3–40.
10. Awasthi, M.K.; Sarsaiya, S.; Patel, A.; Juneja, A.; Singh, R.P.; Yan, B.; Awasthi, S.K.; Jain, A.; Liu, T.; Duan, Y. Refining biomass residues for sustainable energy and bio-products: An assessment of technology, its importance, and strategic applications in circular bio-economy. *Renew. Sustain. Energy Rev.* **2020**, *127*, 109876. [CrossRef]

11. Fu, X.-M.; Zhang, M.-Q.; Liu, Y.; Shao, C.-L.; Hu, Y.; Wang, X.-Y.; Su, L.-R.; Wang, N.; Wang, C.-Y. Protective exploitation of marine bioresources in China. *Ocean. Coast. Manag.* **2018**, *163*, 192–204. [CrossRef]
12. Uddin, M.; Mohiuddin, A.; Hossain, S.; Hakim, A. Eco-environmental changes of wetland resources of Hakaluki Haor in Bangladesh using GIS technology. *J. Biodivers. Endanger. Species* **2013**, *1*, 1000103.
13. Akanmu, A.O.; Babalola, O.O.; Venturi, V.; Ayilara, M.S.; Adeleke, B.S.; Amoo, A.E.; Sobowale, A.A.; Fadiji, A.E.; Glick, B.R. Plant Disease Management: Leveraging on the Plant-Microbe-Soil Interface in the Biorational Use of Organic Amendments. *Front. Plant Sci.* **2021**, *12*, 1590. [CrossRef]
14. Chukwuka, K.S.; Akanmu, A.O.; Umukoro, O.B.; Asemoloye, M.D.; Odebode, A.C. *Biochar: A Vital Source for Sustainable Agriculture*; IntechOpen: London, UK, 2020; p. 86568. Available online: https://www.intechopen.com/online-first/biochar-a-vital-source-for-sustainable-agriculture (accessed on 28 May 2023). [CrossRef]
15. Gaurav, N.; Sivasankari, S.; Kiran, G.; Ninawe, A.; Selvin, J. Utilization of bioresources for sustainable biofuels: A review. *Renew. Sustain. Energy Rev.* **2017**, *73*, 205–214. [CrossRef]
16. Asemoloye, M.D.; Ahmad, R.; Jonathan, S.G. Synergistic action of rhizospheric fungi with Megathyrsus maximus root speeds up hydrocarbon degradation kinetics in oil polluted soil. *Chemosphere* **2017**, *187*, 1–10. [CrossRef]
17. Asemoloye, M.D.; Ahmad, R.; Jonathan, S.G. Synergistic rhizosphere degradation of γ-hexachlorocyclohexane (lindane) through the combinatorial plant-fungal action. *PLoS ONE* **2017**, *12*, e0183373. [CrossRef]
18. Brussaard, L. Biodiversity and ecosystem functioning in soil: The dark side of nature and the bright side of life. *Ambio* **2021**, *50*, 1286–1288. [CrossRef]
19. Adedeji, A.A.; Häggblom, M.M.; Babalola, O.O. Sustainable agriculture in Africa: Plant growth-promoting rhizobacteria (PGPR) to the rescue. *Sci. Afr.* **2020**, *9*, e00492. [CrossRef]
20. Igiehon, N.O.; Babalola, O.O. Rhizosphere microbiome modulators: Contributions of nitrogen fixing bacteria towards sustainable agriculture. *Int. J. Environ. Res. Public Health* **2018**, *15*, 574. [CrossRef] [PubMed]
21. Six, J.; Conant, R.T.; Paul, E.A.; Paustian, K. Stabilization mechanisms of soil organic matter: Implications for C-saturation of soils. *Plant Soil* **2002**, *241*, 155–176. [CrossRef]
22. Alori, E.T.; Dare, M.O.; Babalola, O.O. Microbial inoculants for soil quality and plant health. In *Sustainable Agriculture Reviews*; Springer: Berlin/Heidelberg, Germany, 2017; pp. 281–307.
23. Babalola, O.O.; Emmanuel, O.C.; Adeleke, B.S.; Odelade, K.A.; Nwachukwu, B.C.; Ayiti, O.E.; Adegboyega, T.T.; Igiehon, N.O. Rhizosphere microbiome cooperations: Strategies for sustainable crop production. *Curr. Microbiol.* **2021**, *78*, 1069–1085. [CrossRef]
24. McKinley, V.L. Effects of land use and restoration on soil microbial communities. In *Understanding Terrestrial Microbial Communities*; Springer: Berlin/Heidelberg, Germany, 2019; pp. 173–242.
25. Kay, B. Soil structure and organic carbon: A review. In *Soil Processes and the Carbon Cycle*; Routledge: Oxford, UK, 2018; pp. 169–197.
26. Fadiji, A.E.; Kanu, J.O.; Babalola, O.O. Metagenomic profiling of rhizosphere microbial community structure and diversity associated with maize plant as affected by cropping systems. *Int. Microbiol.* **2021**, *24*, 325–335. [CrossRef]
27. Paerl, H.W.; Pinckney, J.L.; Steppe, T.F. Cyanobacterial–bacterial mat consortia: Examining the functional unit of microbial survival and growth in extreme environments. *Environ. Microbiol.* **2000**, *2*, 11–26. [CrossRef]
28. Akanmu, A.O.; Sobowale, A.A.; Abiala, M.A.; Olawuyi, O.J.; Odebode, A.C. Efficacy of biochar in the management of *Fusarium verticillioides* Sacc. causing ear rot in *Zea mays* L. *Biotechnol. Rep.* **2020**, *26*, e00474. [CrossRef] [PubMed]
29. Keesstra, S.; Mol, G.; De Leeuw, J.; Okx, J.; De Cleen, M.; Visser, S. Soil-related sustainable development goals: Four concepts to make land degradation neutrality and restoration work. *Land* **2018**, *7*, 133. [CrossRef]
30. Wilkinson, M.T.; Richards, P.J.; Humphreys, G.S. Breaking ground: Pedological, geological, and ecological implications of soil bioturbation. *Earth Sci. Rev.* **2009**, *97*, 257–272. [CrossRef]
31. Yuan, L.; Moinet, G.Y.; Clough, T.J.; Whitehead, D. Net ecosystem carbon exchange for Bermuda grass growing in mesocosms as affected by irrigation frequency. *Pedosphere* **2022**, *32*, 393–401.
32. Thapa, V.R.; Ghimire, R.; Duval, B.D.; Marsalis, M.A. Conservation systems for positive net ecosystem carbon balance in semiarid drylands. *Agrosystems Geosci. Environ.* **2019**, *2*, 1–8. [CrossRef]
33. Ye, L.; Zhao, X.; Bao, E.; Li, J.; Zou, Z.; Cao, K. Bio-organic fertilizer with reduced rates of chemical fertilization improves soil fertility and enhances tomato yield and quality. *Sci. Rep.* **2020**, *10*, 177. [CrossRef]
34. Fasusi, O.A.; Cruz, C.; Babalola, O.O. Agricultural sustainability: Microbial biofertilizers in rhizosphere management. *Agriculture* **2021**, *11*, 163. [CrossRef]
35. Walling, E.; Vaneeckhaute, C. Greenhouse gas emissions from inorganic and organic fertilizer production and use: A review of emission factors and their variability. *J. Environ. Manag.* **2020**, *276*, 111211. [CrossRef]
36. Sánchez, E.; Zabaleta, R.; Fabani, M.P.; Rodriguez, R.; Mazza, G. Effects of the amendment with almond shell, bio-waste and almond shell-based biochar on the quality of saline-alkali soils. *J. Environ. Manag.* **2022**, *318*, 115604. [CrossRef]
37. Rasool, M.; Akhter, A.; Soja, G.; Haider, M.S. Role of biochar, compost and plant growth promoting rhizobacteria in the management of tomato early blight disease. *Sci. Rep.* **2021**, *11*, 6092. [CrossRef]
38. Agarwal, H.; Kashyap, V.H.; Mishra, A.; Bordoloi, S.; Singh, P.K.; Joshi, N.C. Biochar-based fertilizers and their applications in plant growth promotion and protection. *3 Biotech* **2022**, *12*, 136. [CrossRef]
39. Dotaniya, M.; Aparna, K.; Dotaniya, C.; Singh, M.; Regar, K. Role of soil enzymes in sustainable crop production. In *Enzymes in Food Biotechnology*; Elsevier: Amsterdam, The Netherlands, 2019; pp. 569–589.

40. Ndambi, O.A.; Pelster, D.E.; Owino, J.O.; De Buisonje, F.; Vellinga, T. Manure management practices and policies in sub-Saharan Africa: Implications on manure quality as a fertilizer. *Front. Sustain. Food Syst.* **2019**, *3*, 29. [CrossRef]
41. Usharani, K.; Roopashree, K.; Naik, D. Role of soil physical, chemical and biological properties for soil health improvement and sustainable agriculture. *J. Pharmacogn. Phytochem.* **2019**, *8*, 1256–1267.
42. Chatterjee, R.; Bandyopadhyay, S. Studies on effect of organic, inorganic and biofertilizers on plant nutrient status and availability of major nutrients in tomato. *Int. J. Bio-Resour. Stress Manag.* **2014**, *5*, 93–97. [CrossRef]
43. Velásquez, A.C.; Castroverde, C.D.M.; He, S.Y. Plant–pathogen warfare under changing climate conditions. *Curr. Biol.* **2018**, *28*, R619–R634. [CrossRef]
44. Arora, R.; Sharma, S. Pre and Post Harvest Diseases of Potato and Their Management. In *Future Challenges in Crop Protection Against Fungal Pathogens*; Springer: Berlin/Heidelberg, Germany, 2014; pp. 149–183.
45. Farrell, G.; Hodges, R.; Wareing, P.; Meyer, A.; Belmain, S. Biological Factors in Post-Harvest Quality. *Crop Post-Harvest. Sci. Technol. Princ. Pract.* **2002**, *1*, 93–140.
46. Neher, D.A.; Hoitink, H.A.; Biala, J.; Rynk, R.; Black, G. Compost use for plant disease suppression. In *The Composting Handbook*; Elsevier: Amsterdam, The Netherlands, 2022; pp. 847–878.
47. Gupta, N.; Debnath, S.; Sharma, S.; Sharma, P.; Purohit, J. Role of nutrients in controlling the plant diseases in sustainable agriculture. In *Agriculturally Important Microbes for Sustainable Agriculture: Volume 2: Applications in Crop Pro-duction and Protection*; Springer: Berlin/Heidelberg, Germany, 2017; pp. 217–262.
48. Zhang, N.; Wu, K.; He, X.; Li, S.-Q.; Zhang, Z.-H.; Shen, B.; Yang, X.-M.; Zhang, R.-F.; Huang, Q.-W.; Shen, Q.-R. A new bioorganic fertilizer can effectively control banana wilt by strong colonization with Bacillus subtilis N11. *Plant Soil* **2011**, *344*, 87–97. [CrossRef]
49. Olowe, O.M.; Nicola, L.; Aemoloye, M.D.; Akanmu, A.O.; Sobowale, A.A.; Babalola, O.O. Characterization and antagonistic potentials of selected rhizosphere Trichoderma species against some Fusarium species. *Front. Microbiol.* **2022**, *13*, 3757. [CrossRef] [PubMed]
50. Sharma, K.; Garg, V. Vermicomposting of waste: A zero-waste approach for waste management. In *Sustainable Resource Recovery and Zero Waste Approaches*; Elsevier: Amsterdam, The Netherlands, 2019; pp. 133–164.
51. Cotrufo, M.F.; Wallenstein, M.D.; Boot, C.M.; Denef, K.; Paul, E. The M icrobial E fficiency-M atrix S tabilization (MEMS) framework integrates plant litter decomposition with soil organic matter stabilization: Do labile plant inputs form stable soil organic matter? *Glob. Change Biol.* **2013**, *19*, 988–995. [CrossRef]
52. Weithmann, N.; Möller, J.N.; Löder, M.G.; Piehl, S.; Laforsch, C.; Freitag, R. Organic fertilizer as a vehicle for the entry of microplastic into the environment. *Sci. Adv.* **2018**, *4*, eaap8060. [CrossRef]
53. McNeill, A.; Eriksen, J.; Bergström, L.; Smith, K.; Marstorp, H.; Kirchmann, H.; Nilsson, I. Nitrogen and sulphur management: Challenges for organic sources in temperate agricultural systems. *Soil Use Manag.* **2005**, *21*, 82–93. [CrossRef]
54. Kobierski, M.; Lemanowicz, J.; Wojewódzki, P.; Kondratowicz-Maciejewska, K. The effect of organic and conventional farming systems with different tillage on soil properties and enzymatic activity. *Agronomy* **2020**, *10*, 1809. [CrossRef]
55. Pradeepkumar, T.; Bonny, B.P.; Midhila, R.; John, J.; Divya, M.; Roch, C.V. Effect of organic and inorganic nutrient sources on the yield of selected tropical vegetables. *Sci. Hortic.* **2017**, *224*, 84–92. [CrossRef]
56. Akanmu, A.O.; Akol, A.M.; Ndolo, D.O.; Kutu, F.R.; Babalola, O.O. Agroecological techniques: Adoption of safe and sustainable agricultural practices among the smallholder farmers in Africa. *Frontiers in Sustainable Food Systems* **2023**, *7*, 310. [CrossRef]
57. Francaviglia, R.; Almagro, M.; Vicente-Vicente, J.L. Conservation Agriculture and Soil Organic Carbon: Principles, Processes, Practices and Policy Options. *Soil Syst.* **2023**, *7*, 17. [CrossRef]
58. Lamine, C. The Role of Interactions Between Organic and Conventional Farming in the Ecological Transition of a Territorial Food System. In *Coexistence and Confrontation of Agricultural and Food Models: A New Paradigm of Territorial Development?* Springer: Berlin/Heidelberg, Germany, 2023; pp. 185–197.
59. Pahalvi, H.N.; Rafiya, L.; Rashid, S.; Nisar, B.; Kamili, A.N. Chemical fertilizers and their impact on soil health. In *Microbiota and Biofertilizers*; Springer: Berlin/Heidelberg, Germany, 2021; Volume 2, pp. 1–20.
60. Ahirwar, N.K.; Singh, R.; Chaurasia, S.; Chandra, R.; Ramana, S. Effective role of beneficial microbes in achieving the sustainable agriculture and eco-friendly environment development goals: A review. *Front. Microbiol.* **2020**, *5*, 111–123. [CrossRef]
61. Yadav, S.K.; Patel, J.S.; Singh, B.N.; Bajpai, R.; Teli, B.; Rajawat, M.V.S.; Sarma, B.K. Biofertilizers as Microbial Consortium for Sustainability in Agriculture. In *Plant, Soil and Microbes in Tropical Ecosystems*; Springer: Berlin/Heidelberg, Germany, 2021; pp. 349–368.
62. Babalola, O.O.; Akanmu, A.O.; Fadiji, A.E. Dataset of shotgun Metagenomic Evaluation of Lettuce (*Lactuta sativa* L.) Rhizosphere Microbiome. *Data in Brief* **2023**, *48*, 4. [CrossRef]
63. Kumar, J.; Ramlal, A.; Mallick, D.; Mishra, V. An overview of some biopesticides and their importance in plant protection for commercial acceptance. *Plants* **2021**, *10*, 1185. [CrossRef]
64. Samada, L.H.; Tambunan, U.S.F. Biopesticides as promising alternatives to chemical pesticides: A review of their current and future status. *Online J. Biol. Sci.* **2020**, *20*, 66–76. [CrossRef]
65. Abbey, L.; Abbey, J.; Leke-Aladekoba, A.; Iheshiulo, E.M.A.; Ijenyo, M. Biopesticides and biofertilizers: Types, production, benefits, and utilization. In *Byproducts from Agriculture and Fisheries: Adding Value for Food, Feed, Pharma, and Fuels*; John Wiley & Sons: Hoboken, NJ, USA, 2019; pp. 479–500.

66. Essiedu, J.A.; Adepoju, F.O.; Ivantsova, M.N. (Eds.) Benefits and limitations in using biopesticides: A review. In *AIP Conference Proceedings*; AIP Publishing LLC: Long Island, NY, USA, 2020; p. 080002.
67. Amoo, A.E.; Enagbonma, B.J.; Ayangbenro, A.S.; Babalola, O.O. Biofertilizer: An eco-friendly approach for sustainable crop production. In *Food Security and Safety*; Babalola, O.O., Ed.; Springer International Publishing: Cham, Germany, 2021; pp. 647–669.
68. Asemoloye, M.D.; Jonathan, S.G.; Ahmad, R. Synergistic plant-microbes interactions in the rhizosphere: A potential headway for the remediation of hydrocarbon polluted soils. *Int. J. Phytoremediation* **2019**, *21*, 71–83. [CrossRef]
69. Olowe, O.M.; Nicola, L.; Asemoloye, M.D.; Akanmu, A.O.; Babalola, O.O. Trichoderma: Potential bio-resource for the management of tomato root rot diseases in Africa. *Microbiol. Res.* **2022**, *257*, 126978. [CrossRef]
70. Babalola, O.O.; Dlamini, S.P.; Akanmu, A.O. Shotgun Metagenomic Survey of the Diseased and Healthy Maize (*Zea mays* L.) Rhizobiomes. *Microbiol. Resour. Announc.* **2022**, *11*, e00498-22. [CrossRef] [PubMed]
71. Son, S.; Khan, Z.; Kim, S.; Kim, Y. Plant growth-promoting rhizobacteria, Paenibacillus polymyxa and Paenibacillus lentimorbus suppress disease complex caused by root-knot nematode and fusarium wilt fungus. *J. Appl. Microbiol.* **2009**, *107*, 524–532. [CrossRef]
72. Ma, L.; Zhang, H.-Y.; Zhou, X.-K.; Yang, C.-G.; Zheng, S.-C.; Duo, J.-L.; Mo, M.-H. Biological control tobacco bacterial wilt and black shank and root colonization by bio-organic fertilizer containing bacterium Pseudomonas aeruginosa NXHG29. *Appl. Soil Ecol.* **2018**, *129*, 136–144. [CrossRef]
73. Asemoloye, M.D.; Jonathan, S.G.; Jayeola, A.A.; Ahmad, R. Mediational influence of spent mushroom compost on phytoremediation of black-oil hydrocarbon polluted soil and response of Megathyrsus maximus Jacq. *J. Environ. Manag.* **2017**, *200*, 253–262. [CrossRef]
74. Woo, S.L.; Ruocco, M.; Vinale, F.; Nigro, M.; Marra, R.; Lombardi, N.; Pascale, A.; Lanzuise, S.; Manganiello, G.; Lorito, M. Trichoderma-based products and their widespread use in agriculture. *Open Mycol. J.* **2014**, *8*, 71–126. [CrossRef]
75. Montesinos, E. Development, registration and commercialization of microbial pesticides for plant protection. *Int. Microbiol.* **2003**, *6*, 245–252. [CrossRef]
76. Olawuyi, O.; Odebode, A.; Olakojo, S.; Popoola, O.; Akanmu, A.; Izenegu, J. Host–pathogen interaction of maize (*Zea mays* L.) and Aspergillus niger as influenced by arbuscular mycorrhizal fungi (*Glomus deserticola*). *Arch. Agron. Soil Sci.* **2014**, *60*, 1577–1591. [CrossRef]
77. Olawuyi, O.; Odebode, A.; Oyewole, I.; Akanmu, A.; Afolabi, O. Effect of arbuscular mycorrhizal fungi on Pythium aphanidermatum causing foot rot disease on pawpaw (*Carica papaya* L.) seedlings. *Arch. Phytopathol. Plant Prot.* **2014**, *47*, 185–193. [CrossRef]
78. Olowe, O.M.; Olawuyi, O.J.; Sobowale, A.A.; Odebode, A.C. Role of arbuscular mycorrhizal fungi as biocontrol agents against Fusarium verticillioides causing ear rot of *Zea mays* L.(Maize). *Curr. Plant Biol.* **2018**, *15*, 30–37. [CrossRef]
79. Yang, J.; Lan, L.; Jin, Y.; Yu, N.; Wang, D.; Wang, E. Mechanisms underlying legume–rhizobium symbioses. *J. Integr. Plant Biol.* **2022**, *64*, 244–267. [CrossRef] [PubMed]
80. Poorniammal, R.; Prabhu, S.; Kannan, J.; Janaki, D. Liquid biofertilizer-A boon to sustainable agriculture. *Biot. Res. Today* **2020**, *2*, 915–918.
81. Cassán, F.; Coniglio, A.; López, G.; Molina, R.; Nievas, S.; de Carlan, C.L.N.; Donadio, F.; Torres, D.; Rosas, S.; Pedrosa, F.O. Everything you must know about Azospirillum and its impact on agriculture and beyond. *Biol. Fertil. Soils* **2020**, *56*, 461–479. [CrossRef]
82. Santos, M.S.; Nogueira, M.A.; Hungria, M. Outstanding impact of Azospirillum brasilense strains Ab-V5 and Ab-V6 on the Brazilian agriculture: Lessons that farmers are receptive to adopt new microbial inoculants. *Rev. Bras. Ciência Solo* **2021**, *45*, e0200128. [CrossRef]
83. Bhat, T.A.; Ahmad, L.; Ganai, M.A.; Khan, O. Nitrogen fixing biofertilizers; mechanism and growth promotion: A review. *J. Pure Appl. Microbiol.* **2015**, *9*, 1675–1690.
84. Raturi, G.; Sharma, Y.; Rana, V.; Thakral, V.; Myaka, B.; Salvi, P.; Singh, M.; Dhar, H.; Deshmukh, R. Exploration of silicate solubilizing bacteria for sustainable agriculture and silicon biogeochemical cycle. *Plant Physiol. Biochem.* **2021**, *166*, 827–838. [CrossRef]
85. Geetha Thanuja, K.; Reddy Kiran Kalyan, V.; Karthikeyan, S.; Anthoniraj, S. Microbial Transformation of Silicon in Soil. In *Microbial Metabolism of Metals and Metalloids*; Springer: Berlin/Heidelberg, Germany, 2022; pp. 503–525.
86. Anand, K.; Kumari, B.; Mallick, M. Phosphate solubilizing microbes: An effective and alternative approach as biofertilizers. *Int. J. Pharm. Sci.* **2016**, *8*, 37–40.
87. Rawat, P.; Das, S.; Shankhdhar, D.; Shankhdhar, S. Phosphate-solubilizing microorganisms: Mechanism and their role in phosphate solubilization and uptake. *J. Soil Sci. Plant Nutr.* **2021**, *21*, 49–68. [CrossRef]
88. Malyan, S.K.; Bhatia, A.; Tomer, R.; Harit, R.C.; Jain, N.; Bhowmik, A.; Kaushik, R. Mitigation of yield-scaled greenhouse gas emissions from irrigated rice through Azolla, Blue-green algae, and plant growth–promoting bacteria. *Environ. Sci. Pollut. Res.* **2021**, *28*, 51425–51439. [CrossRef]
89. Adhikari, K.; Bhandari, S.; Acharya, S. An Overview of Azolla in Rice Production: A Review. *Rev. Food Agric. RFNA* **2021**, *2*, 4–8. [CrossRef]
90. Rajesha, G.; Ray, S.K. Microbial Bio-fertilizers: A Functional Key Player in Sustainable Agriculture. In *Promotion of Improved Cultivation Practices in Agri & Allied Sector for Food and Nutritional Security*; Joint Director ICAR Research Complex for NEH Region, Nagaland Centre: Medziphema, India, 2020; pp. 37–41.
91. Chen, K.; Wang, Y.; Zhang, R.; Zhang, H.; Gao, C. CRISPR/Cas genome editing and precision plant breeding in agriculture. *Annu. Rev. Plant Biol.* **2019**, *70*, 667–697. [CrossRef] [PubMed]
92. Chengala, L.; Singh, N. Botanical pesticides—A major alternative to chemical pesticides: A review. *Int. J. Life Sci.* **2017**, *5*, 722–729.
93. Akanmu, A.; Abiala, M.; Akanmu, A.; Adedeji, A.; Mudiaga, P.; Odebode, A. Plant extracts abated pathogenic Fusarium species of millet seedlings. *Arch. Phytopathol. Plant Prot.* **2013**, *46*, 1189–1205. [CrossRef]

94. Aroge, T.; Akanmu, A.; Abiala, M.; Odebode, J. Pathogenicity and in vitro extracts inhibition of fungi causing severe leaf blight in *Thaumatoccocus danielli* (Benn.) Benth. *Arch. Phytopathol. Plant Prot.* **2019**, *52*, 54–70. [CrossRef]
95. Bagheri, A.; Fathipour, Y. Induced Resistance and Defense Primings. In *Molecular Approaches for Sustainable Insect Pest Management*; Springer: Berlin/Heidelberg, Germany, 2021; pp. 73–139.
96. Jambhulkar, P.P.; Sharma, P.; Yadav, R. Delivery systems for introduction of microbial inoculants in the field. In *Microbial Inoculants in Sustainable Agricultural Productivity: Vol. 2: Functional Applications*; Springer: Berlin/Heidelberg, Germany, 2016; pp. 199–218.
97. Glare, T.; Caradus, J.; Gelernter, W.; Jackson, T.; Keyhani, N.; Köhl, J.; Marrone, P.; Morin, L.; Stewart, A. Have biopesticides come of age? *Trends Biotechnol.* **2012**, *30*, 250–258. [CrossRef] [PubMed]
98. Adenle, A.A.; Wedig, K.; Azadi, H. Sustainable agriculture and food security in Africa: The role of innovative technologies and international organizations. *Technol. Soc.* **2019**, *58*, 101143. [CrossRef]
99. Schreer, V.; Padmanabhan, M. The many meanings of organic farming: Framing food security and food sovereignty in Indonesia. *Org. Agric.* **2020**, *10*, 327–338. [CrossRef]
100. Durham, T.C.; Mizik, T. Comparative economics of conventional, organic, and alternative agricultural production systems. *Economies* **2021**, *9*, 64. [CrossRef]
101. Tscharntke, T.; Grass, I.; Wanger, T.C.; Westphal, C.; Batáry, P. Beyond organic farming–harnessing biodiversity-friendly landscapes. *Trends Ecol. Evol.* **2021**, *36*, 919–930. [CrossRef]
102. Elnahal, A.S.; El-Saadony, M.T.; Saad, A.M.; Desoky, E.-S.M.; El-Tahan, A.M.; Rady, M.M.; AbuQamar, S.F.; El-Tarabily, K.A. The use of microbial inoculants for biological control, plant growth promotion, and sustainable agriculture: A review. *Eur. J. Plant Pathol.* **2022**, *162*, 759–792. [CrossRef]
103. Niu, B.; Wang, W.; Yuan, Z.; Sederoff, R.R.; Sederoff, H.; Chiang, V.L.; Borriss, R. Microbial interactions within multiple-strain biological control agents impact soil-borne plant disease. *Front. Microbiol.* **2020**, *11*, 585404. [CrossRef] [PubMed]
104. MacLaren, C.; Storkey, J.; Menegat, A.; Metcalfe, H.; Dehnen-Schmutz, K. An ecological future for weed science to sustain crop production and the environment. A review. *Agron. Sustain. Dev.* **2020**, *40*, 24. [CrossRef]
105. Behera, K.K.; Alam, A.; Vats, S.; Sharma, H.P.; Sharma, V. Organic farming history and techniques. *Agroecol. Strateg. Clim. Change* **2012**, *8*, 287–328.
106. Argyropoulos, C.; Tsiafouli, M.A.; Sgardelis, S.P.; Pantis, J.D. Organic farming without organic products. *Land Use Policy* **2013**, *32*, 324–328. [CrossRef]
107. Pasupulla, A.P.; Pallathadka, H.; Nomani, M.; Salahuddin, G.; Rauf, M. A survey on challenges in organic agricultural practices for sustainable crop production. *Ann. Rom. Soc. Cell Biol.* **2021**, *25*, 338–347.
108. Baker, B.P.; Green, T.A.; Loker, A.J. Biological control and integrated pest management in organic and conventional systems. *Biol. Control.* **2020**, *140*, 104095. [CrossRef]
109. Giller, K.E.; Delaune, T.; Silva, J.V.; Descheemaeker, K.; van de Ven, G.; Schut, A.G.; van Wijk, M.; Hammond, J.; Hochman, Z.; Taulya, G. The future of farming: Who will produce our food? *Food Secur.* **2021**, *13*, 1073–1099. [CrossRef]
110. Kim, N.; Zabaloy, M.C.; Guan, K.; Villamil, M.B. Do cover crops benefit soil microbiome? A meta-analysis of current research. *Soil Biol. Biochem.* **2020**, *142*, 107701. [CrossRef]