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Biofertilizers and Bioherbicides in a Developing Bioeconomy

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Abstract

The rise in the global population and increasing food demand, especially in developing countries, has increased the use of agrochemicals, herbicides and pesticides over the years for the improvement of soil nutrients and control of pests and weeds. However, these agrochemicals are not eco-friendly due to their chemical toxicity in the environment, such as bioaccumulation in the food chain, eutrophication of water bodies and their negative effects on non-target organisms. Biofertilizers and bioherbicides can be harnessed as viable replacements for agrochemicals. Biofertilizers are formulations of living microorganisms that are applied to improve soil fertility and support the growth of crops. Bioherbicides are various biological agents used in weed control. They have proven effective in nutrient mobilization and uptake in crops and weed control. In this review, we discuss the negative impacts of agrochemicals on health and the ecosystem, their key mechanisms of actions, the categorizations of commercially available products and the challenges limiting their adoption.

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1. Introduction

In the quest to attain sustainable food production and to meet the food demand of their rapidly growing population, developing countries of the world have increased and intensified their agricultural and industrial activities over the last few decades. However, activities aimed at increasing yield and protecting crops have contributed significantly to environmental pollution through bioaccumulation and biomagnification of toxic compounds used as pesticides and herbicides (Mahapatra *et al.*, 2022).

The negative impacts of the resulting pollution pose a great threat to limited natural resources, e.g., soil and the global climate. Besides the harmful pollution effects of these agrochemicals, smallholder farmers, who make up the major proportion of food producers in developing countries, cannot afford these agrochemicals. These disadvantages associated with the conventional production and usage of fertilizers and herbicides have necessitated the need for eco-friendly and affordable alternative sources. Hence, approaches such as the use of biofertilizers and bioherbicides have gained considerable research attention over the years.

Biofertilizers are formulations of living microorganisms that can stimulate the growth of plants through colonization of the rhizosphere, rhizoplane, or interior of plants (Sethi & Adhikary, 2017). They are fungi, bacteria, and algae that enhance plant nutrition by mobilizing new nutrients or increasing the readily available ones in the soil and further facilitating the nutrient uptake into the interior of host plants. These microbe formulations are harnessed for their agricultural benefits in farmland fertilization, serving as potential replacements for synthetic fertilizers. Biofertilizer applications in crop production are utilized in a wide range of aspects, some of which include fixation of nitrogen, solubilization and mobilization of phosphorus, increasing organic carbon content, balanced carbon/nitrogen ratio, plant growth promotion by increasing nutrient absorption, antagonistic activity against plant pathogens and production of hormones (Mahapatra *et al.*, 2022). Biofertilizers are yet to be adopted for commercial agricultural purposes in developing countries despite their great potential. Multi-omics studies in recent years have, however, made significant steps towards a better understanding of plant-microbe interaction mechanisms (Mitter *et al.*, 2021).

The use of bioherbicides is an emerging option for weed control in sustainable food production. It is considered a promising alternative to the conventional chemical herbicides. Weed control in agriculture for sustainable food production requires integrated management options, including crop rotation, intercropping tillage, mulching, biological control, and bioherbicides before the application of chemical herbicides (Hasan *et al.*, 2021).

Bioherbicides are natural products that consist of microorganisms effective for the control of weeds (Hasan *et al.*, 2021). Studies have shown that some plant pathogens are virulent enough to compete commercially with chemical herbicides in their application for weed control, but most pathogens cannot be effectively utilized (Sands & Pilgeram, 2009). Research aimed at improving the target specificity of such pathogens will lead to considerable benefits, including reduced environmental impact and a cost-effective option when used as an alternative source for chemical herbicides.

2. Impacts of Agricultural Chemical Inputs on Health and Environment

Agrochemical inputs have contributed significantly to agricultural production, synthetic fertilizers provide various nutrients to plants, and synthetic herbicides effectively manage invasive weeds. The indiscriminate use of pesticides and herbicides contributes to soil, water, and air pollution and contamination of food products (Zhang *et al.*, 2018). Excessive use of fertilizers can also deplete the soil of essential nutrients and lead to reduced crop yields over time. Cases of environmental pollution resulting from agricultural activities are more pronounced in developing countries, which can be linked to rapid urbanization, negatively impacting limited natural resources available. Toxic effects from direct or indirect toxic agrochemicals such as herbicides and pesticides are responsible for health impairments as shown in Table 1. ranging from acute effects like headaches, skin rashes, and eye irritations to chronic effects such as cancer, endocrine disruption, and congenital disabilities (Zhang *et al.*, 2018). Most farmers in Nigeria apply agrochemicals without personal protective equipment and are at risk of their negative effects. Cases of poisoning symptoms due to farmers' exposure to agrochemicals have been reported in a study by Joko *et al.* (2020). Furthermore, prolonged exposure of pregnant farm workers to agrochemicals causes low birth weight in babies. Children exposed to agrochemicals without protection were about three times more at risk of stunted growth, when compared to unexposed children (Widyawati *et al.*, 2020). Also, the ingestion of agrochemicals in attempts to commit suicide is prevalent around countries of the world. According to WHO (2019), about 20% of approximately 800,000 people that commit suicide yearly do so by ingesting pesticides. The ecological impacts of agrochemical applications occur principally through water contamination caused by runoff fertilizers, pesticides and herbicides from rain or irrigation water, although terrestrial impacts do occur as well (Ongley, 1996). The ecological effects occur through two mechanisms, i.e., bioconcentration and bioaccumulation. First, agricultural chemical inputs carried into water bodies by surface runoff can persist for a long time, easily transported to different parts of water bodies, and dissolve into tissues of living organisms. These attributes make agrochemical pollutants good at bioaccumulating and biomagnifying. Bioaccumulation usually occurs at the primary producer level of the food web. Microscopic photosynthetic organisms called the phytoplankton absorb toxic chemicals from the water bodies faster than they can metabolize. The feeding on phytoplankton and taking up of higher concentrations of toxic chemicals by larger organisms into their body tissues are referred to as biomagnification. A higher concentration of toxic chemicals is passed through this pathway from one trophic level of the food web or food chain to the other.

Controlling the exposure to toxic effects of agrochemicals is a difficult task to achieve in developing countries due to limitations in the Regulations and Acts related to the use of agrochemicals. Registration of agrochemicals requires a complex, legal and administrative process involving the assessment of potential effects

Table 1**.** Effects of agrochemicals on human health

	Adverse Effects	References
Human Health	Acute illnesses: Fatigue, headaches and body aches, skin discomfort, skin rashes, poor concentration, feelings of weakness, circulatory problems, excessive sweating, impaired vision, tremors, panic attacks, cramps dizziness, nausea, vomiting, etc.	Biswas *et al. (*2014**)**
	Chronic illnesses**:** Memory loss, loss of coordination, leukemia, brain tumors, sarcomas, cancer of the prostate, pancreas, lungs, ovaries, breasts, testicles, liver, kidneys, and intestines, etc.	Biswas *et al. (*2014**)**
Environment	Adverse effects on non-target animals: Destruction of biodiversity, retardation of growth, life span reduction, fecundity rate reduction, enzyme inhibition, insect resistance to pesticides, etc.	Mahmood *et al. (*2015)
	Adverse effects on non-target plants: Injures nearby desirable trees and shrubs, results in sublethal effects on plant health.	Mahmood *et al. (*2015) & Biswas *et al. (*2014**)**
	Adverse effects on microbial communities: Reduction in nitrogen fixation rate by bacteria in the soil and transformation of ammonia into nitrates	Feld *et al. (*2015)
	Water contamination: Alter the state of such water bodies by changing its physical, chemical or biological conditions	Syafrudin *et al. (*2021)

associated with the use of pesticides on human health and the environment over a considerable period. Post-registration, agrochemicals are frequently reviewed to ensure they are in line with the updated scientific, safety, and regulatory standards. Reregistration of those that fail to meet the standards set by the regulatory and registration authorities is rejected and banned from use. About 460 agrochemical compounds have been banned globally across 36 developed and 128 developing countries (Bayoumi, 2022). Despite the ban, many agrochemicals are still illegally used in developing countries. For example, a study revealed that most pesticide marketers in the southwestern states of Nigeria failed to comply with the ban on the sales of such agrochemicals (Mokwunye *et al.*, 2014). Bangladesh farmers are reportedly facing a great risk of exposure to the toxic effects of banned agrochemicals such as organophosphate (OP) (Biswas *et al.*, 2014). Chlorpyrifos, endosulfan, cypermethrin, atrazine and glyphosate are banned, but still in use in Argentina and Paraguay (Bayoumi, 2022). Kesavachandran *et al. (*2009) documented the adverse health effects of these banned agrochemicals in India, including neurological, respiratory, dermal, and reproductive effects and the impact on general health.

3. Mechanisms of Action of Biofertilizers and Bioherbicides

3.1 Biofertilizers

3.1.1 Nitrogen-fixing Biofertilizers

Nitrogen is an essential element present abundantly in the atmosphere as N_2. The atmospheric nitrogen is not readily available to plants as it requires an energy-intensive microbial mineralization process in the presence of nitrogenase enzymes to be converted to plant usable forms (Mitter *et al.*, 2021). The process of converting atmospheric N_2 to plant usable ammonia and nitrate forms is called biological nitrogen fixation (BNF). The nitrogenase enzymes involved in this process are found in a small and diverse group of microorganisms referred to as the diazotrophs (N_2 fixing). Such microorganisms are harnessed in the formation of potent biofertilizers using the BNF mechanism (Kumar *et al.*, 2018). Symbiotic associations are the maximum contributors to BNF, and Rhizobia bacteria are the most studied symbiotic nitrogen-fixing organisms (Mitter *et al.*, 2021).

3.1.2 P-Solubilizing Biofertilizers

Phosphorus is one of the essential plant nutrients required for plant metabolic processes. They are available for plants in the two soluble forms: monobasic and dibasic. However, most of the phosphorus present in the soil is insoluble, a limiting factor to its availability for plant uptake. The unavailable phosphorus is present in the organic form or, at times, in the soluble inorganic form due to the immobilization of phosphorus fertilizers. Through the process of solubilization and mineralization, phosphate-solubilizing microbes (PSM) present in the soil can solubilize inorganic phosphorus. The PSM population in the soil is composed of 1 to 50% phosphorus solubilizing bacteria (e.g., *Pseudomonas* *putida* and *Bacillus megaterium*), and 0.1 to 0.5% phosphorus solubilizing fungi (*Aspergillus* and *Penicillium*) fulfill 20–25% of the phosphorus requirement of the plant (Kumar *et al.*, 2018; Chen *et al.*, 2006). These microbes transform insoluble phosphorus to available forms by excreting organic acids, hydroxyl ions, and CO_2, which dissolve the insoluble phosphates directly by lowering the soil pH, then leading to ion exchange of PO_4^{2-} by acid ions; or by releasing chelating compounds that capture and mobilize cations from different insoluble phosphates such as Ca^{2+}, $Al^{3+,}$ and Fe^{3+} (Wei *et al.*, 2018). PSM reduces the manufacturing costs and environmental effects of phosphate fertilizers due to a decrease in mineral phosphorus fertilizer input (Kumar *et al.*, 2018).

3.1.3 K-Solubilizing Biofertilizers

Potassium is an essential plant macronutrient. It is the second most abundant nutrient in the soil after nitrogen. However, only 0.1 to 0.2 % is directly available for plant uptake, approximately 98% is present in non-exchangeable form, and about 1 to 2 % is trapped within crystal structures of the minerals feldspar and mica (Mitter *et al.*, 2021). Microorganisms such as bacteria, fungi, and actinomycetes play a key role in the solubilization of potassium, making it available to plants for uptake. The mechanism of action of potassium solubilizing microbes is similar to those of phosphorus solubilizing microbes, and the processes involved include the production of inorganic and organic acids, acidolysis, polysaccharides, complexolysis, chelation, polysaccharides, and exchange reactions (Sattar *et al.*, 2018; Sharma *et al.*, 2016). Using K-solubilizing microbes in biofertilizer production is a potential alternative to synthetic fertilizers (Kumar *et al.*, 2018).

3.1.4 S-Oxidizing Biofertilizers

Sulphur (S) is a vital plant macronutrient for plant growth mostly present in soils in an organic form with less than 10% available in inorganic form for plant uptake. Inorganic S is commonly available as sulphate (SO_4^{2-}). Oxidation of S to inorganic form is carried out by archaea, bacteria and fungi. The decline in atmospheric deposition of S due to the reductions in SO_2 emissions and the use of low-S fertilizers have increased the attention towards S-oxidizing microbes. S-oxidizing microbes utilize elemental S as an energy source and release plant usable sulphate in the process, which contributes significantly to plant growth. Biofertilizers produced from such microbes are recommended for grain horticultural crops.

3.1.5 Micronutrient Solubilizing Biofertilizer

Micronutrients, although found in trace amounts, are essential for plant development. These nutrients, which include iron (Fe), zinc (Zn), copper (Cu), manganese (Mn), boron (B), molybdenum (Mo), chlorine (Cl), nickel (Ni), cobalt (Co), and silicon (Si), are involved in critical enzymatic reactions in plants (Mitter *et al.*, 2021). A deficiency of micronutrients causes a decline in plant health and productivity, which is most commonly observed in alkaline soils with low organic matter (Rashid & Ryan, 2004). Caldelas and Weiss (2017) reported that zinc deficiency is the most important micronutrient problem in crops. Microorganisms like *B. subtilis, Thiobacillus thioxidans* and *Saccharomyces* sp. are capable of solubilizing zinc present in the soil. Hence, they are potent biofertilizers that can be used to convert insoluble zinc to a soluble form, making it available for plant uptake.

3.2 Bioherbicides

3.2.1 Microbial Bioherbicides

They are active compounds produced by microorganisms including bacteria, fungi, and viruses. This class of bioherbicides inhibits plants' phosphorylation by blocking glutamine synthase, thus increasing ammonia levels (Kumar *et al.*, 2021). Microbes have been subjected to extensive research over the past years and these studies have led to the discovery of new microbial species and strains that produce valuable toxins of marketable quality. The translation of these bioherbicides into commercial products can be achieved using *in vivo* or *in vitro* techniques. Table 2 shows the development of bioherbicides from various sources and their effects on targeted weeds.

3.2.2 Plant Based Bioherbicides

This category of bioherbicides is derived from plants. Plants develop many compounds, including steroids, alkaloids, phenylpropanoids, phenolics, terpenoids, and nitrogenous compounds. These compounds inhibit weed activity by reducing reproduction, growth, and development in weed species. Several research have reported the use of plant extracts in weed management without causing detrimental effects on crops. For instance, Kaab *et al. (*2020) reported that phenolic extract from *Cynara cardunculus* is a viable weed control agent as it possesses phytotoxic properties that significantly contribute to weeds' oxidative stress by destroying their plasma membrane. Alsaadawi & Dayan, (2009) also reported that *Sorghum bicolor* phytotoxic extracts caused a 40% reduction in the biomass of *Echinochloa crus-galli*, resulting in an 18% rice yield increase. Essential oils extracted from plant parts have also been reported to show weed control potential (Verdeguer *et al.*, 2011).

3.2.3 GMO-Based Bioherbicides

Herbicidal compounds can also be derived from transgenesis. The compounds produced by the incorporated genetic materials are called plant-incorporated protectants (PIPs). The first PIP to be approved was called SmartStax Pro (Parween & Jan, 2019). The farmers in the United States of America adopted it to control corn rootworm, a plant disease resistant to several other pesticides. The PIP was based on transformative RNAi technology. However, there are possibilities for non-transformative strategies such as the use of formulations of sprayable RNAs as direct control agents, resistance factor repressors, or developmental disruptors (Zotti *et al.*, 2018).

Table 2. Bioherbicides developed from various sources and their effects on targeted weeds

Source	Organism used	Target Weed	Effects	References
Plants	*Sinapis alba L.*	Powell amaranth (*Amaranthus powellii*) and green foxtail (*Setaria viridis*)	Decreased plant growth rate and dry weight	Morra *et al.,* 2018
	Everniastrum sorocheilum, Usnea roccellina, and *Cladonia confuse*	*Trifolium pretense*	Inhibited germination and root development	Cai & Gu, 2016
	Portulaca oleracea L.	*Triticum aestivum, Brassica napus*	Reduced seed germination, shoot, root length and dry weight	Hamad, 2021
	Cynara cardunculus	*Trifolium incarnatum, Silybum marianum* and *Phalaris minor*	Reduced seedling germination and growth, and caused necrosis or chlorosis	Kaab *et al.,* 2020
	Pinus nigra J.F.Arnold	*Phoenix. canariensis, Trifolium campestre* Schreb., *Sinapis arvensis*	Reduced germination and growth	Hasan *et al.,* 2021
Fungi	*Microsphaeropsis amaranthi* and *Phomopsis amaranthicola*	*Amaranthus rudis*	Decreased Biomass	Cai & Gu, 2016
	Myrothecium verrucaria	*Pueraria lobata* (Wi11d.) Ohwil	Death of seedlings	Hoagland *et al.,* 2007
	Fusarium fujikuroi	*Cucumis sativus* L., *Sorghum bicolor* (L.)	Reduced plant height, root length and caused necrosis or chlorosis	Daniel *et al.,* 2018
	Phytopathogenic fungi	*Cucumis sativus* L.	Reduced plant height and fresh weight	Souza *et al.,* 2017
Bacteria	*Xanthomonas campestris pv poannua*	*Poa annua*	Penetrate the injuries to cause lethal and systematic wilt	Johnson *et al.,* 1996
	Pseudomonas aeruginosa	*Amaranthus hybridus, Solanum lycopersicum, Echinochloa crus-galli, Pennisetum purpureum Schumach*	Suppress seed germination, growth, and germ activity	Hasan *et al.,* 2021

4. Benefits of Biofertilizers and Bioherbicides

The use of biofertilizers and bioherbicides comes with numerous benefits both in the agricultural sector, the ecosystem, and in solving the problem of food security at large. With respect to plant growth and development, the application of biofertilizers helps to provide sufficient nutrients to the crop during growth, enhance root proliferation, safeguard the plant from soil-borne disease attacks, subsequently enhancing the plant growth and development as well as regulation and enhancing the physiological activities of the plant such as photosynthesis and crop yield by 10-25% (Al Abboud *et al.,* 2014; Kumar *et al.,* 2017). In addition, biofertilizers improve the physical properties by improving the soil structure and aggregation, tilth, soil aeration, and water infiltration and decreasing compaction and soil erosion (Mayanglambam *et al.,* 2020**)**. The application of biofertilizers has played a significant role in enhancing plant productivity (Singh *et al.,* 2016). Furthermore, Mahanty *et al.* (2017) reported that the use of a particular strain of rhizobia drastically enhanced the surface area of plant leaves, rate of photosynthesis, stomatal conductance, and water utilization efficiency, demonstrating that the application of rhizobia significantly improves the plant's photosynthetic activities. Interestingly, under stress conditions such as drought, biofertilizers have also been reported to play a crucial role in improving a plant's physiological and biochemical traits, such as photosynthetic rate, root hydraulic conductivity, osmolyte and antioxidant enzyme production, higher membrane stability, and lower lipid peroxidation (Anli *et al.,* 2020). For instance, a study by Heidari & Golpayegani (2012) reported the inoculation of three bacterial species (*Pseudomonades sp., Bacillus lentus, Azospirillum brasilens*) greatly enhanced the chlorophyll content of plant leaves as well as the antioxidant enzyme production under water stress events. Furthermore, the inoculation of strains of *Paenibacillusalcaligenes, Bacillus polymyxa* and *Mycobacterium phlei* produced calcisol and helped to increase the uptake of nutrients and growth of maize under salinity and heat stress conditions (García-Fraile *et al.,* 2015).

Apart from the earlier stated advantages, biofertilizers are also used to control plant diseases and infestation of soil-borne pathogens. The utilization of beneficial soil microbes, including *Bacillus* and *Trichoderma*, to control plant diseases and soil-borne pathogens is a viable and sustainable option compared to chemical pesticides (Wang *et al.,* 2022**)**. Prevention of plant diseases using biofertilizer can either be direct, such as when the microbe metabolism inhibits the pathogen's actions, or indirect, such as when the microbes inoculated compete with pathogens, consequently lowering their potential to cause disease (García-Fraile *et al.,* 2015**)**. The effectiveness of biofertilizers in controlling plant diseases and plant-parasitic nematodes has been demonstrated in scientific literature. For instance, a study by Wang *et al. (*2022) described that pineapple-banana rotation combined with bioorganic fertilizer helped to control or reduce banana *Fusarium* wilt disease**.** Mahanty *et al.* (2017) reported the use of six new commercial Egyptian biofertilizers (nitrobien, rizobacterin, serealin, phosphorine, microbien, blue-green algae) for the control of *M. incognita* to sunflower cv. Giza 101. In this study, the population of nematodes was reduced drastically by all the biofertilizers applied. Furthermore, rizobacter in the treatment resulted in the greatest reduction in nematode populations, followed by phosphorine and nitrobien. In general, biofertilizer-like bacteria secrete many substances such as volatile compounds, fatty acids, hydrogen sulfide, enzymes, hormones, alcohol, and phenolic compounds, all of which are employed to prevent the development of parasite nematodes in plants**.** The application of bacterial biofertilizers was reported to significantly increase the tomato growth traits and to suppress the root-knot nematode *Meloidogyne incognita* (El-Haddad *et al.,* 2011). Biofertilizers are also useful weapons for the restoration of soil pollution. They are environmentally friendly, unlike inorganic fertilizers, which frequently cause environmental pollution by running off into the water bodies, producing eutrophication and methemoglobinemia (blue baby syndrome) when the nitrate level reaches 10mg/L and above. They contribute to improving the soil quality by providing nutrients to the natural environment in the rhizosphere. It will help to reduce overspill or leaching of nutrients, along with crop residue management (Asoegwu *et al.,* 2020**)**. The demand for biofertilizers has increased in recent years due to their benefits. They are affordable and inexpensive, it costs only 2.60 Indian Rupees per kg to supply the equivalent nutrient of chemical fertilizer worth 11.65 Indian Rupees per kg (Praveen & Singh, 2019). As a result, they are easily accessible for small-scale farmers across the globe for sustaining agricultural productivity and a healthy environment.

Bioherbicides are used to control weeds. Their application disrupts the morphological and physiological processes of weed plants, consequently suppressing their growth and development (Hasan *et al.,* 2021**)**. For instance, the application of bioherbicides lowers the germination rate and growth of seedlings of barnyard grass (Irshad & Cheema, 2004**). **Furthermore, bioherbicides do not stay active in the environment for a long period of time, are less likely to pollute soil and water bodies, and do not harm non-target organisms (Hasan *et al.,* 2021).

5. Commercial Biofertilizer and Bioherbicide Products

The first production of a biofertilizer on a commercial scale can be traced back to 1896, when Nobbe and Hiltner patented a *Rhizobium*-based product called Nitragin (García-Fraile *et al.*, 2015). Currently, some multinational companies specialize in the production of biofertilizers. Rizobacter, a company established in 1977 in Argentina, is one such company, with their distribution services reaching countries in different continents. Table 3 presents a number of other biofertilizer production companies and their registered products as reported by García-Fraile *et al. (*2015). The first record on the development and availability of bioherbicides on a commercial scale can be traced back to the mid-1970s. The earliest project reported the discovery of the Mycoherbicide, based on the application of *Fusarium oxysporum* Schlecht, a fungus, against *Opuntia ficus-indica* (L.) Mill., (Pacanoski, 2015). As at 2016, thirteen bioherbicides were reported to be on a global scale, nine have been extracted from fungi, three from bacteria and one from plant extracts (Cordeau *et al.*, 2016). Furthermore, according to Verdeguer *et al.* (2020), six bioherbicides derived from essential oils were registered on a commercial scale in the USA in 2020. Table 4 outlines the currently available bioherbicides as reported by Hasan *et al.* (2021).

An assessment of the efficacy and consistency of the performance of the biocontrol product is critical for the sustainability of its commercialization. Stages in the development and commercialization of a biocontrol product include the isolation of microbes, screening for specific characters, testing under axenic condition, small scale testing, trials under field conditions/*in situ* evaluation and standardization studies. The rush of biocontrol products into the commercialization phase without adequate and proper field trials is partially responsible for not meeting their desired expectations (Korsten & Bornman, 2004). The evaluation of a biocontrol product is best started by an *in vitro* study, as this provides a better understanding of the possible mechanisms involved in its action before the field trial. Korsten & Bornman (2004) reported the accreditation of an *in vitro* dual assay method for evaluating a biocontrol agent against a spectrum of pathogens on a commercial scale at Plant Pathology Laboratories, University of Pretoria, South Africa. In their study on evaluating *Streptomyces violaceusniger* AC12AB as a potential biocontrol agent for managing potato common scab, Sarwar *et al.* (2019) reported a 90 and 80% decrease in common scab severity for the greenhouse and field trials, respectively. The development of the common scab is dependent on multiple physical and biological factors. A field trial, therefore, is important to evaluate *Streptomyces violaceusniger* in the complex environment of the field soil. In addition, an increased yield of more than 25% was also observed in the potato tubers produced. Thus, for the successful and sustainable commercialization of biocontrol products, more time and funding should be dedicated to laboratory and field trials.

Table 3. Commercially available biofertilizers

Product	Company	Bacterial strains
Cell-Tech®	Novozymes	Rhizobia
Nitragin Gold®	Novozymes	Rhizobia
TagTeam®	Novozymes	Rhizobia + *Penicillium bilaii*
Accomplish®	Loveland Products, Inc	PGPR + enzymes + organic acids + chelators
Nodulator®	BASF Canada Inc.	*Bradyrhizobium japonicum*
Nodulator® N/T	BASF Canada Inc.	*Bacillus subtilis* MBI 600 + *Bradyrhizobium japonicum*
Nodulator® PRO	BASF Canada Inc.	*Bacillus subtilis* + *Bradyrhizobium japonicum*
Nodulator® XL	BASF Canada Inc.	*Rhizobium leguminosarum* biovar *viceae* 1435
Bioboots®	Brett-Young Seeds	*Delftia acidovorans*
Bioboots® (soybean)	Brett-Young Seeds	*Delftia acidovorans* + *Bradyrhizobium* sp.
EVL coating®	EVL Inc.	PGPR consortia
Nitrofix®	Labiofam S. A.	*Azospirillum* sp.
Bioativo®	Instituto de Fosfato Biológico (IFB) Ltda.	PGPR consortia
VitaSoil®	Symborg	PGPR consortia
Azotobacterin®	JSC "Industrial Innovations"	*Azospirillum brasilense* B-4485
Mamezo®	Tokachi Federation of Agricultural Cooperatives (TFAC)	Rhizobia (in peat)

R-Processing Seeds®	Tokachi Federation of Agricultural Cooperatives (TFAC)	Rhizobia (coated legume seeds)
Hyper Coating Seeds	Tokachi Federation of Agricultural Cooperatives (TFAC)	Rhizobia (coated grass legume seeds)
Life®	Biomax	PGPR consortia
Biomix®	Biomax	PGPR consortia
Biozink®	Biomax	PGPR consortia
Biodine®	Biomax	PGPR consortia

Source: García-Fraile *et al.* (2015)

Table 4. Commercially available bioherbicides

Source	Target Weeds	Ecosystem	Registered Name	References
Cephalospprium diospyri	*Diospyras virginiana* L.	Pastures, rangelands	Oklahoma	Julien (2014)
Colletotrichum gloeosporioides aeschynomene	*Aeschynomene virginica* L.	Rice, soybean	Commercialized-Collego™	Tateno, (2000)
Alternaria cassia	*Cassia obtusifolia* L.	Soybean	Formulation development-'CASST'	Tateno, (2000)
Phytophthora palmivora	*Morrenia odorata* (Hook. &Arn.) Lindl.	Citrus groves	Commercialized-Devine™	Tateno, (2000)
Xanthomonas campestris	*Poa annua* L.	Turf, athletic fields	Commercialized-Camperico®	Boyetchko *et al. (*2007)
Cylindrobasidium leave	*Acacia* spp.	Forest, rangelands	Commercialized-Stump-Out™	Hintz, (2007)
Colletotrichum gloeosporioides	*Hakea sericea* Schrad. &J.C.Wendl.	Mountain meadows	Commercialized-Hakak	Hintz, (2007)
Colletotrichum gloeosporioides malvae	*Malva pusilla* Sm.	Flex, lentil, horticultural crops	Commercialized-BioMal®	Bailey & Falk (2011)
C. purpureum	*P. serotine*	Forest	Commercialized-Biochon™	Stewart-Wade *et al. (*2002)
Phoma macrostoma	*Reynoutria japonica* Houtt.	Golf courses, agriculture, and agro-forestry	Commercialized-Phoma	Pest Management Regulatory Agency, (2013)
Streptomyces acidiscabies	*Taraxacum officinale* L.	Turf	Commercialized-Opportune®	Mendes & Rezende, (2014)
Alternaria destruens	*Cuscuta* spp.	Cranberry	Field evaluation-Smolder	Bailey *et al. (*2009)
Chondrostereum purpureum (Fr.) Pouz	*Prunus serotina* Ehrh.	Forest, mountains	Commercialized-Mycotech™	Stewart-Wade *et al. (*2002)
C. purpureum	*Populus euramericana*	Guinier Forest	Commercialized Chontrol®	Stewart-Wade *et al. (*2002)
Sclerotinia minor Jagger.	*Taraxacum* spp.	Turf	Commercialized-Sarritor®	Kawuma, (2019)
Puccinia thlaspeos C.	Shub. Isatis *tinctoria* L.	Forest, rangelands, pastures	Commercialized-Woad Warrior®	Cordeau *et al. (*2016)
Pinus radiate D.Don	*Ochna serrulata* Walp.	Grassland, forest	Commercialized-BioWeed™	Travlos *et al. (*2020)
B. napus	*Amaranthus retroflexus* L.	Wastelands, prairies	Commercialized-Beloukha®	Muñoz *et al. (*2020)

Citrus sinensis (L.)	Osbeck *Solanum nigrum* L.	Cultivated lands, roadside	Commercialized-GreenMatch™	Verdeguer *et al.* (2020)
Syzygium aromaticum (L.) Merr. & L.M.Perry and Presl *Cinnamomum verum* J.	*E. crus-galli*	Rice, cultivated lands	Commercialized-WeedZap®	Verdeguer *et al.* (2020)
Citrus limon (L.) Osbeck	*D. sanguinalis*	Cultivated areas	Commercialized-Avenger® Weed Killer	Verdeguer *et al.* (2020)
S. aromaticum	*E. crus-galli*	Rice, cultivated lands	Commercialized-Weed Slayer®	Verdeguer *et al.* (2020)
Cymbopogon citratus (DC.) Stapf	*Euphorbia* spp.	Agricultural lands	Commercialized-GreenMatch™ EX	Avila-Adame *et al.* (2008)

6. Challenges Limiting the Adoption of Biofertilizers and Bioherbicides

The adoption of biocontrol products by farmers in developing countries for commercial agriculture is being hindered by various challenges, despite the reports of their safety and effectiveness. One such hindrance is the limitations encountered while evaluating the long-term effectiveness of biofertilizers and bioherbicides as well as during data collection on their economic and environmental impact. Most data on assessing the efficacy of biocontrol agents are derived from laboratory and glasshouse trials; field data are rare (Morin *et al.*, 2009). Evaluating the efficacy based on laboratory and glasshouse trials alone most often brings about exaggerated results because plants used for experiments are at the early stage of life under a prescribed set of environmental conditions which may differ from the varying environmental parameters in their natural habitats (Morin *et al.*, 2009). Consequently, these biocontrol agents may not live up to expectations projected based on the laboratory experiments. However, establishing field trials for biological control programs and long-term post-release monitoring require adequate resources and funding.

Biofertilizer and bioherbicide formulations are yet to be available to farmers in developing countries on a commercial scale. Despite the rise in the number of commercial biocontrol products for crop protection, they represent only 1% of crop protection measures dominated by chemical agricultural inputs (Lahlali *et al.*, 2022). Lack of methods for the mass production of discovered biocontrol agents is reported to be one of the greatest obstacles to commercialization of biofertilizers and bioherbicides (Junaid *et al.*, 2013). Although the time to develop a biocontrol product may be similar to that of chemical control methods, the cost benefit is higher when considering indirect costs, such as environmental pollution and health effects caused by agrochemicals (Lenteren, 2012). Therefore, government and agricultural regulating bodies should fund biocontrol production research and create an enabling environment for small and large entrepreneurs venturing into the commercial production of biofertilizers and bioherbicides.

The uncertainty of the long-term effectiveness of biocontrol products is one factor limiting the adoption of such products by farmers in developing countries. According to a study report by Tracy (2014), the primary motivation for farmers to adopt biocontrol products over conventional agrochemical inputs is usually economic, targeting increased efficiency and reduced cost of production. Compared to economic sustainability, concerns for environmental sustainability are less important. However, they also observed that, unlike chemical-based crop protection methods, the adoption of biocontrol-based products is highly dependent on specialized knowledge. Understanding the expectations and behavior of these farmers through market research is therefore important for a successful market-oriented bioproduct launch. This will allow producers to identify the demographics and market segments that are most likely to consume the biocontrol products, develop a strategy for addressing them and pricing the products in a way that appeals to them.

7. Biofertilizers and Bioherbicides in Integrative Crop Management

Integrated crop management is a farming approach that combines traditional and modern techniques to optimize crop production. It involves the use of a wide range of techniques, including the application of biofertilizers and bioherbicides, diverse crop rotations, cover cropping and the use of natural predators to improve crop health and productivity with less input from agrochemicals. This approach is aimed at enhancing the crop yields and protecting the ecosystem. The combination of manures (including farmyard manures, compost, green manures, and vermicompost), crop residues, and biofertilizers, along with synthetic fertilizers, can help reduce the amount of fertilizers (N, P, and K) used by 25-50% (Ramakrishnan et al., 2020). The use of individual weed control is considered insufficient to curb weeds on agricultural fields. The combination of different weed control techniques, including physical, genetic, biological, cultural, and chemical methods, has brought about significant improvements in weed management. Relying solely on chemical inputs for agriculture is not sustainable in the long term. The use of integrated crop management systems is considered the best approach for eco-friendly, sustainable agriculture.

8. Conclusion and Recommendation

Addressing threats to global food security in developing countries requires adequate crop yield enhancement and protection measures that are generally acceptable, economically feasible, technically effective, environmentally friendly, and easy to use or to apply. The adoption of biofertilizers and bioherbicides in crop production fits into these demands. However, to successfully implement these methods, it is required to modify the current practices and trials of potential biofertilizers and bioherbicides. An integrated systems approach that combines biocontrol methods with multiple effective crop production methods is more effective and sustainable. Thus, further study is required on isolating effective biological agents, studying the mechanisms of their actions, developing strategies for mass production and application, and investigating the potential impacts of biocontrol agents on non-target organisms and the environment. Furthermore, convincing farmers, who are accustomed to and committed to traditional farming methods, to adopt biocontrol products may be challenging. It will, therefore, be necessary to create an effective marketing strategy to gain the confidence of such farmers through research data that supports the adoption of biofertilizers and bioherbicides for commercial agriculture.

Conflict of Interests

The authors declare no conflicts of interest related to this article.

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