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Role of beneficial soil microorganisms (BSMS) as an alternative for agrochemicals in agriculture

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Abstract
The world population is increasing, and it is becoming more difficult to feed the world using traditional agriculture methods. Farmers use different types of agrochemicals such as chemical pesticides and fertilizers to increase agricultural production. The use of agrochemicals is increasing and due to their extensive usage has been shown to negatively impact soil, water, the environment, and ultimately the health of plants and humans. Thus, scientists are developing several advanced strategies to improve agricultural production and identify the most environmental friendly ones. Application of beneficial soil microorganisms (BSMs) and their based bioformultions (biopesticides and biofertilizers) is considered a good alternative to agrochemicals because they contain a typical population of beneficial microorganisms that supply nutrients from soil needed by plants and control pests without harming the environment. The beneficial effects of BSMs on crop growth and development have been reported by several researchers. This study aims to explore the role of BSMs as an environment friendly and sustainable alternative for agrochemicals in agriculture.

Keywords: Agriculture, biopesticide, biofertilizer, pesticide, fertilizer, environment

Introduction
Agriculture is vital for human existence, and humans are completely dependent on agriculture for food and other sources. Modern agriculture produces unsustainable agricultural production and the agricultural sector is under extreme pressure due to the increasing population and food demand. To meet the food demand, farmers use various agrochemicals like chemical pesticides and fertilizers in agriculture. These agrochemicals and their residues remain in the environment for a long time and have many negative effects on biological systems (Geisseler and Scow 2014) [48].

Agriculture is adversely affected by different types of pests which cause annual crop losses of up to 45% (Mundt 2014) [96]. Pesticides have led to increased agricultural production throughout the world by controlling the pests. Pesticide use is as old as human civilization as human beings started cultivating a sustainable life. In many developing countries, indiscriminate use of pesticides in agriculture has resulted in serious human health issues (Turabi *et al.*, 2007) [130]. An estimated 80,000 tonnes of pesticides are used annually, with the majority of them being used on cotton (45%), rice (23%), fruit and vegetables (8%), cereals, pulses, oilseeds, and millets (6-7%). (Arora *et al.*, 2019) [13]. This increased consumption has resulted in environmental pollution, diminishing soil fertility, and a reduction in sustainable agricultural production. Chemical fertilizers increase agriculture production but it has serious negative impacts on agriculture and as well as the environment. Chemical fertilizer residues lead to an imbalance in the soil's nutritional composition and impair the soil's capacity to retain water and fertility (Hazra 2016) [56]. Humans and other living organisms are exposed to toxic residues when they consume the crops (Arora *et al.*, 2022) [14].

Therefore, there is a great demand for safer agrochemical alternatives that are sustainable, non-toxic, easy to handle, safe for both humans and plants and environmental friendly. BSMs are beneficial microorganisms for plant growth and soil ecosystem and play a vital role in sustainable agricultural production without any negative impact on the environment (Gupta 2007) [50]. The application of BSMs based bioformultions like biopesticide and biofertilizer is increasing due to increased awareness of

the negative environmental effects caused by the excessive use of agrochemicals and a better understanding of the interactions between plants and all soil microorganisms in the rhizosphere. The use of BSMs-based bioformultions in agricultural production has recently become more well-known as a sustainable way to improve crop productivity and manage pests (Hannah and Max 2013, Annunzio *et al.*, 2014) [12, 54]. BSMs-based biopesticides are used to effectively control pests without negative effects (Adeleke *et al.*, 2022) [6]. BSMs produce many compounds that are important in controlling pests and a lot of research has been done in the past few years to develop and commercialize BSM-based biopesticides (Ruiu 2018) [112]. BSMs-based biofertilizers are helpful tools in the agricultural ecosystem that mitigate the adverse effects of chemical fertilizers by enriching the soil with beneficial elements such as nitrogen, vitamins, proteins, and water-holding capacity (Jacob and Paranthaman 2022) [60]. To preserve a healthy ecosystem, soil and plant-associated BSMs perform important biogeochemical cycles and decompose organic materials (Paul 2015) [103]. BSMs play a crucial role in producing microbial-based biofertilizers, which are applied to seeds or soil to improve soil nutrient availability, plant nutrient absorption, and disease resistance (Lopes *et al.*, 2021, Riaz *et al.*, 2020) [78, 110]. This review paper discusses the role of BSMs as an alternative for agrochemicals in agriculture.

Negative consequences of agrochemicals

Chemical fertilizers are vital in modern agriculture to enhance plant growth and agriculture production. Farmers use chemical fertilizers indiscriminately to supply essential nutrients like nitrogen, phosphorus, and potassium to plants to increase growth (Guo *et al.*, 2022) [49]. The excessive use of chemical fertilizers changes the pH of the soil, raises soil acidity, stunts plant growth, reduces organic matter, and negatively affects soil microorganisms (Liliane and Charles 2020) [76]. Chemical fertilizers impact agriculture because their residues alter the soil's fertility, water-holding capacity, and nutritional balance (Hazra 2016) [56]. During the production of chemical fertilizers, several harmful byproducts such as toxic gases like NH4, CO2, and CH4 are released (Kumar *et al.*, 2019) [72]. Only half of the chemical fertilizers used in fields are utilized by plants; the remaining fertilizers enter the atmosphere through volatilization and contaminate groundwater (Kılıç *et al.*, 2020) [68]. The excessive use of chemical fertilizer enhances crop yields resulting in harmful greenhouse gas emissions that destroy the ozone layer, causing global warming and exposing humans to damaging UV radiation (Savci 2012) [116]. The massive use of chemical fertilizers leads to the generation of nitrogen oxides (NO, N2O, and NO2), one of the reasons behind air pollution (Cooper *et al.*, 2018) [34]. Regular application of chemical fertilizers causes heavy metal pollution in agriculture (Sonmez *et al.*, 2007) [120]. Chemical fertilizers also damage several important soil properties and reduce the number and diversity of soil microorganisms (Sterner and Elser 2017) [121].

The use of chemical pesticides to control agricultural pests and enhance crop yields has been used since ancient times (Anani *et al.*, 2020) [11]. The World Health Organization (WHO) recently estimated that approximately 20,000 individuals die globally each year and that over 25 million people in developing nations experience acute occupational pesticide poisoning. Several pesticides such as carbamates, pyrethroids, neonicotinoids, organochlorines, and organophosphates have been developed and widely used globally in agriculture since the discovery of DDT (dichloro-diphenyl-trichloroethane) with no regulation or oversight. Despite their beneficial positive effects on agriculture, chemical pesticides have some detrimental consequences on aquatic life, animals, humans, and soil biodiversity (Farooq *et al.*, 2019) [43]. Pesticides have detrimental side effects that put living organisms at risk for long-term threats. Pesticides cause various diseases like cancers, foetal impairments and several other diseases and they remain in the environment for a long time due to their non-biodegradable nature (Kalliora *et al.*, 2002) [65]. Therefore, the government and public are aware of their negative impact and legislation is limiting their use in agriculture which is causing a 2% annual decrease in the use of chemical pesticides and a 10% increase in the use of biopesticides as an alternative (Damalas and Koutroubas, 2018) [35]. The use of biopesticides to protect crops from pest infestations and the resulting losses has received a lot of interest in recent years.

Biopesticides and biofertilizers as alternatives to agrochemicals

Biopesticides are one of the most important subclasses of pesticides that are based on biological organisms and inhibit the growth and proliferation of pest populations through different methods (Tijjani *et al.*, 2016; Marrone, 2019 [85, 128]; Nuruzzaman *et al.*, 2019 [99]; Wattimena and Latumahina, 2021) [140]. The application of biopesticide in agriculture is an effective approach in pest control which is derived from natural materials or microorganisms and it has the potential to reduce crop loss without sacrificing product quality. Biopesticide application in agriculture is a sustainable alternative to chemical pesticides and it is safe for humans, low cost, residue-free, target-specific and not linked to greenhouse gas emissions (Borges *et al.*, 2021) [25]. Microbial-based pesticides, biochemical biopesticides (phytopesticides and semiochemicals), and plant-incorporated protectants are some examples of biopesticides (Fig 1) (Abdollahdokht *et al.*, 2022; Pan *et al.*, 2023) [5, 101]. Biopesticides account for 5% of the global pesticide market, with microbial biopesticides leading the pesticide market. Biopesticides are effective in controlling pests and are important for sustainable agriculture because they are derived from natural materials (Kumar *et al.*, 2021) [71]. Biopesticides are host-specific and environment friendly and due to this, they are significantly more beneficial than their conventional chemical equivalents (Essiedu *et al.*, 2020) [41].

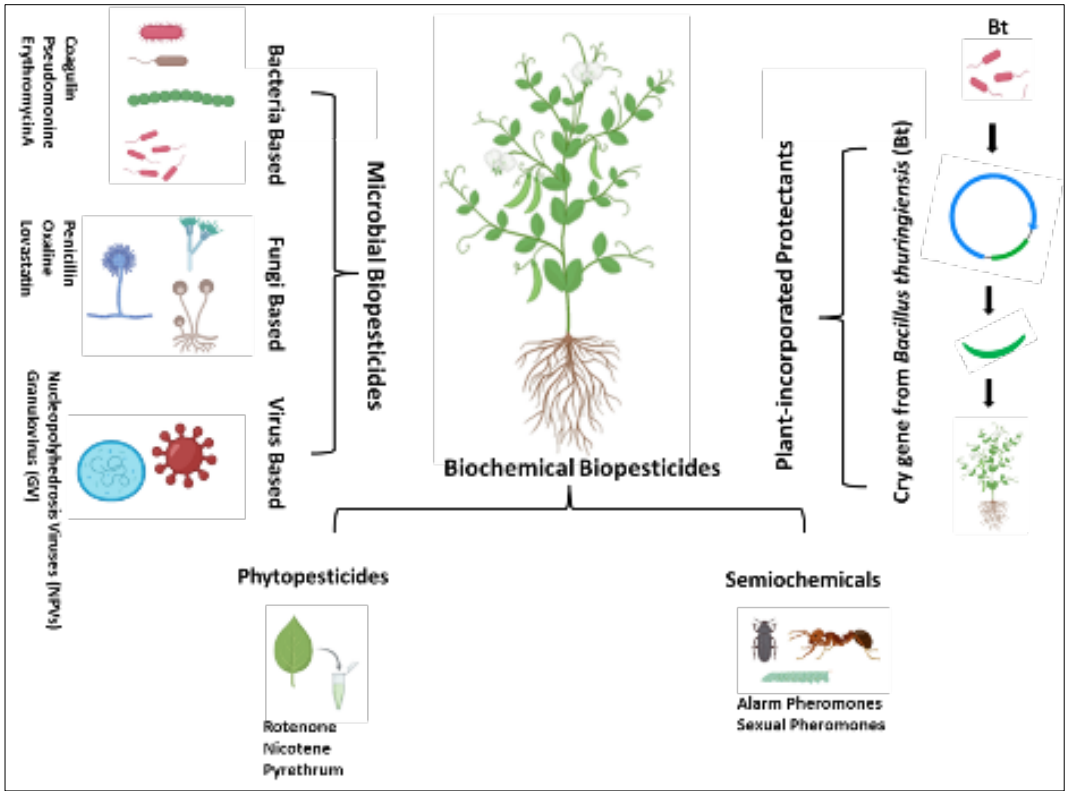

Fig 1: Different categories of Biopesticides

A substance containing living microorganisms that colonize the rhizosphere zone and promote plant growth and development by enhancing the accessibility of essential soil mineral nutrients is referred to as a "biofertilizer," also known as "micro inoculants" (Verma *et al.*, 2019, Malusá *et al.*, 2012) [84, 135]. The primary roles of microorganisms found in biofertilizers include fixing nitrogen, converting phosphorus from an insoluble form to a soluble one, producing compounds that support plant growth, protect against pathogens (Thomas and Singh 2019, Hayat *et al.*, 2010) [55, 127]. Apart from facilitating the uptake of nutrients, several biofertilizers also synthesize different types of vitamins and phytohormones that support plant development (Bhardwaj *et al.*, 2014, Abd El-Fattah *et al.*, 2013) [4, 23]. By producing different growth-stimulating chemicals, they can also promote plant growth and development, and their stability is indicated by their C:N ratio of 20:1 (Wani *et al.*, 2013) [139].

Biofertilizers are receiving more attention worldwide, especially in developing nations, as a result of concerns about chemical-free and sustainable agricultural practices. The demand for biofertilizers in several countries such as China, Europe, Canada, the United States, India and others increased (Raimi *et al.*, 2021, Malusa *et al.*, 2016) [83, 108]. These countries are continuously working on the usage, development and promotion of biofertilizers because they are aware of the many advantages that these fertilizers offer and because their demand for organic products is increasing (Masso *et al.*, 2015, Adeleke *et al.*, 2019, Raimi *et al.*, 2017) [7, 86]. Biofertilizers are gaining popularity in agriculture because they provide a suitable alternative to chemical fertilizers, enhance soil health, low cost, and boost production by 10-25% without causing negative effects on the environment and soil (Rashid *et al.*, 2016) [109]. Biofertilizers can also aid in enhancing water retention and reduce soil erosion (Asoegwu *et al.*, 2020) [16]. Additionally, biofertilizers remediate soil pollution, raise agricultural productivity by improving tolerance to harsh conditions, and aid with several unfavourable conditions including salinization (Abbas *et al.*, 2019, Liu *et al.*, 2022, Hossain *et al.*, 2022) [3, 57, 77]. To lower costs, enhance quality, and increase farmers' acceptance of biofertilizers, agricultural scientists and researchers are continuously working on the development of biofertilizers. Numerous newly created technologies, such as nanotechnology, nanofertilizers, nanobiofertilizers, and others, are being developed and are successfully used in agriculture (Thirugnanasambandan 2018) [126].

BSMs-based biopesticides

BSMs-based biopesticides are applied in agriculture to manage pests, and are made from compounds produced by microorganisms such as bacteria, fungi, viruses, protozoa, and algae (Adeleke *et al.*, 2022) [6]. Several BSMs species, including *Trichoderma harzianum*, *Beauveria bassiana*, *Bacillus thuringiensis*, and *Bacillus subtilis*, are used in agriculture for pest management (Table 1). BSMs-based biopesticides have been discovered and developed over the past 10 years as a result of intensive research efforts and also aid in their commercialization (Ruiu 2018) [112]. BSMs-based biopesticides often have no negative effects on the environment, farmers, or consumers because their constituents are widely regarded as harmless and target-specific (Guven *et al.*, 2021) [51]. Many BSMs species and strains, along with their valuable toxins and virulence factors, were discovered due to the successful application of *Bacillus thuringiensis* (Bt) and a few other microbial species. Some of these discovered strains have also been turned into commercial products (Ujváry 2001) [131]. BSMs controls plant diseases and pests by several methods, such as toxin creation, enzyme and volatile compounds synthesis, direct colonization, inducing resistance in plants, and

competition for resources (nutrients) and space (Freimoser *et al.*, 2019) [45]. Toxins such as antibiotics produced by microorganisms have various features like they are biodegradable, highly specific to a particular target, acting at relatively low concentrations, and can be produced in situ. BSMs produced different types of secondary metabolites and antibiotics which are used as biopesticides and control various types of pests. Coagulin from *B. coagulans*, gentamicin from *Micromonospora purpurea*, pseudomonine from *Pseudomonas*, bacilysocin from *B. subtilis* and erythromycinA from *Streptomyces erythreus* are example of bacterial based biopesticides (Fig 2). Penicillin from *Penicillium chrysogenum*, oxaline from *Penicillium raistricki*, lovastatin from *Aspergillus terreus* and limonene from *Trichoderma viride* are the example of fungal based biopesticides (Fig 3).

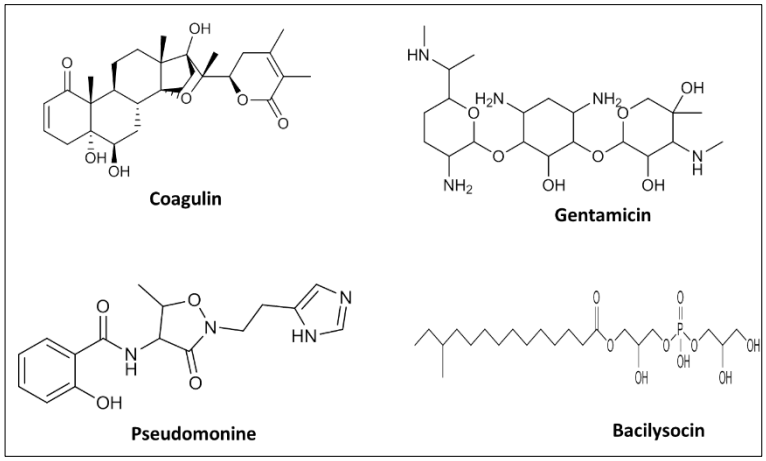

Fig 2: Biopesticide/ Secondary metabolites from Bacteria

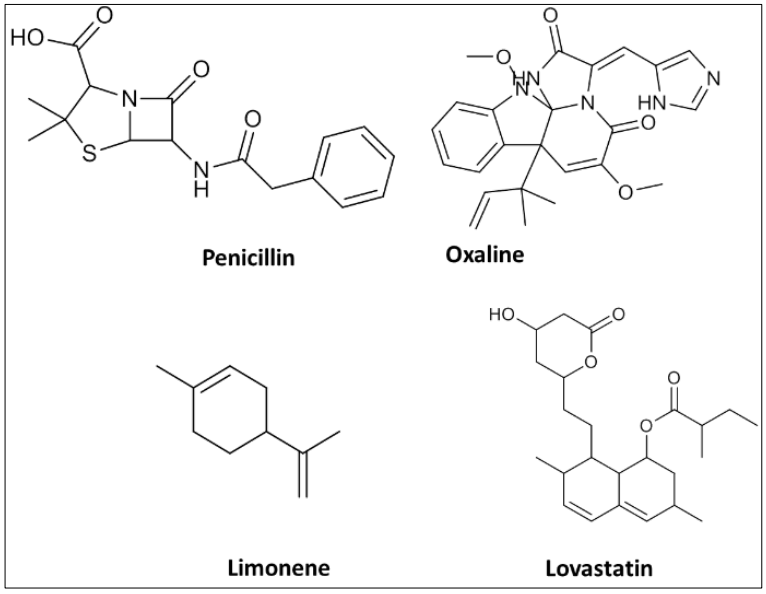

Fig 3: Biopesticide/ Secondary metabolites from Fungus

Table 1: BSMs used in different pest control in agriculture

S. No.	BSMs	Class	Pest	Host	References
1	*Bacillus thuringiensis*	Insecticide	Caterpillars, elm leaf beetle, alfalfa weevil Alfalfa weevil, black flies, larvae of mosquitoes	Vegetables, fruits, ornamentals, and cereals	[69] 2011; Bravo *et al.*2007, [27] Saberi *et al.* 2020, [113] Lee *et al.* (2021) [74]
2	*Bacillus subtilis*	Fungicide	*Botrytis spp., Macrophomina phaseolina,* and *Fusarium graminearum*	Vegetables and fruits	Koul 2011 [59]; Bravo *et al.*, 2007, [27] Torres *et al.*, 2016, [129] Zhao *et al.*, 2014 [144]
3	*Beauveria bassiana*	Insecticide	Whitefly	Ornamental plant	Mcguire and northfield 2020 [87]
4	*Trichoderma harzianum, Piriformospora indica* and *Sebacina vermifera*	Fungicide	Sclerotinia *sclerotiorum, Fusarium oxysporum, Rhizoctonia solani and Rhizoctonia zeae*	-	Dolatabadi *et al.*, 2011 [38]
5	*Chondrostereum Purpureum*	Herbicide	Weeds	-	Bailey 2014 [18]
6	*Paecilomyces lilacinus*	Nematicide	Nematodes	Vegetables, fruit, and ornamentals	Moreno-gavíra *et al.*, 2020 [94]

7	*Beauveria bassiana*	Insecticide	Crucifer flea beetle, cotton leafworm, and cyclocephala lurida, tuta absoluta	-	Miranpuri and khachatourians 1995, [90] Kaur *et al.*, 2011, [67] Wu *et al.*, 2016, [141] Tadele and emana 2017 [123]
8	*Paecilomyces lilacinus*	Nematicide	*Meloidogyne incognita*	Black gram	Bhat *et al.*, 2012 [24]
9	*Metarhizium sp.*	Insecticide	June beetle and ceratitis capitate	-	Erler and Ates 2015, [40] Lozano-tovar *et al.*, 2015 [80]
10	*Pseudomonas fluorescens*	Fungicide, nematicide	Pathogenic fungi, *Meloidogyne incognita*	Blackgram	Prasad *et al.*, 2015, [106] Akhtar *et al.*, 2012 [10]
11	*Verticillium lecanii*	Insecticide	*Trialeurodes vaporariorum*	-	Bouhous and Larous 2012 [26]
12	*Trichoderma spp.*	Nematicide	*Meloidogyne javanica*	-	Javeed *et al.*, 2016 [61]
13	*Beauveria brongniartii*	Insecticide	Caterpillar	Pine	Fan *et al.*, 2013 [42]
14	*Metarhizium brunneum*	Insecticide	*Cyclocephala lurida, and tuta absoluta,*	Common bean	Wu *et al.*, 2016, [141] Tadele and Emana 2017, [123] Bugeme *et al.*, 2015 [29]
15	*Phytophthora capsici*	Fungicide	*Phytophthora capsici*	Pepper	Naing *et al.*, 2013 [97]
16	*Hirsutella thompsonii*	Insecticide	Spider mites and whitefly	-	Saranya *et al.* (2021) [115]
17	*Isaria fumosorosea*	Insecticide	Termites, grasshoppers, caterpillars, and beetles	-	Gautam (2020) [47]
18	*Paecilomyces fumosoroseus*	Insecticide	Insects and mealy bugs	-	Abbas (2020) [2]
19	*Myrothecium verrucaria*	Insecticide	Nematodes	Sugar beet plants	Hagag (2021) [52]
20	*Lagenidium giganteum*	Insecticide	Mosquito	-	Kaczmarek and Boguś (2021) [64]

Bacillus thuringiensis (Bt) is the most common microorganisms known for insect control in agriculture and it covers 90% of the microbial biopesticide market. It is a Gram-positive bacterium which functions as an insecticide by generating exudates like toxic parasporal crystals and endospores. These exudates ingested by insects, dissolve in their midgut due to the alkaline environment and release a protein called delta-endotoxin, which is fatal to insects (Xiao and Wu, 2019) [142]. *B. thuringiensis* can manage lepidopterans in several plants and is used to decrease pest infestation in potatoes and cabbage (Berini *et al.*, 2018 [21]; Samada and Tambunan, 2020) [114]. In 2015, 32,000 tonnes of *B. thuringiensis*-based products were sold globally, making them the second most popular insecticides (including chemical insecticides) (Casida and Bryant 2017) [30]. The specificity and limited acute effects on beneficial and non-target species as well as the lack of environmental persistence of Cry proteins are probably the reasons why *B. thuringiensis* dominates the biopesticide industry (Betz *et al.*, 2000, Federici and Siegel 2007) [22, 44]. *Trichoderma* controls soil-dwelling fungi that cause root rot in groundnut, chickpea, black gram, and other crops (Samada and Tambunan, 2020) [114]. Infestations of several insects such as thrips, beetles, weevils, and mites in ornamental crops, fruits, and vegetables have been reported to be controlled by *Beauveria bassiana* and *M. brunneum* (Dara, 2017; Arthurs and Dara, 2019) [15, 37].

BSMs-based biofertilizers

The biofertilizer used in agriculture contains several important BSMs, such as nitrogen-fixing microorganisms (primarily *Azotobacter spp.* and *Azospirillum spp*.), phosphorus solubilization microorganisms (*Pseudomonas spp*.) effective fungi (*Trichoderma spp*.), rhizosphere bacteria (*Pseudomonas spp.* and *Bacillus spp.),* or arbuscular mycorrhizal fungi. (Castiglione *et al.*, 2021) [32]. BSMs used in the preparation of biofertilizer aid in the growth and development of plants by facilitating nutrient uptake, stimulating root surface growth, increasing plant biomass, yield, and many other benefits (Table 2) (Backer *et al.*, 2018) [17]. *Rhizobium*, *Azotobacter*, *Frankia* and *Azospirillum* are examples of beneficial microorganisms that may fix atmospheric nitrogen into an easily accessible form that is readily absorbed by plants and promotes plant growth (Sessitsch *et al.*, 2010, Cassán *et al.*, 2020) [31, 117]. BSMs that solubilize and mineralize phosphorus, such as *Pseudomonas*, *Bacillus*, and others, can convert both organic and inorganic forms of phosphorus into accessible forms for plant uptake (Tao *et al.*, 2008) [125]. Several BSMs such as *Azotobacter* and *Azospirillum* secret some chemicals that accelerate root development and improve nutrient uptake (Halpern *et al.*, 2015, Egamberdiyeva 2007) [39, 53]. Some BSMs release plant growth regulators (hormones) like auxins, cytokinins and gibberellins that promote plant growth (Luo *et al.*, 2022, Ahmed *et al.*, 2014) [8, 81]. Furthermore, BSMs can protect plants from several stressors such as biotic and abiotic by producing secondary metabolites, antibiotics, and enzymes (Stewart and Roberts 2012, Daniel *et al.*, 2022) [36, 122]. BSMs colonize in root surface and produce a phytostimulating effect with the help of direct and indirect mechanisms. Phytohormone synthesis and nutrient availability in soil (such as nutrient mobilisation and solubilisation) are examples of direct mechanisms (Basu *et al.*, 2021, López-Bucio *et al.*, 2015) [20, 79]. The secretion of enzymes, antibiotics, secondary metabolites, siderophores, and volatile and non-volatile compounds, and enhanced induction of systemic resistance for the suppression of detrimental phytopathogens are examples of indirect mechanisms (Olanrewaju *et al.*, 2017, Hossain *et al.*, 2017) [58, 100]. In addition to being beneficial for plant growth, BSMs is also important for the environment and soil ecosystem (fig 4).

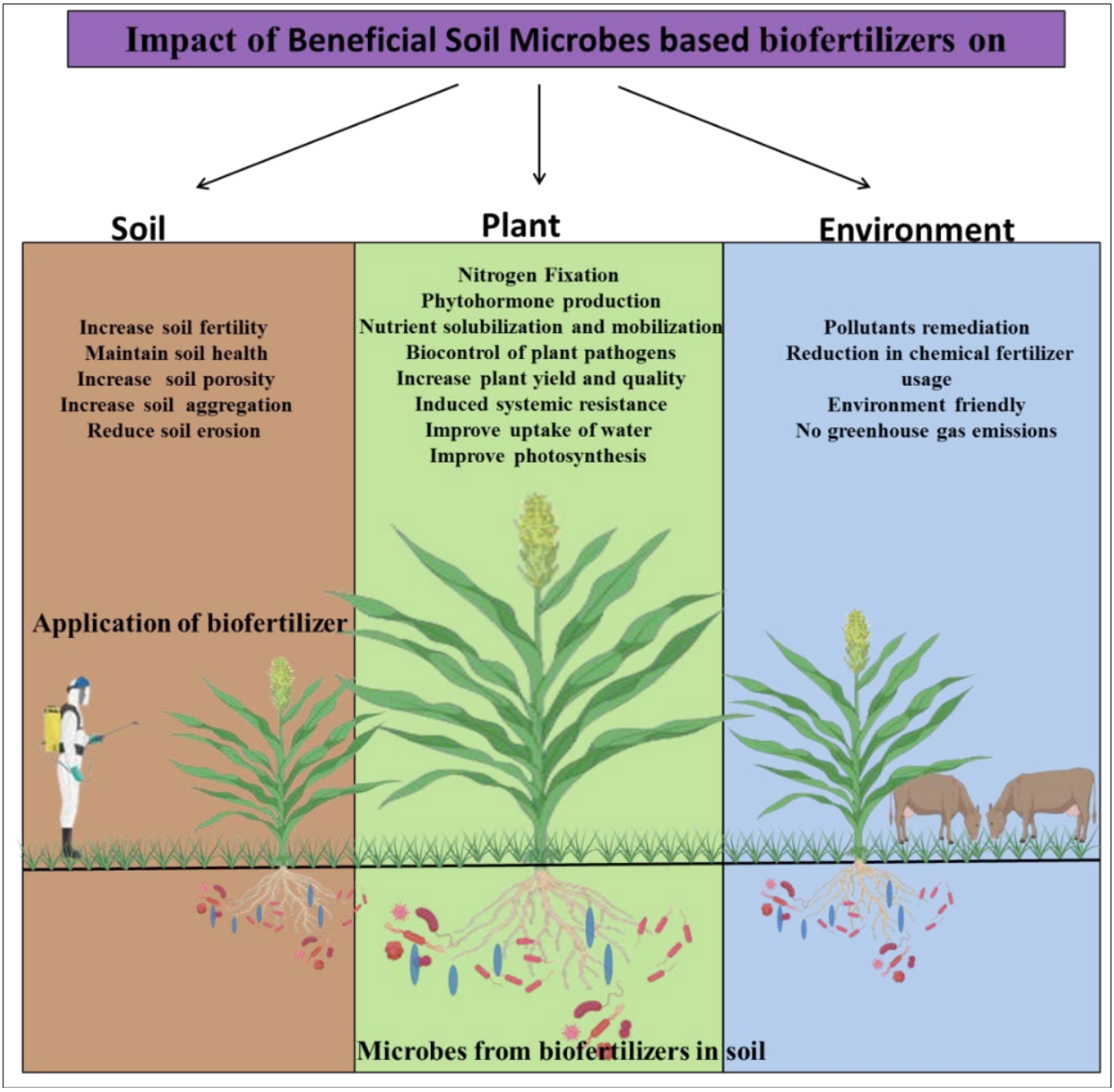

Fig 4: Impact of beneficial soil microorganisms on soil, plants and the environment

The nitrogen content of the soil that chemical fertilizers deliver to the soil is lost due to denitrification, runoff, leaching, and erosion. Nitrogen is abundant in the atmosphere, but plants cannot easily access it in its gaseous state until it is converted to ammonia (Miller and Cramer 2005) [89]. BSMs can promote nitrogen assimilation in this situation primarily by mineralization and nitrogen fixation, increasing the efficiency of N usage (Visconti *et al.*, 2020) [137]. Biofertilizers containing N -fixing BSMs decrease N leaching and enhance growth and development in sugarcane and macadamia plants (Paungfoo-Lonhienne *et al.*, 2020, Gallart *et al.*, 2021) [46, 104]. P, another crucial nutrient for plant growth and development, is available in the soil in enough amounts, but only in trace amounts in the chemical form that plants can absorb (Wang *et al.*, 2017) [138]. BSMs play an important role in P solubilization. *Paenibacillus* and *Trichoderma* solubilize the P by the organic acids production (Li *et al.*, 2015, Brito *et al.*, 2020) [28, 75].

The application of biofertilizers is increasing due to increased awareness of the negative environmental effects caused by the excessive use of chemical fertilizers and a better understanding of the interactions between plants and all soil microorganisms in the rhizosphere. This potential of these microorganisms supports efforts to identify and isolate different types of BSMs that exhibit the ability to promote plant development by directly or indirectly enhancing plant nutrient intake. The use of biofertilizers in agricultural production has recently become more well-known as a sustainable way to improve crop productivity and soil health (Hannah and Max 2013, Annunzio *et al.*, 2014) [12, 54].

Table 2: BSMs role in plant growth promotion

S. No	BSMS	Host	Mechanisms	Beneficial effects	References
1	*Azotobacter spp.*, *Azospirillum amazonense*, *Anabaena*, *Clostridium*, *Rhizobium*, *Frankia*, *Nostoc*, and *Klebsiella*	Chickpea, white spruce and rice	Biological N fixation(BNF)	Increased yield	Rodrigues *et al.*, 2008, [111] Verma *et al.*, 2017, [136] Shoeip *et al.*, 2022, [118] Puri *et al.*, 2020, [107] Aasfar *et al.*, 2021[1]
2	*Bacillus circulans*, *Bacillus subtilis*, *Bacillus licheniformis*, *Bacillus polymyxa*, *Pseudomonas striata*, *Pseudomonas fluorescens*, *Pseudomonas extremaustralis*, *Glomus intraradices*, *Penicillium spp.*, *Micrococcus agrobacterium*, *Enterobacter asburiae*, *Aereobacter* and *Flavobacterium*	Chickpea, Wheat, tomato, pepper and chili	Phosphorus solubilization	Enhanced biomass of root and shoot and P concentration in host	Valverde *et al.*, 2007, [133] Ahsan *et al.*, 2012, Upadhyay *et al.*, 2012, [132] Mohamed *et al.*, 2022, [93] Kudoyarova *et al.*, 2017, [70] Mahdi *et al.*, 2020, [82] Jiménez-Gómez *et al.*, 2017 [63]
3	*Bacillus spp.*, *Arthrobacter spp.*, and *Aspergillus niger*	Rice	Potassium solubilization	Enhanced yield and K nutrition in host	Etesami *et al.*, 2017, Jha 2017 [62]
4	*Mycorhiza*, *Pseudomonas spp.*, *Bacillus spp.*, *Pantoea dispersa*, and *Enterobacter cloacae*	Wheat, maize	Zinc solubilization	Increased lengths of the shoots and roots, along with increased dryweights	Kamran *et al.*, 2017, [66] Mumtaz *et al.*, 2022, [95] Zahra *et al.*, 2023 [143]
5	*Pseudomonas fluorescens*		Siderophore production	Promoted plant growth and enhanced iron inside plant tissues	Vansuyt *et al.*, [134] 2007
6	*Thiobacillus spp.*	Onion, Maize, Pumpkin	Sulfur oxidizing	-	Bhardwaj *et al.*, 2014, [23] Mohamed *et al.*, 2014, [92] Najafi *et al.*, 2021, [98] Itelima *et al.*, 2018 [59]
7	*Burkholderia phytofirmans*, *Aspergillus fumigatus*, *Fusarium proliferatum*, *Piriformospora indica*, *Trichoderma harzianum*,*Trichoderma atroviride*, *Pseudomonas spp.*, *Bacillus spp.*, *Rhizobium spp.*, *Enterobacter*, *Streptomyces*, and *Xanthomonas*	Rice, Bitter gourd, Gladiolus, Arabidopsis Petunia, Pinus,	Plant growth hormones production	Increased crop productivity, improved nutrient availability, primary root growth, and root elongation	Poupin *et al.*, 2016, [105] Meents *et al.*, 2019, [88] Contreras-Cornejo *et al.*, 2009, [33] Backer *et al.*, 2018, [17] Zulueta-Rodriguez *et al.*, 2014, [145] Singh *et al.*, 2017, Modi *et al.*, 2022, [91] Barriuso *et al.*, 2008 [19]
8	*Pseudomonas fluorescens*, *Bacillus subtilis*, and *Trichoderma spp.*,	Tomato and arabidopsis	Volatile organic compounds production	Promoted plant growth, increased biomass and modified root architecture	Tahir *et al.*, 2017, [124] Park *et al.*, 2015, [102] Lee *et al.*, 2016 [73]

Conclusion

Agrochemicals are effective in agriculture by controlling pests and improving yield and these chemicals have been used since many years. However, these chemicals have many negative effects that cannot be ignored. These chemicals negatively affect plants, soil, humans and the entire environment. Therefore, BSMs-based bioformulations are gaining popularity due to their eco-friendly nature and could be used as sustainable alternatives of agrochemicals. They are not only beneficial for agriculture but also beneficial for humans and the environment because they reduce the chemical application and some BSMs degrade harmful chemicals in the soil ecosystem.

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