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REVIEW ARTICLE

Effects of agrochemicals on the beneficial plant rhizobacteria in agricultural systems

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Abstract
Conventional agriculture relies heavily on chemical pesticides and fertilizers to control plant pests and diseases and improve production. Nevertheless, the intensive and prolonged use of agrochemicals may have undesirable consequences on the structure, diversity, and activities of soil microbiomes, including the beneficial plant rhizobacteria in agricultural systems. Although literature continues to mount regarding the effects of these chemicals on the beneficial plant rhizobacteria in agricultural systems, our understanding of them is still limited, and a proper account is required. With the renewed efforts and focus on agricultural and environmental sustainability, understanding the effects of different agrochemicals on the beneficial plant rhizobacteria in agricultural systems is both urgent and important to deduce practical solutions towards agricultural sustainability. This review critically evaluates the effects of various agrochemicals on the structure, diversity, and functions of the beneficial plant rhizobacteria in agricultural systems and propounds on the prospects and general solutions that can be considered to realize sustainable agricultural systems. This can be useful in understanding the anthropogenic effects of common and constantly applied agrochemicals on symbiotic systems in agricultural soils and shed light on the need for more environmentally friendly and sustainable agricultural practices.

Keywords Chemical · Fertilizers · Soil microbiome · Anthropogenic effects · Sustainable agriculture

Introduction

Microbial communities are critical components of every ecosystem (Hayat et al. 2010; Fierer 2017). In agricultural systems, soil microbial communities have many ecological functions, including increasing the availability and accessibility of plant nutrients and plant bioprotection (Figueriredo et al. 2011; Gupta et al. 2015; Prashar and Shah 2016). Rhizobacteria are beneficial components of the plant-soil microbiome with critical functions in sustaining soil and plant health (Adesemoye et al. 2009; Aloo et al. 2019). These microorganisms are widely associated with the solubilization and enhanced solubility and availability of nutrients to plants, nitrogen (N) fixation, and synthesis of plant growth-promoting (PGP) hormones and other plant-beneficial metabolites (Adesemoye et al. 2009).

Conventional agricultural practices generously and indiscriminately employ agrochemicals like insecticides, herbicides, pesticides, fungicides, and fertilizers to control crop pests and diseases and increase production (Malik et al. 2017). Nevertheless, the continued use of agrochemicals in present-day agriculture continues to modify the diversity and structure of the beneficial plant rhizobacteria in agricultural systems (Malik et al. 2017; Hashimi et al. 2020). Literature advances that agrochemicals can affect the population, biochemical processes, and several functions of beneficial soil bacteria (Demanou et al. 2004; Ubuoh et al. 2012). For instance, some pesticides can disturb the molecular interactions between plants and N-fixing rhizobia (Malik et al. 2017) or

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inactivate P-solubilizing and diazotrophic microbial communities (Hussain et al. 2009). This way, agrochemicals can affect the mineralization of organic compounds and related soil biogeochemical processes such as nutrient cycling and bioavailability to plants (Malik et al. 2017). Although insecticides have the greatest effects on soil microbes, followed by fungicides, and herbicides, all agrochemicals impact beneficial microorganisms negatively in one way or another and subsequently affect nutrient cycling and soil fertility (Hashimi et al. 2020).

The importance of beneficial plant rhizobacteria and the vital roles they play in agriculture have widely been popularized (Adesemoye et al. 2009; Abbasi et al. 2011; Ahemad and Khan 2011b, 2012c; Abaid-Ullah et al. 2015; Aloo et al. 2021a). With the renewed efforts and focus on agricultural and environmental sustainability, understanding the effects of different agrochemicals on the beneficial plant rhizobacteria is of paramount importance (Meena et al. 2020). Some studies have attempted to elucidate the effects of chemical fertilizers (Lin et al. 2019; Bai et al. 2020; Reid et al. 2021) and pesticides (Ahemad and Khan 2011b; Kumar et al. 2019; Ankit et al. 2020; Mundi et al. 2020) on the structure, population, and biochemical processes of beneficial plant rhizobacteria in agricultural systems. Other studies have demonstrated that the chemicals affect the beneficial microbial communities because of the changes they induce in soil (Hartmann et al. 2015a; Prashar and Shah 2016; Li et al. 2020). Similarly, some studies have also established the effects of several pesticides on the activities of rhizobacterial enzymes that drive key functions in agricultural systems (Shukla 2000; Hussain et al. 2009; Riah et al. 2014; Meena et al. 2020). Despite the voluminous literature that continues to pile regarding the effects of these chemicals on the beneficial plant rhizobacteria in agricultural systems, our understanding of them is still limited, and a proper account is needed. The present review gives an account of the different types and global proportions of agrochemicals, discusses their effects on the beneficial plant rhizobacteria in agricultural systems, and deliberates on some management options that can be considered for the sustainability of these systems. Such information can facilitate the adoption of measures to reduce the impacts of agrochemicals on the beneficial plant rhizobacteria in agricultural systems and may ultimately promote the development of more sustainable crop production systems.

Proportions and types of agrochemicals used around the world

Agrochemicals comprise herbicides, fungicides, insecticides, nematicides, molluscicides, rodenticides, and fertilizers (Sharma et al. 2019). A general depiction of the different types of agrochemicals and major examples of each type are provided in Fig. 1.

Pesticides are principally employed to control pests like insects and weeds (Sharma et al. 2019). The classification of pesticides can be done according to their chemical structures, modes of action, target molecules, and possible health effects (Hashimi et al. 2020). Pesticides can also be classified according to their target organisms, application requirements, and other factors (Jayaraj et al. 2016). Nevertheless, the common classification of pesticides entails their chemical compositions as organochlorines, organophosphates, carbamates, pyrethroids, microbial pesticides, growth regulators, and neonicotinoids as detailed by Lushchak et al. (2018). The general grouping of pesticides based on their chemical constituents and modes of action is also provided by Jayaraj et al. (2016).

Insecticides are a group of pesticides that are used to control insects in agriculture, horticulture, forestry, gardens, homes, and offices (Gupta et al. 2019). Based on their modes of action, insecticides can be classified as desiccants, disinfectants, attractants, chemosterilants, growth regulators, hormones, or pheromones (Sparks and Nauen 2015). A complete guide to the classification of insecticides based on this criterion according to the Insecticide Resistance Action Committee of the International Crop Protection Organization is provided by Sparks et al. (2020). Herbicides are pesticides that are used for weed control worldwide. According to Lushchak et al. (2018), herbicides comprise about 50% of the total pesticide used globally and are presently the most rapidly expanding segment of the pesticide industry. Like other pesticides, the classification of herbicides is done according to chemical nature, specificity, and time/mode of application (Peterson et al. 2013), with the most popular being glyphosate, followed by metolachlor-S, and atrazine (Sharma et al. 2019). Fungicides are a group of pesticides that prevent, repel, or kill phytopathogenic fungi (Gupta 2011).

Like herbicides, the mode of action of fungicides is closely related to the metabolic pathways of fungi (Lushchak et al. 2018). Some chemical classes of fungicides include benzimidazoles, carbamic acid derivatives, halogenated substituted monocyclic aromatics, organomercury compounds, and phthalimides (Balba 2007).

Despite their different classes and groups, conventional agriculture employs all pesticides as effective and economical means of enhancing crop yield, quality, and quantity (Sharma et al. 2019). The global average consumption of pesticides from 1990 to 2018 is presented in Fig. 2a. Estimates show that the annual global consumption of pesticides is about 2 million tons (Sharma et al. 2019; Hashimi et al. 2020), out of which about 48, 30, 18, and 6% are herbicides, insecticides, fungicides, and other pesticides, respectively (De et al. 2014). The USA, China, India, Italy, Argentina, Japan, Thailand, France, Brazil, and Canada are some of the top pesticide consumers globally (Amber 2017). Recent estimates show that the global use of pesticides will increase to about 3.5 million tons in the present year (Zhang 2018). Although China mainly

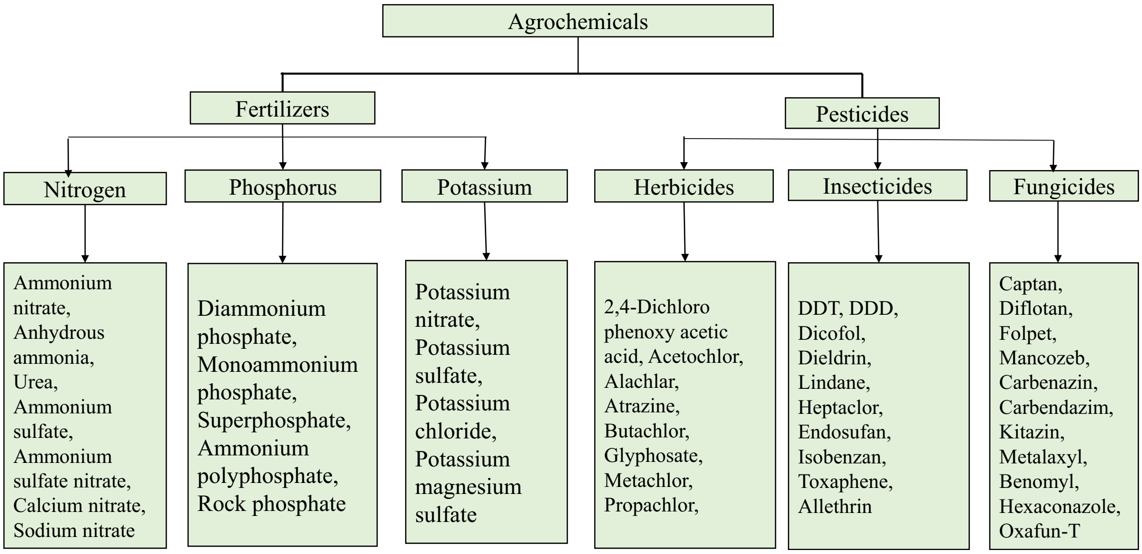

Fig. 1 Types of agrochemicals and major examples

uses pesticides in rice plantations, its pesticide consumption is approximated to have increased from 76 to 146 million tons between 1991 and 2006, and it is currently the largest pesticide manufacturer worldwide. Japan is similarly one of the major pesticide consumers globally and possesses the largest pesticide market in Asia (Zhang et al. 2011). The use of pesticides in Africa is still the least globally (Abate et al. 2000). According to the FAO estimates, Africa accounts for only 2% of the global pesticide consumption (Fig. 2c). Nevertheless, Africa's pesticide consumption is projected to increase in a few decades due to its increasing population and food demand (Snyder et al. 2015). Increased pesticide consumption is also projected for Southern Asia (Schreinemachers and Tipraqsa 2012), where India produces about 90,000 tons of insecticides annually and is ranked the 12th largest insecticide manufacturer globally (Khan et al. 2010).

Besides pesticides, conventional agriculture also relies on chemical fertilizers to boost crop production. The global average consumption of chemical fertilizers from 1990 to 2018 is shown in Fig. 2b, while the total average fertilizer

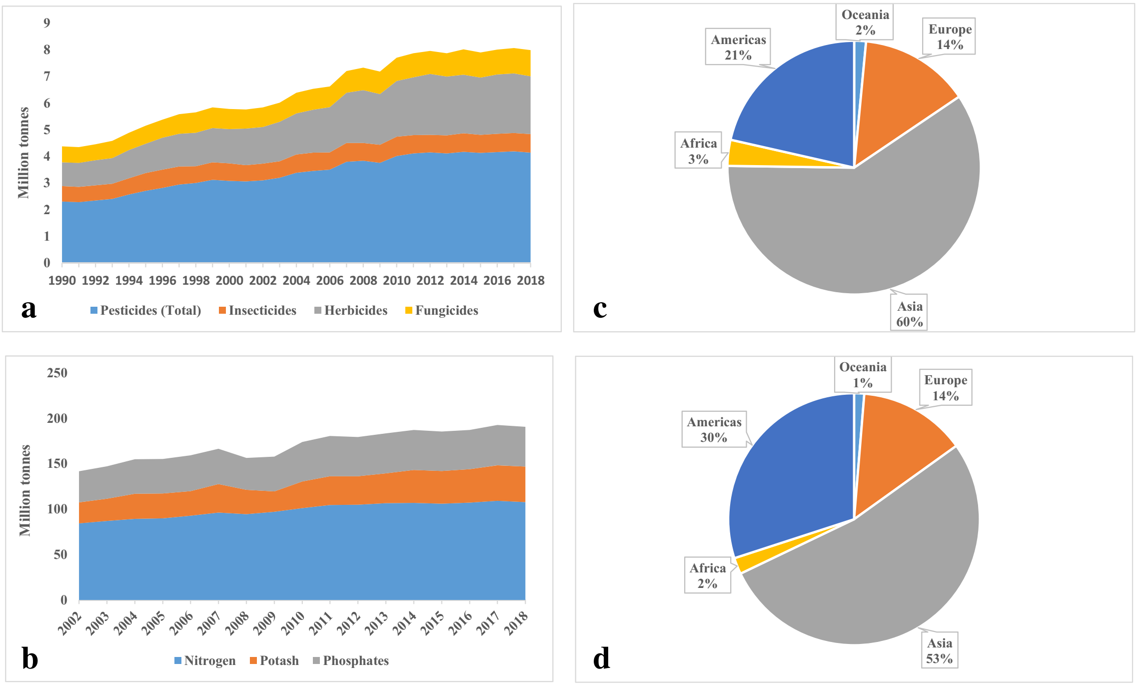

Fig. 2 Global and continental proportions of chemical fertilizer and pesticide consumption. **a** Global average consumption of pesticides from 1990 to 2018 (FAO 2021b), **b** global average consumption of chemical fertilizers from 2002 to 2018 (FAO 2021a), **c** total average pesticide consumption by region from 1990 to 2018 (FAO 2021b), and **d** total average fertilizer consumption by region from 2002 to 2018 (FAO 2021a)

consumption by region is displayed in Fig. 2d. Over 175.5 million tons of mineral fertilizers are used annually in agricultural production (FAO 2011). Futhermore, the consumption of potassium (K), phosphorus (P), and nitrogen (N) fertilizers was estimated to have increased from about 18, 26, and 65 kg ha^{-1}, respectively in 2000 to about 20, 33, and 86 kg ha^{-1} in 2014 when the global population surpassed 7.2 million (FAO 2013). In 2011, the total consumption of K, P, and N fertilizers was estimated at 176 million tons and projected to further increase by 150, 175, and 172% respectively by the year 2050 due to agricultural intensification in efforts to feed the growing world population (Khan et al. 2018). Nevertheless, N fertilizers are the most popular (Fig 2b). According to FAO (2018), the present worldwide production of fertilizers is 123 Tg annually, this being a 9.5-fold increase from its production six decades ago.

Effects of agrochemicals on beneficial plant rhizobacteria in agricultural systems

Different types of agrochemicals affect soil microbial communities differently. The effects of specific agrochemicals on the beneficial plant rhizobacteria in agricultural systems are extensively discussed in the next sub-sections, and a schematic illustration of the general effects of different agrochemicals on the beneficial plant rhizobacteria in agricultural systems is depicted in Fig. 3.

Effects of chemical fertilizers on beneficial plant rhizobacteria in agricultural systems

Chemical fertilizers generally cause changes in soil properties (Hartmann et al. 2015a; Prashar and Shah 2016; Li et al. 2020), which subsequently impact the soil microbial communities (Leff et al. 2015). For instance, fertilizers can increase the nutrient supply in soil for microbial growth (Geisseler and Scow 2014). However, this may only promote the growth of copiotrophs as opposed to the slower-growing oligotrophs which tend to thrive in nutrient-limited soils (Fierer et al. 2012; Hartmann et al. 2015b). Moreover, nutrient availability depends on the types and rates of fertilizer application; hence, different fertilizers may markedly shift the predominant microbial taxa in agricultural soils (Hartmann et al. 2015b; Sun et al. 2015a).

Chemical fertilizers are also commonly linked to soil acidification (Tian and Niu 2015; Zhang et al. 2016; Neog 2018; Bai et al. 2020; Yan et al. 2020), with marked effects on the microbial communities (Weishou et al. 2016; Zhang et al. 2017). It is approximated that globally, N fertilizers have reduced the pH of soils by an average of 0.26 units (Tian and Niu 2015). According to Khan et al. (2018), soil microbial communities are generally sensitive to the continuous application of N, P, and K fertilizers. However, while most bacterial genera may be affected by acidified soils, others like *Acidothermus*, *Acidobacterium*, *Acidobacteria*, and *Acidicaldus* which are acidophilic may thrive in such conditions (Lin et al. 2019). Thus, the continued application of chemical fertilizers can ultimately alter the biological properties, functioning, and quality of agricultural soils (Bünemann et al. 2018).

Diazotrophs are important rhizosphere microbes owing to their symbiotic N-fixing interactions with leguminous plants which account for up to 100 Tg N globally, per year (Fan et al. 2019). However, various studies have established negative correlations between these microbial communities and continuous/intensive mineral N fertilization (Feng et al. 2018; Liao et al. 2018; Fan et al. 2019; Li et al. 2019a; Wang et al. 2020).

The effects of N fertilizers on rhizosphere microbiota assemblages and the performance of lettuce have recently been investigated by Chowdhury et al. (2019). Various other studies have evaluated the effects of various fertilizers on agriculturally beneficial plant rhizobacteria (Table 1). The effects of N fertilization on the abundance of N-cycling genes in agricultural soils have also been established (Kelly et al. 2011; Sun et al. 2015b; Yang et al. 2017; Ouyang et al. 2018). Although N fertilization can shrink the diversity and richness of microbial species in soil (Fierer et al. 2012), uncertainties remain regarding specific effects of N fertilization on the abundance of N-fixation genes (Reardon et al. 2014; Wang et al. 2016) and nitrification (Carey et al. 2016).

Like other microbes, the effects of synthetic fertilizers on diazotrophs are largely linked to the physicochemical changes of soil like pH alterations and subsequent acidification (Geisseler and Scow 2014; Zhao et al. 2014; Wang et al. 2017b, 2018b) that they induce in soils (2020). Reports on the effects of soil pH on the structure and composition of microbial communities are numerous (Lauber et al. 2009; Rousk et al. 2009; Zhang et al. 2017; Wan et al. 2020). Soil pH also exerts a strong influence on the abundance and diversity of various N-cycling genes (Hallin et al. 2009; Liu et al. 2010; Prosser and Nicol 2012; Hu et al. 2013).

An earlier study by Juo et al. (1995) demonstrated that the pH of soil under maize cultivation and continuous application of ammonium-sulfate fertilizer decreased from 5.8 to 4.5 after 5 years. According to Omar and Ismail (1999), the constant application of synthetic N fertilizers in agricultural systems and the subsequent elevation of N levels can also increase the osmotic potential of soils to potentially lethal levels to soil microbiota.

In the short term, N fertilizers can induce the proliferation of fast-growing diazotrophs due to increased nutrient availability for vegetative growth (Fierer and Jackson 2006). However, the continuous use of N fertilizers may have far more reaching consequences on N-fixation rates because diazotrophs prefer assimilating the availed inorganic N instead

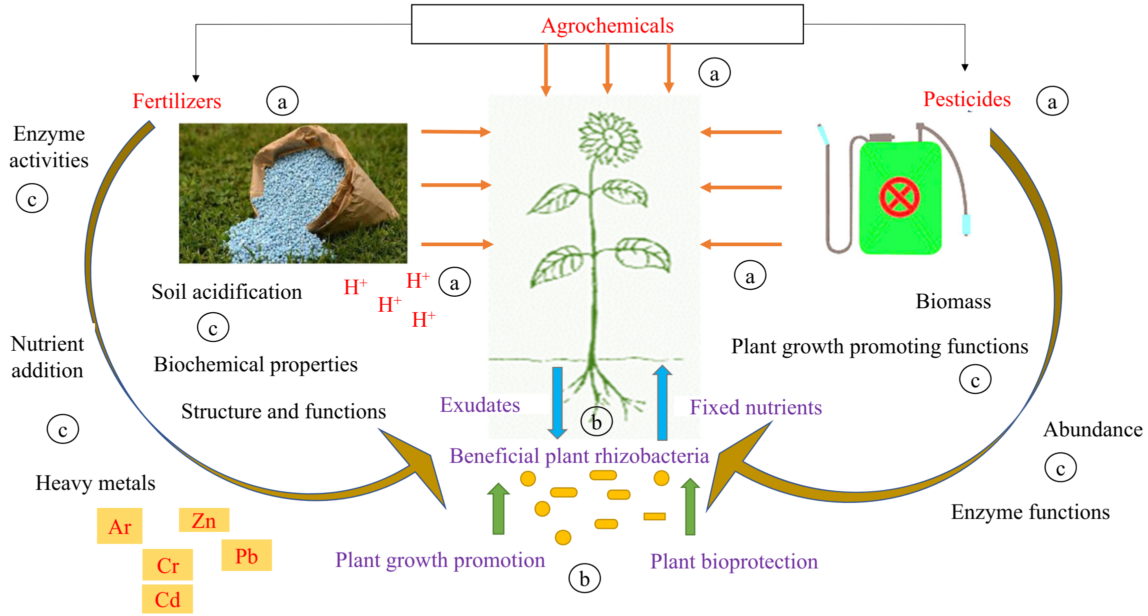

Fig. 3 Effects of different agrochemicals on the beneficial plant rhizobacteria in agricultural systems. **a** The application of different types of agrochemicals into crop fields for yield maximization, **b** the beneficial functions of plant rhizobacteria in agricultural systems, and **c** changes in soil and/or effects of agrochemicals on the beneficial plant rhizobacteria in agricultural systems

of engaging in the energy-intensive N-fixation process (Norman and Friesen 2017; Fan et al. 2019).

Although fertilization can be beneficial to facultative N-fixers like *Bradyrhizobium* spp. that may, in turn, down-regulate N-fixation (Sheffer et al. 2015), it can be disadvantageous to oligotrophic soil microbes and obligate N-fixers which have limited abilities to down-regulate N-fixation (Fan et al. 2019). Cognizant of this, fertilization practices may in the long run have different consequences on N-fixers and their N-fixation rates in agricultural systems (Feng et al. 2018). However, these effects need further exploration (Fan et al. 2019).

Compared to N fertilization, P fertilization has received much less attention and appears to have lesser effects on soil microbial communities (Li et al. 2020). However, a recent experiment investigating the effects of mineral fertilization on grassland diazotrophic soil communities in China showed that the diversity and composition of diazotrophs were primarily affected by P rather than N fertilization (Xiao et al. 2020b). Unlike N, P exhibits low mobility and solubility in soil and does not circulate in the atmosphere; hence, continuous P fertilization can cause its accumulation in soil (Bennett and Adams 2001). Since biological N-fixation (BNF) is energy-intensive in terms of the adenosine triphosphate (ATP) requirements (Reed et al. 2011; Shen et al. 2019), the accumulation of P in soil can be advantageous to diazotrophs (Pajares and Bohannan 2016; Tang et al. 2017; Xiao et al. 2020b). Generally, this means that N-fixation may be limited under N fertilization but stimulated under P fertilization. Nevertheless, this depends on the timing, rates, and forms of N and P fertilization (Xiao et al. 2020b). The abundance of P in agricultural soils may also induce changes in diazotrophic community structures by enhancing the competition for trace elements like molybdenum (Mo) and iron (Fe) which are important constituents of nitrogenases (Zhao et al. 2006; Rousk et al. 2017; Winbourne et al. 2017). The stimulation of N-fixation by diazotrophs can further occur due to the presence of Mo contamination in the commonly used triple superphosphate fertilizers (Barron et al. 2009; Wurzburger et al. 2012). Apart from the effects on nitrogenases, P fertilizers may also interfere with the biosynthesis of alkaline phosphomonoesterases which are important in inorganic P-solubilization and increased availability of P in agricultural soils (Chen et al. 2017, 2019). However, some contrary results had previously been reported by Ekin (2010).

The use of chemical fertilizers in agricultural systems has further been linked to the accumulation of heavy metals in soils (Mortvedt 1996; Lin et al. 2019) and undesirable effects on the diversity, size, and activities of soil microbiota (Glodowska and Wozniak 2019; Donkova and Kaloyanova 2008. According to Thomas et al. (2012), P fertilizers are the major sources of heavy metals like cadmium (Cd), lead (Pb), arsenic (Ar), and chromium (Cr). Although some bacteria may exhibit resistance to these metals, some are extremely sensitive. Therefore, the accumulation of heavy metals in soils can reduce the population and diversity of some bacterial groups but have no effects on others (Giller et al. 2009).

Chemical fertilizers can also fuel the creation of stressful conditions for microorganisms and increase their vulnerability to heavy metal toxicity (Glodowska and Wozniak 2019). However, physicochemical soil properties like organic matter, clay, and pH were previously shown to alter the effects of

Table 1 Experiments evaluating the effects of different chemical fertilizers on beneficial plant rhizobacteria

Plant(s)	Rhizobacteria	Type of fertilizer	Test conditions	References
Alfalfa (*Medicago sativa* L.)	*Bacillus megaterium*	P	Laboratory	Liu et al. (2020a)
Cucumber (*Cucumis sativus*)-tomato (*Solanum lycopersicum*) rotation	Firmicutes, Acidobacteria, Betaproteobacteria, Planctomycetes	N	Field	Weishou et al. (2016)
Fir (*Abies sp.*)	Diazotrophs	N and P	Field	Wang et al. (2018b)
	Proteobacteria, Actinobacteria	N and P	Field	Wang et al. (2018a)
	Not mentioned	N and P	Field	Dong et al. (2015)
Elephant grass (*Pennisetum purpureum*)	Diazotrophs	N	Field	Xiao et al. (2020a)
Grassland (*Imperata cylindrical, Microstegium vagans, Apluda mutica* L.)	Diazotrophs (Rhizobiales, Rhodospirillales, Burkholderiales)	P and N	Field	Xiao et al. (2020b)
Lettuce (*Lactuca sativa*)	N-fixing	N	Field	Chowdhury et al. (2019)
Maize (*Zea mays*)	*Azospirillum brasilense, Herbaspirillum seropedicae, B. pumilus, B. subtilis, Gluconacetobacter diazotrophicus, B. amyloliquefaciens,*	N and P	Field	Nascimento et al. (2020)
	Diazotrophs	N	Field	Wang et al. (2017b)
	Nitrifying bacteria	Zn and N	Field	Montoya et al. (2021)
	Diazotrophs	N	Laboratory	Fiorentino et al. (2016)
	Not specified	N, P, K	Field	Semenov et al. (2020)
Maize (*Z. mays*)-vegetable rotation	Diazotrophs	N, P, K	Field	Zhang et al. (2017)
Milk vetch (*Astragalus sinicus*)	Not specified	N	Field	Li et al. (2019b)
Potato (*Solanum tuberosum*)	N-fixing bacteria	N, P, K	Field	Semenov et al. (2020)
Rice (*Oryza sativa*)	Diazotrophs	N and P	Field	Huang et al. (2019)
	Diazotrophs	N, P, K	Field	Wang et al. (2020)
	Bacillus, Pseosporales, *Pseudomonas*	N, P, K	Field	Liao et al. (2018)
	Not specified	P	Field	Long and Yao (2020)
Soybean (*Glycine max*)	Various	Zn	Field	Andrade et al. (2020)
Sugarcane (*Saccharum officinarum*)	Diazotrophs	N	Field	Yeoh et al. (2016)
Tea (*Camellia sinensis*)	*Nitrospira* and *Burkholderia*	N	Filed	Lin et al. (2019)
Tomato (*S. lycopersicum*)	Not specified	N	Field	Caradonia et al. (2019)
White mustard (Sinapis alba*Sinapis alba*)	Not specified	N, P, K	Field	Semenov et al. (2020)
Wheat (Triticum aestivum*Triticum aestivum*)	Not specified	N and P	Field	Li et al. (2020)
	Acidobacteria, Planctomycetes, Bacteroidetes	N	Field	Kavamura et al. (2018)
	Diazotrophs	N	Field	Wang et al. (2016)
	Streptomyces, *Paenibacillus, Pseudomonas*	N, P, K	Glasshouse	Reid et al. (2021)
Wheat (T. aestivum*T. aestivum*)-maize (Z. mays*Z. mays*) rotation	Not specified	N, P, K	Feld	Bei et al. (2018)
	Bacillus sp.	N, P, K	Field	Chu et al. (2007)
	Alphaproteobacteria, Gammaproteobacteria, Bacteroidetes, Deltaproteobacteria	N, P, K	Filed	Liu et al. (2020b)
Wheat (*T. aestivum*)-soybean (*G. max*) rotation	N-fixers, e.g., *Geobacter* spp.	N	Field	Fan et al. (2019)

certain heavy metals on soil microbiota (Babich and Stotzky 1980). Nevertheless, this is yet to be clearly understood.

Effects of pesticides on beneficial plant rhizobacteria in agricultural systems

The effects of pesticides on the biomass, enzymatic activities, respiration, and other physiological functions of beneficial microbial communities are extensively reviewed by Ankit et al. (2020), Chowdhury et al. (2008), and Hussain et al. (2009). A lot of pesticides used in the world today are generally broad spectrum and can, thus, also affect non-target organisms (Duchet et al. 2018; Hashimi et al. 2020). According to Meena et al. (2020), only around 0.1% of applied pesticides reach the targeted pests, while the rest reach non-target soil microorganisms and affect their functional diversity (Jayaraj et al. 2016). Generally, most pesticides affect the multiplication of beneficial plant microbes and their PGP functions like N-fixation and P-solubilization (Hussain et al. 2009), probably because they can penetrate bacterial cell walls and interfere with their normal metabolism (Prashar and Shah 2016).

Different studies have established the effects of several pesticides on the activities of rhizobacterial like nitrogenases and phosphatases that drive key functions and nutrient cycling in soils (Shukla 2000; Hussain et al. 2009; Riah et al. 2014; Meena et al. 2020). Since some bacteria may be resistant to certain pesticides while others are susceptible, agricultural soils may become dominated by a few functional bacterial groups depending on the regularly applied pesticides, which can affect their overall biological structure and processes (Prashar and Shah 2016). The risk assessment of pesticides on beneficial organisms is evaluated by the International Organization for Biological and Integrated Control in terms of mortality rates. In this system, a chemical is harmless or harmful if it kills < 25 and > 75% of beneficial microbial species (Thomson 2012). Notwithstanding, the effects of pesticides on soil microbiota are complex and dependent on environmental aspects like temperature, pH, moisture, salinity, and organic matter contents as well as the structure and concentration of the chemical constituents (Chowdhury et al. 2008). The effects of specific types of pesticides are further discussed in the next sub-sections.

Effects of herbicides on beneficial plant rhizobacteria in agricultural systems

Shortly after application, herbicides get transformed into secondary metabolites which are toxic to both target and non-target microbial communities (Meena et al. 2020). According to Kremer and Means (2009), herbicides generally affect microbial biodiversity and alter their enzymatic activities, cellular compositions, and biosynthetic mechanisms. For instance, fomesafen can be very toxic to many bacterial taxa, but resistant species can outcompete and displace other rhizobacterial communities (Hu et al 2019). Due to their structural homology with glutamate, glufosinate-based herbicides can similarly inhibit glutamine synthetase which is responsible for the conversion of glutamate and ammonia to glutamine during N metabolism (Thiour-Mauprivez et al. 2019). The effects of herbicides on the diversity, functions, and biochemical processes of beneficial plant rhizobacteria have extensively been investigated both in vitro and in planta (Table 2). Most herbicides can inhibit rhizobacterial phosphatases (Cycoń et al. 2013), which are important in the mineralization of organic phosphates (Aloo et al. 2021a). While studying the effects of glyphosate, paraquat, atrazine, and carbaryl herbicides on the activities of microbial enzymes, Sannino and Gianfreda (2001) showed that glyphosate had up to 98% inhibitory effect on microbial phosphatases.

Different herbicides can modify the rhizobia-legume symbiotic interactions and interfere with their N-fixation potential (Meena et al. 2015). Khan et al. (2006) established severe negative impacts of herbicides on the symbiotic association of chickpea (*V. radiata*). At high concentrations, some common triazine herbicides like simazine, terbutryn, bentazone, and prometryn can also reduce rhizobial functions (Singh and Wright 2002). The application of 0.5–1.0 kg pendimethalin ha^{-1} can also disrupt plant-*Rhizobium* symbioses (Strandberg and Scott-Fordsmand 2004). Similarly, 2,4-D tends to affect *Rhizobium* and inhibit its nitrification and BNF processes in beans, which has previously been confirmed by the presence of significant amounts of its residues in *Rhizobium* cells and cytosols (Fabra et al. 1997). *Azotobacter* which is a free-living N-fixing symbiont is also highly sensitive to herbicides, but the extent of inhibition of its growth, activities, development, and population depends on the type and dosage of herbicidal constituents (dos Santos et al. 2005). Herbicides generally affect BNF in legumes by disturbing the phytochemical-signaling needed for coordination and regulation during nodulation (Fox et al. 2001; Hussain et al. 2009). While some herbicides can affect symbiotic N-fixation by affecting ATP synthesis and rhizobial nitrogenases, non-selective herbicides like glyphosate and paraquat can affect symbiotic N-fixation due to ethylamine formulation (dos Santos et al. 2005).

Although glyphosate is one of the most common herbicides in the world, a lot of debate continues to surround its usage (Wolmarans and Swart 2014; Richmond 2018; Van Bruggen et al. 2018; Kudsk and Mathiassen 2020). Whereas some researchers advance that the herbicide presents no apparent threat to the beneficial rhizobacteria in agricultural systems (Lane et al. 2012; Imparato et al. 2016; Newman et al. 2016), others maintain that it is extremely hazardous to these microbes (Neumann et al. 2006; Kremer and Means 2009). Recent studies have shown its effects on rhizobacterial communities of agriculturally important crops like wheat (Lupwayi et al. 2020), soybean (Lu et al. 2018), and maize (Akintokun et al. 2020).

Table 2 Experiments evaluating the effects of herbicides on plant-beneficial rhizobacteria

Test/source crop	Bacterial strains affected	Herbicide	Test conditions	Reference
Alfalfa (*M. sativa*)	*Sinorhizobium meliloti*	2,4-D, 2,4,5-T	Laboratory	Fox et al. (2001)
Not mentioned	*P. fluorescens*, *R. leguminosarum*, *B. brevis*, *Azotobacter vinelandii*	Acephate, glyphosate, monocrotophos	Laboratory	Kumar et al. (2019)
Not mentioned	*P. fluorescens*, *B. subtilis*, *Mycobacterium phlei*	Acetochlor, carbendazim, simazine, EPTC	Laboratory	Virág et al. (2007)
Wheat (*T. aestivum*)	*Pseudomonas*	Apyros 75 WG	Laboratory	Kucharski and Wyszkowska (2018)
	Azotobacter	Diflufenican + mesosulfuron-methyl + iodosulfuron-methyl-sodium	Laboratory	Baćmaga et al. (2015)
Cassava (*Manihot esculenta*)	Actinomycetes	Atrazine, primeextra, paraquat, glyphosate	Laboratory	Sebiomo et al. (2011)
Soybean (*G. max*)	*Rhizobium*	Bentazone, metribuzin, trifluralin	Field	Aliverdi and Ahmadvand (2018)
	Bradyrhizobium japonicum	Chlorimuron-ethyl	Greenhouse	Zawoznik and Tomaro (2005)
	Proteobacteria, Actinobacteria	Glyphosate	Greenhouse	Newman et al. (2016)
	Sphingomonas sp., *Acinetobacter calcoaceticus*, *Burkholderia* sp., *Ralstonia pickettii*, *Enterobacter sakazakii*, *B. gladioli*, *Klebsiella pneumoniae*, *P. oryzihabitans*, *A. junii*, *P. straminea*	Glyphosate	Field	Kuklinsky-Sobral et al. (2005)
	Not specified	Sulfosate	Greenhouse	Avanzi et al. (2018)
Chickpea (*Cicer arietinum*)	*Mesorhizobium cicero*	Bentazone, isoproturon, fluchloralin, 2,4-D	Greenhouse	Khan et al. (2004)
Rice (*O. sativa*)	Diazotrophs	Butachlor	Field	Chen et al. (2009)
	N fixing, P-solubilizers	Butachlor, fluchloralin, oxadiazon	Feld	Das and Debnath (2006)
Chickpea (*C. arietinum*)	*Mesorhizobium cicero*	Chlorsulfuron	Laboratory	Anderson et al. (2004)
	Mesorhizobium sp.	Methabenzthiazuron, terbutryn, linuron	Greenhouse	Khan et al. (2006)
	Mesorhizobium sp.	Glyphosate, quizalafop-p-ethyl,metribuzin, clodinafop	Laboratory	Ahemad and Khan (2012d)
Pea (*Pisum sativum*)	*R. leguminosarum*	Terbutryn/terbuthylazine, trietazine/simazine, prometryn, bentazone	Laboratory	Singh and Wright (2002)
	Rhizobia	Glyphosate	Laboratory	Mohamad and Al-naser (2018)
	Rhizobium	Imazethapyr	Field	Gonzalez et al. (1996)
	Rhizobium	Metribuzin, glyphosate	Laboratory	Ahemad and Khan (2012a)
	Rhizobium	Quizalafop-p-ethyl, clodinafop	Laboratory	Ahemad and Khan (2009)
Grapes (*Vitis vinifera*)	Not specified	Fenhexamid	Laboratory	Borzì et al. (2007)
Mung bean (*Vigna radiata*)	*Bradyrhizobium* sp., *Pseudomonas* sp.	Glyphosate, quizalafop-p-ethyl	Laboratory	Shahid and Khan (2017)

Table 2 (continued)

Test/source crop	Bacterial strains affected	Herbicide	Test conditions	Reference
	Bradyrhizobium sp.	Metribuzin, glyphosate	Laboratory	Ahemad and Khan (2011b)
	Rhizobia and P-solubilizers	Pendimethalin, fluchloralin	Laboratory	Jeenie and Khanna (2011)
	R. leguminosarum, *Stenotrophomonas maltophilia*	Pendimethalin, imazethapyr	Field	Singh and Singh (2020)
Cotton (*Gossypium* sp.)	*P. fluorescens*, *B. cepacian*	Pendimethalin, prometryn, trifluralin	Greenhouse, field	Heydari et al. (1997)
Maize (*Z. mays*)	*Azotobacter* sp.	Flufenacet, isoxaflutole	Field	Tomkiel et al. (2019)
	Proteobacteria, Actinobacteria	Glyphosate	Greenhouse	Newman et al. (2016)
Lentil (*Lens culinaris*), Faba bean (*Vicia faba*)	Rhizobia	Glyphosate	Laboratory	Mohamad and Al-naser (2018)
Banana (*Musca* sp.)	Proteobacteria	Glyphosate, glufosinate, paraquat, paraquat-diquat	Laboratory	Dennis et al. (2018)
Pigeon pea (*Cajanus cajan*)	*Rhizobium*	Imazethapyr, paraquat, pendimethalin	Laboratory	Khanna et al. (2012)
Not mentioned	*Azotobacter* sp.	Isoproturon	Laboratory	Mundi et al. (2020)
Not mentioned	*A. vinelandii*	Kitazin, metalaxyl, hexaconazole, glyphosate, imidacloprid, quizalafop, atrazine, monocrotophos, fipronil,	Laboratory	Shahid et al. (2019)
Not mentioned	N_2-fixing bacteria	Lunorin	Laboratory	Cycoń et al. (2010)
Apple (*Malus domestica*)	Nitrifying bacteria	Mancozeb	Laboratory	Walia et al. (2014)
Not mentioned	Not specified	Mesotrione	Laboratory	Crouzet et al. (2010)
Oilseed rape (*Brassica napus*)	*Azotobacter* spp.	Metazachlor	Field	Baćmaga et al. (2014)
Mustard (*Brassica campestris*)	*P. aeruginosa*	Metribuzin, glyphosate,imidacloprid, thiamethoxam, hexaconazole, metalaxyl, kitazin	Laboratory	Ahemad and Khan (2011a)
	P. putida	Clodinafop, metribuzin, glyphosate, quizalafop-p-ethyl	Laboratory	Ahemad and Khan (2012c)
Not mentioned	Fluorescent Pseudomonads	Metsulfuron methyl, chlorsulfuron, thifensulfuron methyl	Laboratory	Boldt and Jacobsen (1988)
Not mentioned	Not specified	Napropamide	Laboratory	Cycoń et al. (2013)
Not mentioned	*Pantoea agglomerans*, *R. nepotum*, *R. radiobacter*, *R. tibeticum*	Paraquat	Laboratory	Maldani et al. (2018)
Tea (*C. sinensis*)	Not specified	Paraquat, fipronil	Laboratory	Devashree et al. (2014)
White mustard (*S. alba*)	Not specified	Triflurotox 20 EC	Greenhouse	Wyszkowska and Kucharski (2004)

Glyphosate can induce decreased nutrient solubility by soil microbes and is lethal to plant-beneficial bacteria like Pseudomonads because of its high affinity to clay minerals in acidic soils (2009). Interestingly, the effects of herbicides on beneficial plant rhizobacteria can be fueled in the presence of heavy metals. In a previous study by Wang and Zhou (2006), the effects of 10 mg Cd kg^{-1} of soil and 5, 10, and 50 mg butachlor kg^{-1} of soil on the activities of bacterial enzymes like phosphatases were strongly related to the applied ratios. In another study, Maliszewka-Kordybach and Smreczak (2003) demonstrated that the combined effects of some polycyclic aromatic hydrocarbons (PAHs) like fluorene, anthracene, pyrene, and chrysene and heavy metals on soil microbial activities were stronger than their effects when applied separately. The authors also established the connection of the effects on the tested organisms, the soil properties, and the concentrations of PAHs.

Effects of insecticides on beneficial plant rhizobacteria in agricultural systems

The effects of insecticides on the beneficial plant rhizobacteria in agricultural systems have been reported by several studies. Carbamate insecticides like carbaryl, carbofuran, and methiocarb have various negative impacts on soil microorganisms (Sannino and Gianfreda 2001) and their enzymatic activities (Kalam and Mukherjee 2001). Similarly, organophosphate insecticides like quinalphos, dimethoate, malathion, lindane, diazinon, and chlorpyrifos also inhibit bacterial enzymes (Singh and Singh 2005; Reddy et al. 2011; Tejada et al. 2015), growth, and abundance (Van Zwieten et al. 2003; Pandey and Singh 2004; Singh and Singh 2005; Virág et al. 2007). A recent study by Madhavi et al. (2019) has also confirmed the effects of oxydemeton methyl and emamectin benzoate on the population of beneficial *Azospirillum sp.* of groundnuts (*Arachis hypogaea* L.) under laboratory conditions. The results further showed that organophosphate insecticides caused the cells of the bacterium to become pleomorphic and affected their PGP activities. Apart from enzymatic processes, insecticides can also affect microbial growth and metabolic functions (Muturi et al. 2017; Hashimi et al. 2020).

Insecticides can affect the growth, persistence, and functions of symbiotic rhizobial interactions that are extremely important for the N-nutrition in legumes (Niewiadomska 2004). The detrimental effects of insecticides may not be easily apparent and are variable depending on the group and type of insecticide (Das and Mukherjee 2000) and the N-fixers (Meena et al. 2020). Nevertheless, the prolonged and increased use of these chemicals continues to raise serious concerns (Meena et al. 2020). At higher rates of application, insecticides like monocrotophos, lindane, dichlorvos, endosulfan, malathion, and chlorpyrifos may inhibit the nitrification process and the microbes involved therein (Madhaiyan et al. 2006). Similar results have also recently been reported by Mundi et al. (2020) after investigating the effects of chlorpyrifos on the kinetics and PGP activities of *Azotobacter* sp. in vitro. In another study, the ecotoxicological effects of chlorpyrifos and cypermethrin on the substrate utilization, diversity, and structure of *V. radiata* symbiotic microbes were established (Walvekar et al. 2017). *Azotobacter*'s growth and population are also suppressed in the presence of insecticides like fenthion, phosphamidon, parathion, malathion, and methyl phosphorothioate (Pandey and Singh 2004).

The effects of insecticides on other beneficial rhizobacteria have also been established. A study by Rani et al. (2018) showed the inhibitory activities of endosulfan on the PGP traits of the P-solubilizing *Paenibacillus* sp. in vitro. A separate study by Das et al. (2003) also showed that phorate and carbofuran have varied effects on rice (*O. sativa*) rhizoflora. Further investigations into the effects of insecticides on rhizobacterial communities include those by Das and Mukherjee (2000), Dubey et al. (2012), Dutta et al. (2010), Das et al. (2016), Ahemad and Khan (2011b), Filimon et al. (2015), and Tripti et al. (2015).

Interestingly, while some insecticides may have negative effects on the growth and/or survival of beneficial plant microorganisms, others may exhibit stimulatory or no effects on them. In the study by Das et al. (2003), while phorate decreased the populations of rice rhizoflora like *Bacillus*, *Escherichia*, *Pseudomonas*, *Klebsiella*, and *Flavobacterium*, carbofuran stimulated the growth of *Bacillus*, *Corynebacterium*, and *Flavobacterium*. Similarly, phorate, carbofuran, and disulfoton also portrayed minimal effects on *Azotobacter* populations in soil (Meena et al. 2020). According to Gundi et al. (2007), insecticides may portray stimulatory effects on soil bacteria because of increased substrate availability from insect fatality. Nevertheless, there are limited reports on these stimulatory or zero effects of insecticides on plant-beneficial bacteria, and more investigations are necessary to understand these dynamics.

Effects of fungicides on beneficial plant rhizobacteria in agricultural systems

The effects of fungicides on the growth and activities of soil microbes have been also reported by several studies (Table 3). According to Meena et al. (2020), the residues and constituents of fungicides are toxic to several rhizobacterial enzymes. For instance, the suppression of phospho-monoesterases has previously been established in soils treated with thiram, captan, and trifloxystrobin fungicides (Marfo et al. 2015). Recently, ridomil was also shown to significantly reduce the activities of bacterial amylases (Micuti et al. 2018). While some fungicides like mancozeb, benomyl, and tridemorph may inhibit phosphatases and other rhizobacterial enzymes (Shukla 2000), others like ridomil may have no apparent effects on phosphatases (Demanou et al. 2004), xylanases, and cellulases (Micuti et al. 2018). The synthesis of some bacterial

Table 3 Experiments evaluating the effects of fungicides on growth, diversity, and activities of plant-beneficial rhizobacteria

Test/source crop	Bacterial strains affected	Fungicide	Test conditions	Reference
Barley (*Hordeum vulgare*)	*Pseudomonas* spp.	Oxafun T	Field	Kaszubiak and Durska (2000)
Cabbage (*Brassica oleracea*)	*B. subtilis*	Kitazin, hexaconazole, metalaxyl, carbendazim	Laboratory	Shahid and Khan (2018)
Chickpea (*C. arietinum*)	*Rhizobium ciceri*	Thiram, captan, metalaxyl	Controlled	Kyei-Boahen et al. (2001)
Green gram (*V. radiata*)	*Bradyrhizobium* sp.	Hexaconazole, metalaxyl, kitazin	Laboratory	Ahemad and Khan (2011b)
Groundnut (*A. hypogaea* L.)	*Azospirillum* sp.	Benomyl, dithane Z-78	Laboratory	Madhavi et al. (2019)
Lentil *(L. culinaris,* Faba beans (*V. faba*)	Rhizobia	Mancozeb	Laboratory	Mohamad and Al-naser (2018)
Mustard (*B. campestris*)	*E. asburiae*	Tebuconazole, hexaconazole, metalaxyl, kitazin	Laboratory	Ahemad and Khan (2010)
	P. putida	Tebuconazole, hexaconazole, metalaxyl, kitazin	Laboratory	Ahemad and Khan (2012b)
Not specified	Not specified	Carbendazim	Laboratory	Shao and Zhang (2017)
Not specified	*Bacillus*	Falcon 460 EC	Laboratory	Baćmaga et al. (2016)
Not specified	Nitrifying bacteria	Mancozeb, dimethomorph	Laboratory	Kinney et al. (2005)
Not specified	*Azotobacter* sp.	Raxil	Laboratory	Mundi et al. (2020)
Not specified	*G. diazotrophicus*	Ridomil	Laboratory	Madhaiyan et al. (2006)
Not specified	Nitrifying bacteria	Ridomil gold (+ copper)	Field	Demanou et al. (2004)
Pea (*P. sativum*)	*Rhizobium* sp.	Hexaconazole, metalaxyl, kitazin	Laboratory	Ahemad and Khan (2012a)
	Rhizobia	mancozeb	Laboratory	Mohamad and Al-naser (2018)
Pepper (*Piper nigrum*)	*Paenarthrobacter*	Iprodione	Laboratory	Katsoula et al. (2020)
Soybean (*G. max*)	*R. japonicum*	Captan, carbendazim	Field	Kaur et al. (2007)
Tomato (*S. lycopersicum*)	*Burkholderia* sp.	mancozeb	Laboratory	Tripti et al. (2015)
Wheat (*T. aestivum*)	*Pseudomonas*, *Bacillus*, *Azospirillum*, *Agrobacterium* sp.	Alert plus, darosal, mancozeb, benlate, captan, vitavax	*Laboratory*	Mubeen et al. (2006)

amino acids may also be suppressed by glucopyranosyl fungicides (Molaei et al. 2017).

Most copper-based fungicides portray toxic effects on diazotrophic bacteria (Van Zwieten et al. 2003). The tendency of apron, arrest, and captan residues to affect N-fixation in legume-*Rhizobium* symbioses has previously been established (Kyei-Boahen et al. 2001). Mancozeb and chlorothalonil fungicides can similarly reduce the nitrification process (Omar and Ismail 1999), while carbendazims are moderately toxic to *P. fluorescens* and *B. subtilis* (Virág et al. 2007), which are the most common PGP rhizobacteria (Aloo et al. 2019, 2020).

The assessment of metabolic quotient (qCO_2) (the rate of respiration per unit of microbial biomass) is a perfect way of approximating the extent of microbial disturbances in soil (Glodowska and Wozniak 2019). According to Anderson and Domsch (1990), qCO_2 increases in soil after the application of pesticides probably because microorganisms are forced to use more energy to maintain their cells under these conditions. Earlier investigations by Jones and Ananyewa (2001) also confirmed that the addition of metalaxyl in soil can disturb qCO_2 for 21 days. In another study, qCO_2 was established to be significantly higher in soils treated with atrazine herbicides than in untreated soils (Moreno et al. 2007). In rare cases, certain beneficial plant rhizobacteria such as those involved in P-solubilization and N-fixation may be stimulated by some fungicides (Sun et al. 2020), but the cause of this is not yet established.

Prospects and possible solutions for agricultural sustainability

Reducing the environmental costs of contemporary agriculture requires novel technological tools and management strategies to shift the current use of agrochemicals to more sustainable methods. Soil amendment with biochar has received much attention over the last few decades, probably due to its ability to improve soil fertility and increase crop yields (Backer et al. 2018). According to Brtnicky et al. (2019), the amendment of soil with biochar may counteract the deleterious effects of herbicides on soil microbiota. Fairly recently, Glodowska et al. (2016) showed that biochar can promote the viability of PGP bacteria for about half a year. Using molecular techniques such as the next-generation sequencing and terminal restriction fragment length polymorphism, Anderson et al. (2011) established the positive effects of biochar-amended soils on Bradyrhizobiaceae. This is probably because biochar induces various physicochemical changes in soil that together improve microbial survival and functions in agricultural soils (Zimmerman 2010; Backer et al. 2017; Jenkins et al. 2017). It is, however, important to note that biochar materials vary and other factors like production conditions and feedstock materials may influence the biological, chemical, and physical properties of the final material and, subsequently, its field performance (Nguyen et al. 2017; Wang et al. 2017a).

Lime can be used to manage soil acidification from prolonged chemical fertilization and its effects on beneficial plant rhizobacteria in agricultural systems (Glodowska and Wozniak 2019). Although studies by Ma et al. (2018) have disputed this, several reports concur that liming can help to counteract the effects of long-term fertilization on soil properties and bacterial community structures (Jaskulska et al. 2014; Lu et al. 2016; Li et al. 2019a). In tempered climates, lime can raise the pH of soils to between 5.7 and 6.5 and positively influence their physicochemical conditions (Hynes and Naidu 1998).

Microbial inoculants or biofertilizers are promising options for mitigating the negative environmental effects of chemical fertilizers due to their PGP potential and capacity to promote nutrient availability and uptake by plants (Aloo et al. 2020; Basu et al. 2021). Although microbial inoculants do not always compete favorably with the inherent microbial strains in soil, isolates from specific soils can perform well in similar habitats and exhibit better adaptation to the typical ecological stresses and prevailing environmental conditions (Shaikh and Sayyed 2015; Bakhshandeh et al. 2017). Although rhizobacteria-based technology is an emerging technology for crop production worldwide, its adoption and integration as biofertilizers are still subject to research, improved field performance, and development of effective inoculants (Aloo et al. 2021b).

Conclusion

Contemporary agriculture continues to rely on pesticides, herbicides, and fertilizers to boost crop production. Despite the indisputable contribution of these chemicals to global crop production and food security, a lot of uncertainty and controversy still surrounds their continued application in agricultural systems. Although a lot of evidence suggests that they can directly alter soil properties and affect the beneficial plant microbes in agricultural systems, some studies show that they can stimulate the proliferation of some beneficial soil microorganisms. Notwithstanding, alternative crop cultivation mechanisms that employ fewer agrochemicals should be considered, pursued, and maximized to avoid the possible deleterious effects of agrochemicals on beneficial plant rhizobacteria in agricultural systems and promote agricultural sustainability on a global perspective.

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