Chapter 9

Future Perspective in Organic Farming Fertilization: Management and Product

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9.1 INTRODUCTION

The concept of "organic farming" appeared during the second green revolution in the mid-20th century as an alternative to the prevailing conventional agriculture systems, in order to increase crop production for feeding a continuously growing world population (Srivastava et al., 2016). So-called conventional farming consists mainly of the application of two basic principles: the application of synthetic pesticides for the elimination of pests or diseases that can compromise, damage, or reduce crop production and the use of synthetic chemical fertilizers to enhance crop yields (Seufert et al., 2009). These principles are in agreement with those of organic farming; however, organic farming is restricted to the application of the "natural version" of pesticides and fertilizers (Stolze and Lampkin, 2009). The key point is the reduction of external threats that can compromise crop production, to obtain higher yields (Bellon et al., 2014).

The use of chemical fertilizers lead to the rapid industrialization of their synthesis processes and reduced the dependence on external factors to produce them (i.e., manure production). Fertilizers can be applied depending on the nutritional deficiencies of the plant, allowing the farmer to take direct actions to solve the problem. However, the use of those fertilizers and the

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Organic Farming. DOI: https://doi.org/10.1016/B978-0-12-813272-2.00010-0

agriculture practice by if self generate a rapid and constant loss of soil nutrients and biodiversity (Bellon and Penvern, 2014). Thus, a reduction in the use of chemical fertilizers will mitigate this loss with the aid of external contributions or the integration with other activities, such as livestock and their nutrient stocks recycling (Reganold and Wachter, 2016).

The application of synthetic fertilizers can be considered an advantage at first, however, it has generated several environmental impacts in many agricultural areas of the planet (Van Stappen et al., 2015). The uncontrolled use of these fertilizers, their application in suboptimal or negative conditions, as well as the losses of nutrients by runoff, leaching, or volatilization have caused public health problems and environmental deterioration (Jeločnik et al., 2015).

In this sense, organic farming aims to maintain rationalized production levels, friendly with the ecosystem where it is farmed, acting according to the inherent limits of the region (Van Stappen et al., 2015). Moreover, organic farming seeks the diversification of nutrient inputs as long as they do not generate an associated environmental problem and take advantage of the outputs generated in other farming systems, such as wastes or products derived from livestock, crop residues, or sewage sludges (Wezel et al., 2014).

The concept of “organic farming” is based on a holistic view of farming systems, which has each part completely integrated in the system, such as soil and its microbiota, climatic conditions, plants, and animals (Acs et al., 2005). Soil microbiota is also considered in the global analysis of agricultural systems, suggesting that a soil with the correct microbiota favors the development of healthier plants. Thus, plants are capable of efficiently capturing nutrients and dealing with different diseases. In this sense, plant growth-promoting bacteria (PGPB) are capable of interacting positively with plants, promoting their development directly and indirectly (Garcia-Fraile et al., 2015; Grobelak et al., 2015; Menéndez et al., 2016). Amongst these PGPB, the genus *Rhizobium* and related genera, which are commonly known as legume symbionts, are the best examples of beneficial microorganisms contained in soils (Bhattacharjee and Dey, 2014).

Moreover, this holistic view determines that the application of nutrient inputs must be conditioned to their geographical availability, making cultural practices the most cost-effective action (Provost and Pedneault, 2015). Farmers need to maximize their crops yields through specific actions, such as crop rotations and the application of nonsynthetic fertilizers, seeking the integration and synergy of different actions, such as cultural techniques and crop diversification (Benoit et al., 2016; Mu et al., 2016; Viaene et al., 2016).

Every action produces different effects on the organic farming system; for example, the application of intercropping, which is the mixed cultivation of different crops, is one of the agricultural practices matching perfectly with organic farming philosophy (Mao et al., 2015). In many cases, intercropping practices involve the cultivation of cereals in a row with leguminous plants, due to the biological nitrogen fixation occurring in their root nodules (Hauggaard-Nielsen et al., 2009; Ngwira et al., 2012; Scalise et al., 2015). Legumes act as providers of nitrogen and make available other essential nutrients, due to the microbiota associated with their nodules and roots, which are able to solubilize phosphates and potassium and to mobilize other nutrients as well as produce phytohormones in order to enhance plant development (Chapagain and Riseman, 2014; Latati et al., 2016). Moreover, through indirect mechanisms, the microbiota associated with leguminous plants might play a role as biocontrollers in order to prevent or reduce plant diseases (Bhardwaj et al., 2014). Apart from intercropping, there are many agricultural and/or management practices. Thus, in this chapter, we will analyze each of the techniques used to improve the fertility of the agronomic systems in conditions of organic farming. Additionally, we will make a distinction between what are considered management practices and the application of organic or biological inputs employed to increase the fertility of fields in organic farming.

9.2 MANAGEMENT PRACTICES

To achieve a well-balanced agricultural system, the application of the best possible management practices is absolutely necessary. In the case of organic farming, these management practices have focused on the maintenance of the available pools of nutrients, and moreover they should explore new ways to obtain more nutrients in agricultural fields (Gomiero et al., 2011).

9.2.1 Conservation Tillage

The use of tillage in agriculture was one of the first techniques implemented by humans and generated many benefits in terms of weed control and soil aeration, making nutrients assimilable or mixing depths of soils, which were not explored by plant roots (Drakopoulos et al., 2016). However, tillage was one of the practices that most actively contributes to the loss of edaphic material, due to surface exposure of unconfined material that can be washed away by runoff or wind action (Crittenden et al., 2015).

Conservational tillage is based on the minimal disruption of the soil composition structure and biodiversity, reducing soil degradation and also water contamination (Holland, 2004). Ancient civilizations, such as Egyptians and Incas, also used this kind of practice, inserting seeds directly on the soil (Derpsch, 1998).

There are many studies analyzing the outcomes of this kind of practice (Karlen et al., 2013; Martínez et al., 2013; Nascente et al., 2013; Garcia-Franco et al., 2015); however, some of were of short duration and did not show the full reality (Derpsch et al., 2014). The implementation of agricultural practices with minimum tillage is a difficult task, due to the problems of obtaining correct homogenization and integration of external nutrients to the environment, such as the necessity for inverting and mixing horizons, which is not in agreement with the restrictive point of view of conservational tillage (minimum actions and impact on the fields) (Säle et al., 2015).

The main potential positive effect on field fertility is the increase in the percentage of organic carbon available in the soil, which in turn affects the creation of humic–fulvic complexes that act by retaining the ions of the different nutrients (Soane et al., 2012; Zikeli et al., 2013). Soils with high concentrations of organic carbon influence positively the microbial activity and its diversity (Raphael et al., 2016). These parameters are directly related to crop production (Sun et al., 2016).

The application of conservational tillage is extremely interesting for tropical agricultural systems, due to the positive influence on the content of organic carbon in the soils. The climatic conditions, high temperatures, and precipitation rates, tend to accelerate the mineralization process of organic matter in agricultural soils, which is also favored by tillage, helping the development of aerobic microorganisms and causing the degradation of organic matter of the upper horizon into CO_2 (Chivenge et al., 2007; Lienhard et al., 2013; Raphael et al., 2016).

Nontillage systems tend to be deficient in K and P, due to their "extraction" along with crops. Most studies focus on how the different practices have an influence on these nutrients (Gadermaier et al., 2011; Rosolem and Calonego, 2013). Their loss can be partially compensated for by crop rotation, but it is often necessary to make external amendments (Rosolem and Calonego, 2013).

As a conservation practice, the main effects are reflected in the populations where the densities and their biological activities are affected (Mathew et al., 2012), being increased by the bacterial and fungal biomass in direct relation to the increase in organic carbon (Lienhard et al., 2013). This diversity and density decreases as depth increases, unlike in conventional tillage soils (Huang et al., 2013).

Nontillage systems are associated with the absence of cropping practices that break or produce inversions in surface horizons, thus, direct sowing is usually carried out (Lienhard et al., 2013; Nascente et al., 2013). In this type of system, the greatest problem is associated with the correct fertilization, since the use of fertilizers in solid form is difficult without mechanical incorporation to substrates. In some cases, occasional tillage is recommended to reduce the undesirable effects of loss of productivity, which, depending on the soil, may not affect the microbiota (Rincon-florez et al., 2016).

A very conservative cultural practice, but not as restrictive as the absence of tillage, is so-called minimum tillage, which only disturbs the first few centimeters of soil (not more than 20 cm), keeping the soil structure closer to natural conditions and allowing the application of both solid and liquid residues, thus, the farmer might incorporate external nutrients more easily (Debiase et al., 2016).

9.2.2 Crop Rotation

This is one of the oldest techniques used in agriculture, dating back to the pre-Roman era in Europe, although it was this civilization that developed a forceful technique using the "food-feed-fallow" system. This system involves the division of cultivable land into three equal parts, one of which cultivated human-food vegetables, another with crops intended for animal feed and, finally, another part left for a year as pasture for cattle in order to regain fertility. This system is continuously reinitiated, rotating the three parts for annually (White, 1970).

There are old treaties about this practices dating back to Roman times, showing how to use crops in these rotational systems, as well as their contributions to soil fertility. In this sense, the Roman agronomist Columela (54 BC) showed the utility of the leguminous plants *Vicia* and *Lupinus* for the maintenance of soil fertility. Since the mid-19th century, scientific knowledge has been applied to agriculture, showing how different crops have different nutritional requirements. Moreover, it has been shown that the alternation of crops on the same land has a positive impact on land fertility, producing selective extraction or helping to mobilize some nutrients (Liebig and Playfair, 1847).

The concept of crop rotation defines all temporary succession of crops in the same field. This succession has to be done considering the environmental characteristics, such as climate and substrate, but also the agronomic requirements of crops (Brankatschk and Finkbeiner, 2015).

There are models that aim to automatically create crop rotations in an integrated way with regional conditions (Schönhart et al., 2011); however, these models do not usually take fertility factors directly into account because they are based on observations and measurements made under a conventional agriculture point of view (Dury et al., 2012). Only some of these models consider the inclusion of legumes in these systems as a positive factor with respect to nitrogen fixation, which is essential for crop rotations (Dogliotti et al., 2003).

Crop rotations were classified into different categories depending on the length and the rotation order (Castellazzi et al., 2008). There are four variants: (1) fixed duration and fixed rotation; (2) fixed duration and flexible rotation; (3) flexible duration and fixed rotation; and (4) flexible duration and flexible rotation. In those variants, crops with different nutritional requirements, root systems, and allelopathic qualities should be alternated (Hilton et al., 2013).

This action modifies the soil microbiota mainly due to changes in carbon concentrations, since it tends to improve fertility in crop rotations (Ferrari et al., 2015). Although soil organic stability is also improved, soil components exhibit less variation and greater resilience (Venter et al., 2015). Moreover, this management practice is related to an increase in soil phosphatase activity, which influences the concentration of phosphorus available to plants (Jahan et al., 2016).

One of the most commonly used crop rotations is the maize/soybean association (Riedell et al., 2009; Karlen et al., 2013; Souza et al., 2013; Tomer and Liebman, 2014; Sindelar et al. 2015), although, this legume has also been combined with other monocotyledonous crops, such as wheat (Riedell et al., 2009; Souza et al., 2013), oat (Merlin et al., 2013), or rice (Hokazono and Hayashi, 2015). However, the use of soybean presents two disadvantages: Soybean is a summer crop and the biological nitrogen fixation taking part in its nodules is subjected to the presence of endosymbionts. Those endosymbionts do not exist naturally in Europe or America, thus this crop is usually replaced with *Pisum*, *Trifolium*, *Vicia*, or *Lupinus* (Espinoza et al., 2012; N'Dayegamiye et al., 2015; Pandiaraj et al., 2015), these two last legumes being those that give the best results (Angus et al., 2015). Multiannual legume crops such as alfalfa are also used, although in this case it is important to implement long rotations of over 8 years, being the nitrogen supply to soil is very significant (Triberti et al., 2016).

The so-called double-up legume rotation is also used to improve soil fertility; this rotation is based on cultivate leguminous crops in two successive years and later, concatenated with an exigent crop, such as maize (Smith et al., 2016).

Within nonleguminous crops used in rotations, the most attractive for farmers are those that develop pivotal and powerful root systems, such as rapeseed or sorghum (Hilton et al., 2013; Rosolem and Calonego, 2013). These crops are also useful for the acquisition of other nutrients because their root systems allow nutrient uptake from lower levels and mobilize them to agricultural horizons (Götze et al., 2016), as well as breaking of the consolidation structures in the soil, which allows for better distribution of the crop roots (Kumar et al., 2014).

Many studies focus on the implications of crop rotations in the nitrogen soil stock; however, other elements that should be as important as nitrogen, such as phosphorus and potassium, usually remain unnoticed. Nonleguminous crops play an important role due to differences in root systems with leguminous crops (Arroyo-Garcia et al., 2013). Another crop that might be of interest is ruzzi grass (*Brachiaria ruziziensis*), which facilitates an increase in the concentration of labile phosphorus in the soil (Merlin et al., 2013; Almeida and Rosolem, 2016). However, the main tendency is not the inclusion of other kinds of crops, it is to include these nutrients through amendments of different types (Cavigelli et al., 2013; Maltais-Landry et al., 2016).

Another rotation employed in organic farming, which can increase yields is canola with wheat or potato. This is applied in conventional agriculture or organic farming with good results in temperate climates. The results are related to high root system development and biofumigation effects (Bernard et al., 2014; Angus et al., 2015; Turinek et al., 2016).

Crop residues play an important role in the supply of micronutrients. Mobilization of essential nutrients is carried out through the action of previous crops, and they are stored temporally associated to organic matter. This affects positively the concentration in the soil and its availability, although the nutrient losses usually have to be compensated with external inputs (Jahan et al., 2016).

9.2.3 Cover Crops

The use of different crops, whose main objective is not production but maintenance of the land surface covered, is a concept that began to be considered from the beginning of the 20th century. Traditional agriculture has always eliminated other plants in order to maximize the use of resources by the crop of interest, leading to a massive use of herbicides. Therefore, we must first define the concept of cover crops to differentiate it from crop rotation systems. This is a short-term rotation that happens when the principal crop is not sowed (Robacer et al., 2016).

The main purpose of cover crops is the prevention of the loss of edaphic resources by erosion. These crops reduce the kinetic energy of water or wind, decreasing the aggression that they cause on the agricultural systems (Reeves, 1994). In this sense, it is possible to prevent erosion, and also reduce losses of soluble nutrients by runoff (Klodd et al., 2016).

The application of cover crops is considered by some relevant institutions, such as the USDA in its National Organic Program (USDA, 2010), which provides the actions, recommendations, and bases, highlighting the importance and determination that this kind of practice might have in organic farming. The document gathers evidence on the benefits of cover crops, such as elimination of weeds, soil compaction, or erosion reduction, and it also exposes possible contributions to mineral and organic content and, by extension, to crop nutrition (Scholberg et al., 2010).

In terms of soil fertility, the most notable advantages of the use of cover crops is the reduction in nitrogen losses (Novara et al., 2013), as well as the stabilization and recycling of other nutrients such as phosphorus, potassium, and magnesium, ensuring their permanence in the upper horizon of the soil for a longer time (Rosolem and Calonego, 2013). In addition, crops with pivotal or highly developed root systems are often used in order to reach deeper horizons, being beneficial for the transportation of nutrients from deep to superficial horizons and providing available nutrients for crops with superficial root systems like wheat (Pedraza et al., 2015). For this reason, some species of the genus *Brassica* are widely used; their pivotal root systems explore deeper into the horizon, making available soil nutrients to other crops and reducing soil compaction (Maltais-Landry et al., 2016). Cover crops can be divided according to their periodicity into winter, summer, or annual crops (Snapp et al., 2005), the latter being applicable only to multiannual and mainly woody crops. Summer cover crops are usually rapidly growing legumes, such as soybeans, which incorporate nitrogen to other crops or cereals (Raphael et al., 2016). In this case sorghum sudan grass is also widely used because of its extremely broad root system, which is capable of exploring a large volume of substrate per plant. This crop also shows several adaptations to environments with high temperatures, offering remarkable productivity. In this respect, the species used must be resistant to drought and heat, so that the cited sorghum sudan grass, and legumes such as soybean or cowpea are used in hot areas (Blanco-Canqui et al., 2012).

The second option is the use of winter cover crops. This option is applied to crops with spring and summer cycles, such as soybean, corn, peanut, or cotton. In addition, during the stage where the cover crop is active, there are often times of great rainfall that can trigger the loss of nutrients due to leaching and erosion (Lourenzi et al., 2015). A great solution to this problem is winter cover crops, like cereals or legumes, alone or in combination (Campiglia et al., 2014). In this regard, sowing legumes must be done carefully to avoid frost during the time of seed emergence. In this way, a double dividend is obtained on the nutrient pools, reducing the loss of nutrients and increasing it by means of the contribution of nitrogen carried by the legumes. The most commonly employed species from the genus *Vicia* include *V. villosa* (Campiglia et al., 2014; Pedraza et al., 2015) and *V. sativa* (Duval et al., 2016; Gabriel et al., 2016). Some species like *Avena sativa* (Duval et al., 2016), *Triticum aestivum* (Balota et al., 2014), or *Secale cereale* (Higashi et al., 2014) are widely employed due to this frozen resistance.

Cover crops might also be applied to woody crops, such as orchards or vineyards, recycling nutrients through part of the cover crop biomass (Novara et al., 2013). The use of well-adapted and rustic legumes can improve the concentration of N, P, and K in these soils by up to 30% (Gómez-Muñoz et al., 2014). Nevertheless, a correct analysis of the water crop is needed, as it can produce reductions in production due to the high demand on water (Klodd et al., 2016). Therefore, the inclusion of fast-growing legumes in monoculture or mixed with a cereal is important to improve the consolidation of C stocks in the soil and favor the retention of nutrients (Lee et al., 2013).

Generally, any use of cover crops usually triggers an improvement in soil osmotic potential due to an increase in organic carbon concentration (Sánchez de Cima et al., 2015). The increase in the available nitrogen is usually caused by the legumes in crop rotations. In this management, the election of the correct winter legumes, like the species of the genus *Vicia*, is determinant for ensuring correct development (Gabriel et al., 2016). This genus can substitute any other external nitrogen contribution with available quantities of 100 kg N/ha (Robacer et al., 2016). The results are similar with summer cover crops, with the choice varieties having later maturity, which is essential to avoid the mobilization of nitrogen fixed to the seeds and to reduce the input of this element (Blanco-Canqui et al., 2012).

9.2.4 Green Manures

One of the difficulties that farmers face in is the maintenance of an optimum level of productivity during successive campaigns, with nitrogen being the most sensitive and determinant element to reach optimal production. There is an intense nitrogen flow from the soil to the product. In many cases, a reduction in nitrogen supply is compensated by the application of different inputs derived from livestock activity; however, this type of application may have some limitations (Paredes et al., 2014). The application of green manure presents itself as a useful farming practice to avoid those limitations.

Green manure can be applied in two different ways: one in which the green manure crop and the main crop are cultivated in the same plot in different seasons, and another in which the green manure crop is cultivated in a different place and transported to the main crop plot (Skuodienė et al., 2012).

Green manures involve several crops, mainly legumes, which are cultivated after the main crop harvest or during its standard growing season. These crops are described in Table 9.1, where we can distinguish between legume and nonlegume crops in temperate and tropical weathers. Crops used as green manures are planted with the objective of being incorporated back to the land without proceeding to the collection of the vegetal matter or at least of the aerial biomass (Talgre et al., 2012).

European farmers adopt this management practice due to its easiness and potential benefits, which not only improve soil fertility, but also prevent soil erosion, help with weed management, and maintain soil structure, features shared with the application of cover crops (Løes et al., 2016). Under normal conditions it is easy to reach an average yield of 100 kg N/ha, considerable values that ensure a good yield of the following crop. If it is carried out in short cycles or winter periods, the total productivity of the crop will be reduced, on account of reducing nitrogen fixation (Cookson et al., 2002).

The selection of crops for green manure is another relevant aspect; several studies have reported the use of different crops in temperate and tropical regions (Egodawatta et al., 2012; Raphael et al., 2016). In temperate regions, there are intrinsic variations depending on when the sowing happens. Thus, selected crops have to present further adaptations and the farmer must adhere to the sowing times for best results (Ferreira et al., 2013)

TABLE 9.1 Green Manures Applied in Temperate and Tropical Weathers Climates

Crop Type	Climate Region	Species	Season	Authors
Legumes	Temperate	*Astragalus sinicus*	Winter	Lee et al. (2010); Kim et al. (2012)
		Glycine max	Summer	Northupl and Rao (2015)
		Lablab purpureus	Summer	Northupl and Rao (2015)
		Lens culinaris	Winter	Cicek et al. (2014b); Vaisman et al. (2014)
		Medicago media	Annual	Talgre et al. (2009)
		Medicago sativa	Annual	Skuodienė et al. (2012)
		Melilotus officinales	Annual	Bruning et al. (2015)
		Pisum sativum	Winter	Cicek et al. (2014a); Olesen et al. (2009)
		Trifolium pratense	Annual	Talgre et al. (2009); Skuodienė et al. (2012); Sharifi et al. (2014)
		Trifolium repens	Annual	Skuodienė et al. (2012)
		Vicia faba	Winter	Olesen et al. (2009)
		Vicia villosa	Winter	Cicek et al. (2014b); Hwang et al. (2015); Vaisman et al. (2014); Tarui et al. (2013)
	Temperate and tropical	*Crotalaria juncea*	Summer	Miyazawa et al. (2014); Subaedah et al. (2016)
		Lupinus angustifolius	Winter	Olesen et al. (2009)
		Lotus corniculatus	Summer	Talgre et al. (2009)
		Lathyrus sativus	Winter	Vaisman et al., (2014)
	Tropicalwarm	*Albizia lebbeck*	Annual	Kareem et al. (2014)

(*Continued*)

TABLE 9.1 (Continued)

Crop Type	Climate Region	Species	Season	Authors
		Arachis pintoi	Seasonal	de Araujo Neto et al. (2014); Wang et al. (2015b)
		Cajanus cajan	Seasonal	Ferreira et al. (2013); Nascimento et al. (2016)
		Canavalia ensiformis	Annual	Ferreira et al. (2013); de Araujo Neto et al. (2014)
		Crotalaria spectabilis	Seasonal	de Araujo Neto et al. (2014)
		Crotolaria ochroleuca	Seasonal	Ferreira et al. (2013)
		Gliricidia sepium	Annual	Egodawatta et al. (2012)
		Glycine ussuriensis	Seasonal	Dabin et al. (2015)
		Mucuna pruriens	Seasonal	Ferreira et al. (2013); Poku et al. (2014)
		Phaseolus radiatus	Seasonal	Dabin et al. (2015)
		Pueraria phaseoloides	Seasonal	de Araujo Neto et al. (2014)
		Sesbania aculeata	Annual	Premi et al. (2013)
Non legumes	Temperate	*Avena sativa*	Winter	Cicek et al. (2014a),
		Brassica napus	Winter	Sánchez de Cima et al. (2015)
		Brassica rapa	Winter	Cicek and Entz (2014)
		Hordeum vulgaris	Winter	Hwang et al. (2015)
		Lolium multifloru	Annual	Sánchez de Cima et al. (2015)
		Lolium perenne	Winter	Kim et al. (2012)
		Phleum pratense	Annual	Skuodienė et al. (2012)

(*Continued*)

TABLE 9.1 (Continued)

Crop Type	Climate Region	Species	Season	Authors
		Raphanus sativus	Winter	Cicek and Entz (2014)
		Sinapis alba	Winter	Bogužas et al. (2015)
		Sorghum bicolor	Summer	Miyazawa et al. (2014)
	Tropicalwarm	*Pennisetum glaucum*	Seasonal	Nascimento et al. (2016)
		Sorghum drummondii	Seasonal	Mkhathini and Modi (2012)
		Tithonia diversifolia	Seasonal	Partey et al. (2014)
		Urochloa ruziziensis	Seasonal	Nascimento et al. (2016)

Nowadays, the use of green manures is growing in importance and farmers are considering the employment of crops adapted to adverse conditions. Moreover, they should consider longer periods of application (more than 2–3 years), in order to increase the amount of available nutrients (Skuodienė et al, 2012). Several legumes might be applied as green manure following these new trends; i.e., red clover (*Trifolium pratense*), which improves available concentrations of N, P, and K in the soil, or vetch (*Vicia sativa/villosa*), which provides between 140–180 kg N/ha (Snapp et al., 2005).

The use of green manures in orchards is an extended practice with good results, since it improves nutrient retention and tree availability, compared to conventional production systems (Garcia-Franco et al., 2015; Park et al., 2015). In this sense, most of the studies reported the use of *Vicia*, *Cajanus*, *Arachis*, or *Avena* as green manure crops (Lim et al., 2012; Park et al., 2015; Millan et al., 2016).

The use of green manures is also widespread in cereal production systems such as wheat, barley, or rye, due to the global demands for these types of crops and the nutritional requirements, mainly of nitrogen. It is common practice in temperate latitudes, where it has been carried out continuously for hundreds of years, even allowing for areas with low productivity. However, the use of other nonleguminous green manure, such as radish (*Raphanus sativum*), which has a significant pivotal root, is useful in the extraction and incorporation of K and P into the agricultural system from lower edaphic horizons (Cicek et al., 2014a).

9.2.5 Intercropping

Intercropping consists of the simultaneous cultivation of two or more plant species acting in synergy and avoiding competition at the foliar, root, and nutritional levels (Andrew and Kassam, 1976). Intercropping is not a simple mix of crops, where the competition for space and nutrients is common. The use of this management practice was common in European countries in past centuries and is recently raising importance in commercial agriculture. This practice is also widely used in tropical farming systems.

Intercropping has many advantages, such as the easiness and efficiency of its application and reversion of the loss of soil biodiversity caused by the application of monocultures. Moreover, there is maximization of land use and benefits, and harvest yields are increased. However, it also presents a number of negative points compared to other techniques used in organic farming, such as a lower contribution of nitrogen and other nutrients to soils or difficulties in harvesting both crops at the same time, it being necessary for post-processing to separate yields.

Despite the disadvantages, this is an extremely versatile technique that can be applied to annual, perennial, arbustive, or mixed crops. The most common associations are cereals and legumes, i.e., corn/soybean association. In recent years, tuber crops have been used, due to the potential advantages that this kind of crops might have (Weerarathne et al., 2016). This practice has a very important effect on the soil nitrogen balance, reducing nitrogen losses that are not used by the crop, as well as reducing the needed for nitrogen (Tribouillois et al., 2016). Moreover, this practice can be applied together with green manures. In this case, pulse shoots are cut and incorporated into the main crop, usually a cereal; thus, the main crop will have a constant nitrogen contribution (Hödtke et al., 2016), However, the election of both crops should be done correctly; some authors described the association of oat and pea, which was used in certain regions of Europe, may not have the desired effect in nodulation and nitrogen fixation rates (Jannoura et al., 2014).

Although the results are endorsed by good yields, the cycle of nutrients such as phosphorus and potassium is not clear, and the influence of this activity on micronutrients such as iron, magnesium, or manganese are undefined. Only a few relationships have tested, for example, maize and peanut (Guo et al., 2014).

The association of wheat/chickpea generates an increase in the availability of phosphorus in the rhizosphere of both plants with respect to them as monocultures (Betencour et al., 2012). In tropical areas, *Gliricidia sepium*, an arboreal legume, is used in intercropping with maize, improving the availability of potassium and nitrogen supply (Beedy et al., 2010). Other authors suggest that the use of trees (*Acer* sp. and *Juglans* sp.) improves microbial populations of both bacteria and mycorrhizae, improving nutrient absorption and production (Lacombe et al., 2009).

The incorporation of nonleguminous plants may also have an effect on nitrogen cycles, generating rapid reabsorption, as observed in *Festuca rubra* intercropped with maize (Manevski et al., 2015). Nevertheless, despite most of the studied systems having good results in practice, the new associations need to be tested in order to avoid associations that produce allelopathic problems.

9.3 APPLICABLE AMENDMENTS

The application of management practices, such as those described above, does not always meet the necessary conditions to ensure proper agricultural production. In organic farming, the applications of diverse inputs of natural origin are allowed, including the application of minerals such as rock phosphate, potassium salts, or natural sulfates (Regulation (EC) No 889/2008). In this section, we will focus on the application of inputs other than those described above, which might present novel application forms or be novel itself.

9.3.1 Manures

Manure is a byproduct generated during livestock activity that has been used since ancient times as a fertilizer to enhance field productivity. Usually, it is mixed with crop residues or straw to increase water retention and facilitate its subsequent fermentation (Castellanos-Navarrete et al., 2014; Omari et al., 2016). The fermentation of this type of byproduct is air-filled, producing a change in the chemical composition of the product to less soluble but more stable forms, resulting in a loss of ammonium nitrogen (Gustafson et al., 2003). The application of manure depends on its composition, the crop needs, and the soil characteristics. This is a product that will undergo important transformations in the soil after its application, occurring before sowing (Yue et al., 2016).

The use of manure is still widespread because it is a source of fast-absorbing nutrients with proven effects for decades, with variable doses to obtain optimum yields in crops such as cereals (Borugă et al., 2016). This is due to the fact that nutrient concentrations have a wide variation, depending on the producer species, the animal nutrition, and the manure post-processing (Poku et al., 2014; Chaudhary et al., 2017).

Phosphorous is one of the most important elements to guarantee proper agricultural production; an adequate concentration of available phosphorus in the soil can be maintained by the application of manure (Shen et al., 2014).

Cow manure is one of the most commonly used manures, due to the hydrolytic action of its microbiota on plant fibers, allowing better processing in small-scale conditions and improving its integration into the soil. Also, the low water content and its volume allow easy storage and use of this kind of manure (Wang et al., 2015a).

Other manures produced by hens and chickens have highly desirable characteristics for agriculture, such as high nitrogen, phosphorus, and potassium contents (Li et al., 2016). These manures have proven useful for demanding crops, such as rice or sugarcane (Showler, 2015). In addition, this type of product has begun to be commercialized by being pelletized, facilitating its transport, reducing the geographic dependence and ceasing to be a purely local product (Burnett et al., 2015; Fernandez et al., 2016).

Many authors suggest that the application of manures of different species, such as horse, rabbit, or sheep, has short-term efficacy, which is usually associated with the chemical form in which the nutrients are present (Fernández-Hernández et al., 2014; Islas-Valdez et al., 2015). In some cases the concentrations of P are noteworthy, with high concentrations of P and K available (Jannoura et al., 2013). This fact is determined by the presence of readily available nonsoluble phosphorus (Vanden Nest et al., 2016).

9.3.2 Compost and Vermicompost

9.3.2.1 Compost

Compost is a versatile product generated by the fermentation of different residues, such as green or dry vegetation, manures from diverse origins, or urban waste (Zhao et al., 2017). The origin of the raw materials, mainly waste or remnants of other activities, has an important effect, increasing the concentration of carbon, usable nitrogen, and/or phosphorus (Castán et al., 2016; Meena et al., 2016).

Some efforts have been made to maximize the use of different residues through composting, such as food remains and urban solid waste, allowing the recirculation of outputs in the agricultural system (Papafilippaki et al., 2015; Pandey et al., 2016a,b). Residues of low potential or that are incompatible for agricultural use may become a product with homogeneous properties to be applied in different crops due to their concentrations of N, P, K, and micronutrients (Trivedi et al., 2015). Mature composts must have an acceptable C/N ratio of less than 20, acidic or slightly acidic pH, and discrete concentrations of soluble P or K (Showler, 2015; Cavoski et al, 2016; Pandey et al., 2016a,b).

The use of compost might represent the transition from conventional agriculture to organic agriculture. The use of high doses allows a high maintenance of the fertility, reaching a balance between soil and agricultural production (Hernández et al., 2015). However, an excess may lead to environmental problems similar to those occurring when there is an excessive use of inorganic fertilizers, such as nitrate losses (Papafilippaki et al., 2015).

Moreover, the use of compost often leads to an increase in diversity and microbial activity, like most organic amendments; however, the structure of these populations is not affected by their application, in contrast, the soil type influences the microbial population (Hernández et al., 2015; Allard et al., 2016).

In general, after the composting process, the concentration of certain elements, such as nitrogen or carbon, tends to be similar in composts of different origins. The elements that do not produce volatile compounds show a great dependence on the initial product, such as Cu, Zn, Cd, or Pb, with Cd and Pb usually being present in urban waste (Meena et al., 2016). However, the use of compost derived from residues from agricultural activities does not present high concentrations of metal elements (Scotti et al., 2016).

The amounts of phosphorus derived from compost amendments are variable but usually have relatively low values (below 10 g/kg) compared to other organic amendments (Evanylo et al., 2008; Hall and Bell, 2015). This element has a recovery rate of 30%, since it has not undergone intense processes of oxidation or mineralization (Christel et al., 2014); however, it usually decreases with application in soil (Jorgensen et al., 2010). In some cases, the addition of rock phosphate, allowed in organic farming, may be of interest in order to improve phosphate availability (Bustamante et al., 2016; Moharana and Biswas, 2016).

Potassium is also of special interest in agriculture, as its concentration in compost is higher than phosphorus (2- or 10-fold; McLaughlin et al., 2015; Strik, 2016). However, it is a very soluble element that can be lost during compost processing; thus, its concentration is variable and depends on the compost raw material (Madejón et al., 2016).

Micronutrients will show great variability depending on the raw material, although they usually present concentrations that can be consumed by the crop fields, always within normal values (Morales-Corts et al., 2014). The application rates vary and will depend on the elemental composition of the applied compost, but are considered between 10 and 300 t/ha, although the optimum values are usually between 20 and 40 t/ha (Papafilippaki et al., 2015). Although many of the studies carried out cover a relatively short period of 2–4 years (Castán et al., 2016; Debiase et al., 2016), there are some works performed in long-term trials which can help us to understand its effects (Vanden Nest et al., 2016; Xin et al., 2016).

The application of composts has benefits in other parameters related indirectly to soil fertility, such as porosity and particle size, giving lower density and smaller particle size, through an increase in the high-molecular-weight carbon compounds. Additionally, this application helps to establish nutrient solution and regulate the immobilization and mineralization of elements such as N, P, or K (Showler, 2015; Xin et al., 2016).

9.3.2.2 Vermicompost

Vermicompost is composed of the organic waste transformed through different earthworm species' digestive systems into a homogeneous product of high nutritional value and with great possibilities for its application in agriculture (Suthar, 2009). This process allows the stabilization of solid residues, showing great possibilities when the concentration in cellulose fibers is high (Sahariah et al., 2014). In this case, different species of earthworms are used, although the most frequently used species are *Eisenia foetida*, *Eudrilus eugeniae*, and *Perionyx excavatus* (Pattnaik and Reddy, 2010; Soobhany et al., 2015; Subbulakshmi and Thirunee, 2015).

One of the main advantages of the use of earthworms in the production of compost is the production of a higher concentration of nutrients through the biological activity of these worms, which might be compared to traditional composting and allow the reuse of residues of low fertilization potential (Soobhany et al., 2015; Swarnam et al., 2016). Starting from the same raw material, the increase in the concentration of P, K, Ca, or Mg is usually between 30% and 120%, obtaining a product that can be used in crops with high nutritional requirements (Soobhany et al., 2015). However, this situation does not occur with nitrogen, which is lost by volatilization in the form of ammonium.

Interestingly, earthworms have the ability to remove toxic organic compounds that may present problems in traditional composting systems, being effective in the recovery of degraded agricultural soils with decreased nutrient reservoirs (Lim et al., 2015; Hussain et al., 2016). Moreover, being a pathogen-free end product and the high percentage of nutrients in available forms makes composts extensively used in horticulture or extensive crops, both in cereals and legumes (Baradari et al., 2013; John and Praba, 2013; Joshi et al., 2014; Wang et al., 2014; Sreevidya et al., 2016).

9.3.3 Biochar

Biochar is a product generated through a thermochemical process called pyrolysis, in which organic matter of low density and low caloric power and, in the absence of oxygen and high temperatures (400–700°C), generates three different byproducts: Syngas, bio-oil, and biochar, also called charcoal. All these derivatives have a high calorific value, can be used as fuels, and also allow the reuse and storage of organic waste with subsequent environmental benefit.

The employment of biochar in agriculture began more than 40 years ago but in the last 10 years, there has been a great increase due to its unique features and the easiness of its production at a small scale (Galgani et al., 2014; Kuppusamy et al., 2016). However, its production at an industrial scale allows for greater use of all its byproducts, not only biochar, in addition to diversification in production methods (Li et al., 2016).

For several years, most studies have focused on the use of wood or city waste as a raw material for the production of biochar, which has generated some criticism due to the associated deforestation problems (Ahrends et al., 2010; Gwenzi et al., 2015; Zhang et al., 2016a). However, this trend has changed, especially in developing countries, where raw materials are more diverse (Chidumayo and Gumbo, 2013; Jones et al., 2016; Khan et al., 2016a,b; Gonzaga et al., 2017). Also, trends are changing in industrialized countries, which are aware of the need to diversify raw materials for biochar production (Manolikaki et al., 2016; Thakkar et al., 2016).

From the point of view of agriculture, biochar presents various characteristics: basic pH between 8.5 and 10, high C/N ratio, moderate K and P concentrations, and high porosity (Joseph et al., 2015; Jeong et al., 2016; Plaza et al., 2016; Pluchon et al., 2016). Most of these features are derived from the raw material used, such as pruning, crop residues, logging residues, or sewage sludge (Paneque et al., 2016).

Although biochar is characterized by a low concentration of N, it can contribute to the soil with large amounts of other nutrients, such as K or P. Biochar structure allows a gradual release of phosphorus, emphasizing to some authors that its application can stimulate the transformation to labile forms of these nutrients (Plaza et al., 2016; Dari et al., 2016). As in other organic amendments, biochar structure will vary depending on the raw material, i.e., wood-derived biochars tend to have a lower concentration of K and P than those derived from pruning or crop residues (Gul et al., 2015; Buss et al. 2016). However, their application does not show any improvement in the N concentration alone (Hansen et al., 2016).

Due to the high percentage of organic carbon and its structure, the use of biochar for sandy soil amendment is an option to take into account due to the improvement of soil quality and water retention rate (Molnár et al., 2015; Suliman et al., 2017). The effectiveness of biochar will depend on the type of soil, climatic conditions, crop, and application (Obia et al., 2016). However, its greatest impact will be found in the recovery of overexploited soil (Novak et al., 2016; Paneque et al., 2016; Zhang et al., 2016b). Therefore, the application of biochar can be a tool in the transition from conventional to sustainable and ecological systems, allowing us to rapidly increase the percentage of organic matter due to its high C/N ratio (Iqbal et al., 2015; Plaza et al., 2016). The large specific surface area of the biochar can be one of the keys to understanding the effect shown on microbial populations since it works by creating new spaces where bacteria can be established (Kookana et al., 2011).

Despite all of the described benefits, biochar has some disadvantages, mainly associated with its high pH, which increases the immobilization of the trace elements of a range of metals (Bell and Worrall, 2011).

Nevertheless, the high pH, together with its high porosity, makes the application of charcoal a widespread strategy for sandy soils and tropical acid soils with low organic matter concentration (Raboin et al., 2016). In addition, it presents a high cation exchange capacity (CEC), which makes it possible to retain soluble ions of the different nutrients in the soil (Xu et al., 2016).

Biochar can also be used to improve the qualities of other organic inputs used in organic agriculture, such as compost or manure. Its application in the animal composting process improves the fraction of humic—fulvic acid and provides stability (Jindo et al., 2015). Although the biochar is supplied with another product, such as compost, it has a synergistic effect on the absorption of this nutrient by the plant (Iqbal et al., 2015; Agegnehu et al., 2016)

The best results in terms of nutrient utilization are associated with combined solutions, i.e., the use of biochar and compost mixed with the application of phosphate-solubilizing bacteria, which can improve the efficiency in the absorption of this nutrient (Sáez et al., 2016; Wei et al., 2016). It is also described that biochar, in combination with vermicompost, green manure, or other amendments, has synergistic effects, improving nutrient absorption, contributing to the stability of humic—fulvic acid fraction, and slowing nutrient release (Ponge et al., 2006; Iqbal et al., 2015; Jindo et al., 2015; Agegnehu et al., 2016; Zhang et al., 2016c).

9.3.4 Other Amendments

Organic farming should explore all possible options to achieve better environmental benefits, mainly through the re-utilization of different byproducts. In this sense, the use of sewage sludge has been shown to be an effective tool in the case of cereals, even in conservative cases such as minimum tillage, where production similar to conventional treatments can be achieved (Debiase et al., 2016).

The application of sewage sludge generates high yields due to the very soluble chemical forms of its nutrients (Debiase et al., 2016). In many cases, the generation of these soluble forms is produced after anaerobic digestion, which is commonly called biogas, and also have some intermediate derivatives (Weiland, 2010). Biogas and derivatives have many advantages, such as easiness of application (on surfaces or by injection) and efficiency in nutrient managing, avoiding the loss of nitrogen and, thus, reducing its release to the atmosphere (Holm-Nielsem et al., 2009; Fangueiro et al., 2015). The production of biogas from residues and wastes derived from agricultural practices and livestock activities match perfectly with the holistic view of organic farming, also allowing energy recycling while producing a high-quality organic fertilizer (Siegmeier et al., 2015).

The separation of the different fractions is used to produce nutrient enrichment in the solid fraction, resulting in better yield (Hou et al., 2015). In spite of this enrichment, C/N ratios are high due to losses that occur during the digestion process (Lopedota et al., 2013). Nutrient levels are also very varied, although in most cases high concentrations of K and P can be obtained and nitrogen is relatively abundant (Nkoa, 2014). However, it is necessary to monitor the application of sewage sludge in order to avoid an overdose of certain elements, such as heavy metals (Debiase et al., 2016).

The use of sewage sludge and products from anaerobic digesters is feasible in extensive cereal production and also in intensive crops, such as horticultural crops (Lopedota et al., 2013; Sieling et al., 2014; Alvarenga et al., 2015). However, as expected, the excessive application of this type of product can generate undesirable environmental effects; thus, it is recommended not to exceed 120 kg N/ha (Duffková, et al., 2015).

Slurry is widely applied in conventional agriculture and with good prospects in organic agriculture due to the elevated concentration of nutrients (N, P, K) in easily assimilable forms (Saez et al., 2016). The contribution of slurry to agricultural production should be considered due to the large amount of organic nitrogen and other organic compounds that, together with their liquid state, facilitate its application and dispersion in the soil (Penha et al., 2015).

The composition of pig slurry is highly variable depending on the type of farm, use, feeding, and climatic region (Antezana et al., 2016). Its use, single or combined, provides better soil qualities and reduces the toxicity of heavy metals, such as Zn and Cu, which are found in high concentrations (Sáez et al., 2016). However, excessive use of livestock slurries may adversely affect soil microfauna populations (Murchie et al., 2015).

Another amendment that seems to have a promising future is the biomass of *Spirulina platensis*, which is an alga that can be grown in sewage sludges and slurries of different types (Aung, 2011). Its application is able to contribute up to 8% of nitrogen, and also varying concentrations of Fe and Mg. This alga is able to recover nitrates and nitrites that are dissolved in those wastes (Wuang et al., 2016).

Finally, there are infinite possible options for agriculture inputs that can be applied as fertilizers in organic farming. Different climatic regions have different residue types derived from agriculture. In this sense, Mediterranean countries, such as Spain or Italy, have a potential source of fertilizers in the residues generated from olive oil production, a solid waste commonly called “alperujo,” which can be used in raw or composted crops (Proietti et al., 2015; Russo et al., 2015). The composting process of this residue generates a product with a high concentration of humic acids, slightly basic pH, 20−30 g/kg of nitrogen, 1−3 g/kg phosphorus, and varying concentrations of potassium and other micronutrients (Roig et al., 2006; Tortosa et al. 2014). Its use is common in woody crops, mainly olive orchards but also others, such as poplar plantations (Madejón et al., 2016). These amendments have demonstrated that they are able to perform a systematic improvement of the production of olives in both the quantity and quality of the final product (Fernández-Hernández et al., 2014).

9.4 BIOFERTILIZERS

Organic farming is a practice that considers the maintenance of strong and competent microbial populations as essential, being aware of the impact of microorganisms on plant health (Bhardwaj et al., 2014). The interaction of crops with other organisms occurs through the root, where dense microbe populations live in a soil fraction called the rhizosphere (Mendes et al., 2013; Zandi and Basu, 2016). Those microbes live in a close relationship with plant roots and are suitable to be employed as biofertilizers. However, not all microorganisms can be employed due to possible pathogenicity issues, technological difficulties, or inadequate interaction capacity with different crops (García-Fraile et al., 2012).

Microbial-based biofertilizers, with current global production estimated at over US$5 trillion, are able to act directly and indirectly on plants, providing nutrients through their own biological activity, such as biological nitrogen fixation, phosphate mobilization, potassium solubilization, phytohormone production, and biological control (Lugtenberg and Kamilova 2009; Garcia-Fraile et al., 2015; Gupta et al., 2015; Velázquez et al., 2016). Therefore, the selection of those microorganisms that present better features is the key to agriculture improvement, although some have been sold and applied for decades, such as nitrogen-fixing bacteria.

Nitrogen-fixing bacteria, either free-living or associated with legumes, have already been commercialized, as is the case of *Azotobacter, Azospirillum*, *Rhizobium*, and related genera (Brockwell and Bottomley, 1995; Sivasakthivelan and Saranraj, 2013). Moreover, there are other kinds of microorganisms that can be applied as biofertilizers, such as cyanobacteria, mycorrhizae, potassium- and/or phosphate-solubilizing bacteria, biocontrollers, and other plant growth-promoting microorganisms (Berruti et al., 2016; Velázquez et al., 2016). Genera such as *Azoarcus, Exiguobacterium, Methylobacterium, Paenibacillus*, or *Pantoea* are also described as being able to interact with multiple plant species, to tolerate elevated temperatures, or to improve mycorrhizae interactions (Chauhan et al., 2015).

9.4.1 Carriers

One of the biggest challenges for industrial biofertilizer production is to solve the problems related to the transport and maintenance of the inocula during periods of storage and distribution. The formulation of a biofertilizer must maximize the chances of inocula survival, providing a suitable environment for the microbial component, as well as minimizing environmental changes in order that the farmer employs less time and effort to carry out the biofertilization. Unfortunately, the perfect formulation does not exist and we will always find problems associated with population decline or the type of inoculation.

The loss of effectiveness due to the death of inocula produces a decay of biological activity, an issue that can be solved with the inclusion of a proper carrier material. In this sense, carriers have been developed based on substrates that allow the transport of microorganisms in different presentations (Bashan, 1998). There are four possible types of carrier used in the preparation of commercial biofertilizers: Powder, liquid, granules, and encapsulated cells (Bashan et al., 2014).

Peat is the dominant solid carrier material in the market due to the easiness of its sterilization, obtention, and relatively low price (Chandran et al., 2014). Liquid formats based on aqueous solutions or oily suspensions are also widely used and easy to apply; however, they have disadvantages in storage and preservation, as well as the need for protectors (Pushpa et al., 2014). Calcite or silica is used as granulated carriers, which might be impregnated with a known concentration of microorganisms, favoring storage and subsequent dispersion of the biofertilizer (Swapna et al., 2016). Last but not least, cell encapsulation is possibly the most promising of all, because it employs a polymer to integrate microbial cells/spores/hyphae into a matrix that provides nutrients and protects against variations in pH, humidity, or salinity. There are up to 1350 polymers that have possibilities as carriers, although polyacrylamide and alginate are the most commonly used (Vassilev et al., 2015).

9.4.2 Plant Growth-Promoting Microorganisms Used in Formulations

Biofertilizers are used whilst taking into account the biological activities that can develop the microorganisms that form them; thus, their design and application can be conducted in a targeted manner, depending on the conditions under which the crop is grown (Edi Husen et al., 2007). Due to the different capacities that microorganisms exhibit, we can alleviate crop deficiencies by attending to the microbes composing the biofertilizer ability to fix atmospheric nitrogen, solubilize or mobilize nutrients, or to control biotic or abiotic stresses.

9.4.2.1 Nitrogen Fixation

One of the most limiting elements for optimal agricultural production is nitrogen. For this reason, it is necessary to replenish the nitrogen stock in the soil by the application of external inputs. Some prokaryotes have the ability to fix atmospheric nitrogen and provide it to the plant for the synthesis of amino acids. This process can be carried out by endosymbiotic species, such as those from the genera *Rhizobium*, *Mesorhizobium*, or *Bradyrhizobium*, the latter being used with great assiduity in soybean crops (Vejan et al., 2016). The nitrogen fixation process in leguminous crops occurs by establishing strict symbiotic relationships between plant and host that culminate in the formation of specific structures called nodules where the nitrogen fixation takes part (Haag et al., 2013). This process can contribute an average of 140 kg N per ha per year, which is higher than that from other inputs such as vermicompost or green manures (Franche et al., 2009; Das and Singh, 2014; Tyagi et al., 2014).

In addition, nitrogen fixation can also be performed by bacteria under free-living conditions, being independent of the formation of nodules, as is the case of cereals and other nonleguminous crops (Santi et al., 2013). Formulations based on those free-living nitrogen-fixers are more attractive for biofertilizer markets (Sivasakthivelan and Saranraj, 2013). *Azotobacter, Azospirillum, Bacillus, Beijerinckia, Clostridium, Enterobacter*, and *Pseudomonas* are the most popular bacterial genera (Zandi and Basu, 2016).

Azospirillum is one of the most widely used free-living nitrogen-fixing microorganisms, both in legume and nonlegume crops, with a well-developed technology for its production as an inoculant (Roy et al., 2015; Lesueur et al., 2016). *Azotobacter* is a similar example, with its application being made on legumes and other crops also (Aseri et al., 2008; Ansari et al., 2015). The commercially propagated *Azolla* fern is also used in India because of its association with cyanobacteria genus *Anabaena*, which is able to fix atmospheric nitrogen (Mahdi et al., 2010). This strategy is more effective than the inoculation of free cyanobacteria, since symbiosis induces the proliferation of heterocysts, where nitrogen fixation is carried out (Santi et al., 2013).

9.4.2.2 Nutrient Mobilization and Solubilization

Phosphorus is another element with a special importance in agricultural production; in this aspect, the application of microorganisms is able to maximize the use of the available phosphorus in the soil. The use of bacteria produces better results than the application of fungi, except in the case of mycorrhizae, being able to solubilize 50% of available phosphorus (Chen et al., 2006; Mohammadi and Sohrabi, 2012).

The development of biofertilizers based on microbial consortia with complementary activities—either bacterium–bacterium, bacterium–fungus, or fungus–fungus—is the current trend (Vassilev et al., 2015). Those complementary activities will involve the synthesis of organic acids (lactic, citric, glycolic, succinic, fumaric, malic, oxalic, tartaric), inorganic acids (sulfuric acid), the production of specific enzymes (phosphatases), and chelating agents (Rathi and Gaur, 2016). Amongst phosphate-solubilizing bacteria, the common genera used as inoculants belong to the genera *Lactobacillus*, *Bacillus*, *Pseudomonas, Azotobacter, Beijerinckia, Burkholderia, Enterobacter, Erwinia, Flavobacterium, Microbacterium, Rhizobium*, and *Serratia* (Edi Husen et al., 2007; Bhattacharyya and Jha, 2012; Bhattacharjee and Dey, 2014; Anand et al., 2016; Youssef and Eissa, 2016). In the case of fungi, the genera most commonly used are *Aspergillus, Penicillium, Agaulosposra, Sclerotium, Trichoderma, Rhizophagus, Gigaspora,* and *Glomus* (Ogbo, 2010; Suja et al., 2012; Naher et al., 2013; Abd-Alla et al., 2014; Saxena et al., 2014; Taktek et al., 2015; Anand et al., 2016; Li et al., 2016). However, it is necessary to know more about the bacterial interactions within biofertilizers and with plant hosts to avoid negative reactions, since the combination of nitrogen fixers and phosphate solubilizers does not always generate the desired result (Azimi et al., 2013).

In recent years, the use of microorganisms capable of solubilizing potassium is growing in importance, mainly in the solubilization of micas that are found in soil composition (Velázquez et al., 2016). The species *Acidothiobacillus ferrooxidans, Bacillus edaphicus, Bacillus mucilaginosus, Burkholderia* sp., *Paenibacillus* sp., and *Pseudomonas* sp. are used for this purpose (Gupta et al., 2015, Saha et al., 2016a,b). However, this is not a well-understood feature and its involvement in the production of biofertilizers went unnoticed until a few years ago (Parmar and Sindhu, 2013).

Microorganisms have also shown important qualities to solubilize elements, such as Zn, Cu, Ca, B, or Mo, indirectly through their metabolism, making important quantities of these micronutrients available to plants. In most cases, it is related to the synthesis of organic acids that modify the solubility of the elements. *Glomus*-based inoculant has been shown to have a positive effect on the absorption of Zn or Cu, also reducing the absorption of potentially hazadous elements, such as Pb or Cd (Baum et al., 2015).

9.4.2.3 Organic Compounds Synthesis

Microorganisms are able to produce different substances that improve crop production or affect directly plant development; i.e., siderophores or phytohormones (Lugtenberg and Kamilova, 2009). Whereas phytohormone production is considered as a direct mechanism of plant growth promotion, the production of siderophores has been considered as an indirect mechanism because it limits the accessibility of the iron present in soil (Saha et al., 2016a,b), nevertheless, currently siderophore production is also considered a direct mechanism since it allows the mobilization of this element to plants (Freitas et al., 2015).

Siderophores are organic compounds of varied nature that have the peculiarity of chelating iron, making it available for plants. These compounds are synthesized by both bacteria and fungi and play a prominent role in the biocontrol of phytopathogenic microbes (Chu et al., 2010). Amongst siderophore-producing microbial genera are *Rhizobium, Phyllobacterium, Streptomyces, Pseudomonas,* and *Bacillus* (Flores-Félix et al., 2013, 2015; Sreevidya and Gopalakrishnan, 2015; Złoch et al., 2016).

The production of phytohormones is an extended capacity amongst rhizobacteria, in which the production of auxins, gibberellins (GAs), cytokinins (CK), or abscisic acid (ABA) has been described (Mangmang et al., 2015; Wong et al., 2015). The production of cytokinins, which promotes cell division, has been described in bacterial genera such as *Paenibacillus, Methylobacterium,* or *Bacillus* (Ahemad and Kibret, 2014) and the production of phytohormones like gibberellins and abscisic acid in *Rhizobium, Azospirillum,* and *Bacillus* (Gupta et al., 2015; Vejan et al., 2016). Nevertheless, indole acetic acid (IAA) is perhaps the most studied phytohormone produced by bacteria such as *Rhizobium, Azospirillum, Bacillus,* or *Streptomyces* that generate, amongst other effects, a greater development of the root system, being able to interact with a larger volume of soil (Duca et al., 2014).

Biofertilizers can also act on the crop by enhancing their ability to cope with stress situations. The synthesis of ACC-deaminase, which disrupts the synthesis of ethylene that is synthesized in stress situations, helps to support the stress stages (Glick, 2014). This ability has been described in a wide variety of genera, such as *Acinetobacter, Achromobacter, Agrobacterium, Alcaligenes, Azospirillum, Bacillus, Burkholderia, Enterobacter, Pseudomonas, Ralstonia, Rhizobium, Serratia,* or *Stenotrophomonas* (Ahemad and Kibret, 2014).

Some strains of the genus *Azotobacter,* used as biofertilizers, are able to synthesize vitamins of group B and contribute them to the plant (Mahdi et al., 2010; Pal et al., 2015). This mechanism has also been observed in the application of biofertilizers formulated based on cyanobacteria in wheat (Bhardwaj et al., 2014). The synthesis of other substances such as antibiotics can indirectly contribute to increased production by eliminating biofertilizers and pathogens in the plant (Gupta et al., 2015).

9.5 CONCLUSION

Due to the demands of markets, the production of organic food must increase to meet the needs of consumers. For this reason, farmers must begin to act to improve crop production under organic farming. For this, there is no universal tool applicable to all systems, but the farmer must adapt to the environmental conditions and crop needs through the use of various inputs, giving priority to those whose geographical availability ensures the integration of agricultural activity in the ecosystem. In addition, new technologies for the digestion of livestock or urban byproducts allow the integration of agriculture with the human environment.

We must emphasize that it is the mixed or integrated solutions that generate the best results, because as we have seen there is no perfect input, but the deficiencies of some can be compensated for with the application of others. In this sense, microorganisms play a fundamental role through various mechanisms such as nitrogen fixation or solubilization and nutrient mobilization. In this way, the use of mixed inoculants of several bacterial strains or mixtures of bacteria and fungi generates very attractive results. The efficiency of the applied inputs is improved, favoring the recycling of nutrients and the production of the crop. There are also products, such as charcoal, with very interesting prospects because in addition to providing nutrients to the soil, they can be used as carriers for the application of microorganisms.

Cultivation techniques play a fundamental role in the development of new strategies, especially crop rotations with nitrogen-fixing crops or phosphate mobilizers. Green manure also has a promising future, where an improvement in nutrient availability can be achieved in addition to an improvement in soil structure. Improvement of organic matter is another consequence of management techniques, this will ensure a healthy microbial population, improving crop yields. In these cases, knowing the characteristics in depth of the agricultural system will help the farmer to carry out the actions correctly, using adequate techniques and applying the appropriate inputs.

ACKNOWLEDGMENTS

The authors would like to thank our numerous collaborators and students involved in this research over the years. Funding was provided by Ministerio de Economía, Ciencia Industria y Competitividad (MINECO) through the Projects AGL2015-70510-R and AGL2013-48098-P, by Junta de Castilla y León through the project JCyL SA169U14 and by the Diputación de Salamanca (local government) through the project V113/463AC06. JDFF is funded by a PhD fellowship of Salamanca University; EM was granted a postdoctoral of project AGL2013-48098-P.

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