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MINI-REVIEW

Recent advancements for microorganisms and their natural compounds useful in agriculture

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Abstract

During the past years, microorganisms have been the cause of many problems for human's health. However, today with the development of many techniques of microbiology, the researchers have studied several roles of microorganisms which may help the society. Microbial-based products are expected to play important role in agriculture-enhancing plant production and therefore increasing crop's yieldeswani et al. . Microorganisms can act by several action mechanisms including antibiosis or mechanisms in plant-microbe interactions underlining the dual function of microbial strains toward plant nutrition and protection. The market has increased with the development of microbial-based products. Currently, it is normal to think that microorganisms help us in agriculture by applying them as biological control. In this mini review, we collect the last findings about this topic including very recent literature.

Key points

- *Microorganisms play a beneficial role in agriculture by different mechanisms.*
- *One of these mechanisms is the secretion of chemical compounds with different activities.*

Keywords Microbial-based products · Biofertilizers · Biopesticides · Plant growth–promoting rhizobacteria

Introduction

The worldwide population is increasing, and a sustainable agricultural production is needed to maintain the world population demand. However, overexploitation of the crops has led to the use of chemical fertilizers and pesticides which have caused an environmental contamination accompanied by human health risks. Current global vision is more environmentally friendly, and the use of eco-friendly alternatives is desirable. Keeping in mind that beneficial microorganisms can help us to improve agricultural production worldwide, in the last years, the research has turned to this group of microorganisms. But, it is imperative firstly to know the interactions that occur between plants and microorganisms.

People are used to think about microorganisms in a negative way since many of them cause health problems in human beings or are the reason why thousands of crops are spoiled causing serious economic losses (Sarmah et al. 2018). However, today, the science has guided the research toward the "friendly or positive microorganisms" which are microorganisms that offer advantages without causing problems (Kowalska et al. 2020). There are two main problems affecting crops such as plant pathogens and pests. Useful microorganism can be grouped in two main groups. To fight against pest and diseases caused by plant pathogens, integrated pest management through the biological control agents (BCAs) plays an important role to protect the crops controlling the pests. On the other hand, we can find plant growth–promoting rhizobacteria (PGPR) which are soil-borne bacteria, isolated from rhizosphere with the capacity to enhance the growth of the plant (Singh et al. 2019).

The microorganisms are living organisms that like humans make the basic metabolic activities to live such as eat, have a metabolism, and secrete substances. These secreted substances are chemical compounds which we can use for our benefit. Therefore, we can think of microorganisms as little chemical factories producing a wide range of chemical

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compounds with beneficial effects in our lives (Keswani et al. 2019a; Ortiz and Sansinenea 2019).

The chemical compounds produced by these microorganisms can be antibiotics against multidrug-resistant bacteria or antifungals against some phytopathogens which cause crop diseases or compounds that promote the growth of a plant (Keswani et al. 2020b). Therefore, many microorganisms such as fungi or bacteria are useful in agriculture since they are attractive eco-friendly alternatives to further applications of mineral fertilizers and chemical pesticides. In this way, beneficial microorganisms can help to improve agricultural production worldwide (Singh et al. 2019). These microorganisms help the crops by fighting against harmful bacteria and fungi, and they are the source of providing nutrition to the crops.

In recent decades, the focus on crop production has moved from yield to quality and safety, then more recently sustainability. Integrated crop management (ICM) is a pragmatic approach to crop production which includes integrated pest management (IPM) focusing on crop protection. While considering pest and disease management, the use of biological control methods is considered to complement physical and cultural methods. In this context, biopesticides are formulations made from naturally occurring substances that control pests by non-toxic mechanisms and in an ecofriendly manner.

Therefore, biopesticides, which consist natural compounds from microorganisms, the microorganism themselves, or genetic material that has been incorporated to the plants to produce pesticidal substances, are applied to control pests. The specific mechanism that they use is varied, the production of toxic natural compounds being one of the most studied (Sansinenea 2019a). These compounds are interesting to develop since they have a great potential in a growing market. In recent years, there has been a lot of research about the beneficial microorganism for the agriculture; therefore, in this mini review, we have cited some of the latest works about this interesting topic. This mini review is a compilation of some very recent works and reviews focusing on microorganisms that have been applied to agriculture with special emphasis in *Bacillus* sp. since this genus has been the most used in agriculture and contains *B. thuringiensis* as one of the best-known and studied entomopathogenic bacterium that has been extensively applied in agriculture.

The way the good microorganisms act in agriculture

The world population is increasing, and this implies that the improvement of agriculture is necessary to increase the crops yield. Chemical fertilizers have been the most used method to achieve this improvement; however, their continuous and excessive use has led to environment contamination causing a great damage to the ecology and creating pest resistance and health problems leading to a reduction of crop yield (Youssef and Eissa 2014). Biofertilizers can replace chemical fertilizers to increase crop production in a green manner. “Biofertilizer” is a substance that contains living microorganism which when applied to seed, plant surfaces, or soil colonizes the rhizosphere or the interior of the plant and promotes growth by increasing the supply or availability of primary nutrients to the host plant (Bhattacharjee and Dey 2014). Biofertilizers add nutrients through the natural processes of fixing atmospheric nitrogen, solubilizing phosphorus, and stimulating plant growth through the synthesis of growth-promoting substances (Malusá et al. 2016). They can be grouped in different ways based on their nature and function.

In this sense, we can find PGPR, which are a group of bacteria that colonize the roots of plants enhancing the growth of these plants by producing plant hormones or secondary metabolites, controlling diseases, forcing an induction of systemic resistance, or through changing physicochemical interactions with plants (Keswani et al. 2019c). There are many PGPR that have been studied in the last decades such as *Rhizobia*, *Mycorrhizae*, *Azospirillum*, *Bacillus*, *Pseudomonas*, *Trichoderma*, and *Streptomyces* species (Backer et al. 2018). *Bacillus* can act using different direct and indirect mechanisms, which can be acting simultaneously in the plant growth. The direct mechanisms include their ability to obtain nutrient supply such as nitrogen, phosphorus, potassium, and minerals or modulating plant hormone levels. The indirect mechanisms include the secretion of antagonistic substances to inhibit plant pathogens, or the induction of resistance to pathogens (Sansinenea 2019b), as shown in Fig. 1.

Another strategy that has been successfully applied during the last years has involved biological control organisms whose formulations have been available commercially to control diseases in agricultural and horticultural crops. One of the most known examples is *B. thuringiensis* an entomopathogenic bacterium used by some decades as natural biopesticide (Sansinenea 2012). Several bacteria and fungi ubiquitous in different soils are known to assist plant growth by mobilization of insoluble forms of potassium (Meena et al. 2014; Ortiz and Sansinenea 2020) being *Bacillus* sp. the most used in agriculture to control insects and plant pathogens. *Bacillus* spp. have been widely used on biopesticide market around the world because of its capacity to produce many important products for food, pharmaceutical, environmental, and agricultural industries with high impact in human activities. Recent studies have shown that these aerobic spore formers can produce fine chemicals with interesting biotechnological applications that open perspectives for new biotechnological applications of *Bacillus* and related species. The members of the genus *Bacillus* are often considered as microbial factories to produce a vast array of biologically active molecules, some of which are potentially inhibitory for fungal growth, as

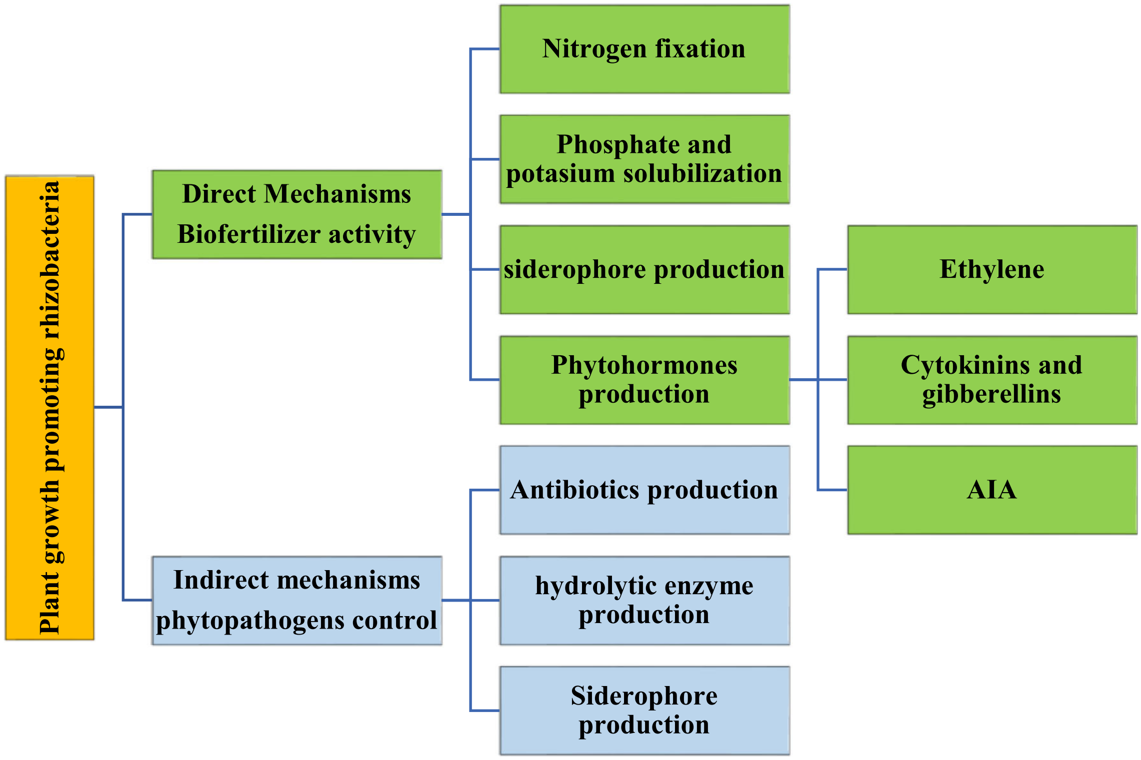

Fig. 1 Mechanisms by which PGPR affect plant growth (taken from Sansinenea 2019b)

shown in Fig. 2 (Ortiz and Sansinenea 2019). Many antifungal compounds isolated from these bacteria have been identified such as mycobacillins, iturins, plistatins, bacillomycins, surfactins, mycosubtilins, fungistatins, zwittermicin, and macrolactins among others (Sansinenea 2020).

The beneficial microorganisms improve soil quality, soil health, and the growth, yield, as well as quality of crops. This improvement is through producing bioactive substances such as hormones (Keswani et al. 2020a) and enzymes, controlling soil diseases, and accelerating decomposition of lignin materials in the soil promoting the plant growth. These effects are due to the chemical compounds secreted by microorganisms (Keswani et al. 2014, 2019a, b, 2020b). These substances act through different mechanisms which include induction of the plant innate immune response system (Jain et al. 2011) or acquired systemic resistance (Choudhary and Johri 2009; Iavicoli et al. 2003), alteration of plant functional traits (Friesen et al. 2011), and prevention of pathogen settling secreting antifungal compounds (Bakker et al. 2012).

The growth promotion in bacteria derives mainly from the synthesis of several plant growth hormones (Radhakrishnan and Lee 2016; Keswani et al. 2020a) or their indirect regulation through production of volatile organic compounds (Tahir et al. 2017; Rath et al. 2018) and 1-aminocyclopropane-1-carboxylate deaminase (Glick et al. 2007), as well as the solubilization or mineralization of mineral nutrients (Malusá et al. 2016; Ortiz and Sansinenea 2020).

As we have mentioned, among the exploited bacteria for protection against pathogens, *Bacillus* genus has commercial use and frequently is exploited also for plant growth promotion (Fan et al. 2018). A rich literature exists on this genus of bacteria (Ortiz and Sansinenea 2019). The secondary metabolism of *Bacillus* sp. is very rich to produce antimicrobials such as some lipopeptides and other compounds which function as antifungals against many phytopathogens that cause economic losses in agricultural crops (Salazar et al. 2020), as shown in Table 1.

Many commercial products have been marketed as biofungicides which are based on various *Bacillus* species such as *B. amyloliquefaciens*, *B. licheniformis*, *B. pumilus*, and *B. subtilis* (Fravel 2005). They are employed to control fungal diseases. For example, *Bacillus subtilis* B246 was commercially registered as Avogreen and used as a biocontrol agent against avocado pre- and postharvest anthracnose disease. The formulated product resulted in significant control of anthracnose caused by *Colletotrichum gloeosporioides* fungus (Demoz and Korsten 2006). Ballad Plus and Sonata were two marketed products from Bayer CropScience based on *B. pumilus* (strain QST 2808). Ballad Plus and Sonata produce an antifungal amino sugar compound which disrupts cell metabolism and destroys cell walls, killing plant pathogens (Serrano et al. 2013). The product line RhizoVital offers a range of biostimulating microbial inoculants, containing spores of the naturally occurring soil bacteria *Bacillus*

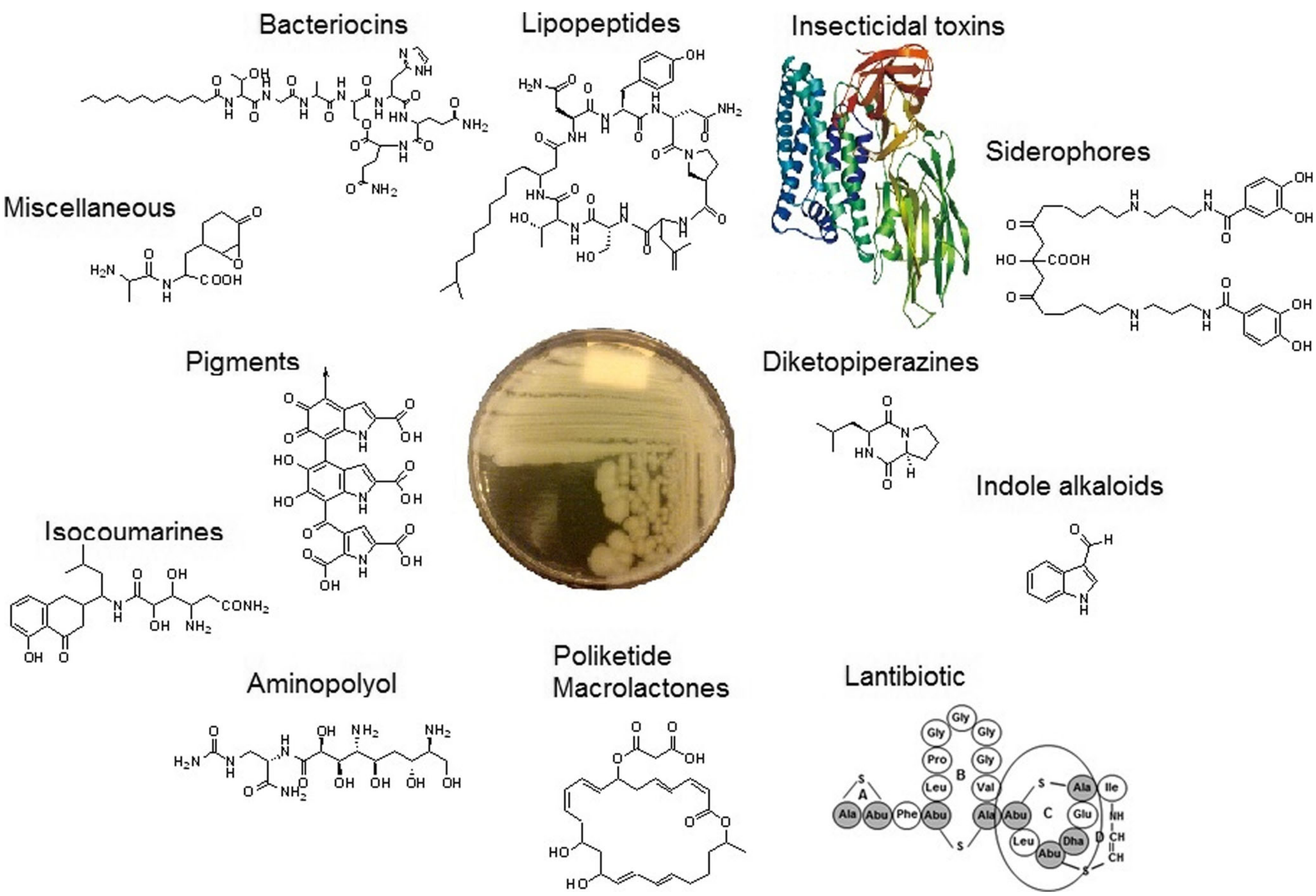

Fig. 2 Chemical compounds isolated from *Bacillus* sp.

velezensis (synonym *B. amyloliquefaciens* ssp. *plantarum*) or *Bacillus atrophaeus*. It is successfully commercialized as biofertilizer by AbiTEP GmbH (Chowdhury et al. 2013).

Conclusions and future perspectives

A sustainable agriculture is desirable since chemical pesticides that improve the crops have caused critical damages to environment and human health. The potential function of plant growth–promoting rhizobacteria in biological control has been long known. Since then, many studies have allowed to characterize the process of root colonization and the biotic and abiotic factors that are affecting it as well as the identification of genes and traits in bacterial fitness underlying the mechanisms of pathogen suppression (Islam et al. 2019). However, notwithstanding this knowledge, the major difficulties and weakness in a broad use of PGPR strains in agricultural practices reside in formulation and registration of the bacteria for commercial use (Bashan et al. 2014; Borriss 2020).

Several studies have demonstrated that PGPR-based formulations improve the growth attributes of the subjected plant such as shoot elongation, yield, plant biomass, seed germination, seedling vigor, plant height, fresh and dry weight, and leaf area of economically important crops, including rice, tomato, soya bean, and wheat (Tabassum et al. 2017; Backer et al. 2018). PGPR-based formulations not only help protect plants from several pathogens by acting as biocontrol agents but also trigger different biological promotion effects in various plant-growth parameters. Effective utilization of PGPR for disease reduction or crop protection in the future will demand a rational choice of organism as well as technical improvements in up scaling and formulation techniques.

It is known that many microbial-based products present on the market have been designed for some common crops such as legumes and cereals; however, there is an increasing demand for these products in fruit and vegetable crops. Mineral fertilizers can be partially replaced by biofertilizers (Saeid and Chojnacka 2019), improving plant protection green strategies and contributing with environmentally safe alternatives. However, extreme care must be taken in the production and

Table 1 Secondary metabolites of *Bacillus* sp. with beneficial effect on plants

Structural class of compounds	Source	Biological activity	Reference
Cyclic lipopeptides	*B. subtilis* *B. amyloliquefaciens* *B. licheniformis* *B. pumilus* *B. subtilis*	Antifungal	Ortiz and Sansinenea (2019)
Insecticidal toxins	*B. thuringiensis*	Insecticidal	Sansinenea (2012)
Siderophore	*B. cereus* *B. subtilis* *B. anthracis*	Iron chelators	Ortiz and Sansinenea (2019)
Diketopiperazines	*B. thuringiensis*	Growth promotors	Ortiz and Sansinenea (2019)
Indole alkaloids	*B. pumilus* *B. velezensis* *B. thuringiensis*	Antifungal	Vaca et al. (2020)
Polyketide macrolactone	*B. amyloliquefaciens* *B. subtilis*	Antifungal	Salazar et al. (2020)
Aminopolyol	*B. cereus* *B. thuringiensis*	Bactericidal	Ortiz and Sansinenea (2019)
Pigment	*B. thuringiensis*	UV protector	Ortiz and Sansinenea (2019)
Miscellaneous	*B. subtilis*	Antifungal, antibacterial	Ortiz and Sansinenea (2019)
Succinic acid	*B. megaterium*	Phosphate solubilizing	Ortiz and Sansinenea (2020)

the marketing of these microbial-based products to ensure that they comply with safety assessment (Keswani et al. 2019b; Singh et al. 2016). There are a great variety of genera and species which have been identified as beneficial for the plant growth; however, there is a limited number of them that have been marketed as biofertilizers (Umesha et al. 2018). This point is a limitation for the use of biofertilizers that is worth to mention. The lack of an adequate legislation and the care that needs to be taken in consideration in order to liberate the biopesticides to the environment make its market slowly expand.

The variability of the chemical structures of the secreted compounds has led the chemists and pharmaceutical industry to search new compounds in microbial extracts. There are many recent works reporting the isolation of new compounds with antifungal properties; however, many of them require more research to apply on crops since they have to fill safety assessments. Besides, some compounds act in synergism between them when the microorganisms are applied as biopesticides; however, when the compounds are isolated and individually probed, the biological efficacy is moderate in the best cases. The quantity or the stability of the isolated compounds is another problem that has caused a delay in the development of the natural compounds with potential to use in agriculture.

In this sense, the *Bacillus* species have been extensively used in agriculture as biocontrol agent using several mechanisms to promote plant growth. The last decades have been successfully exploited and commercialized applying them to several crops against several plant pathogens. Some problems have to be overcome to improve their efficacy. Currently, the regulatory procedures for the registration and commercialization of biostimulants are complex. Genetic engineering has been a modern technique to accentuate these mechanisms; however, it is necessary to control the commercialized products, their results and risk evaluation, for the better employment of these products. There is even a need for methods of optimization of fermentation and formulation processes to improve their introduction in agriculture industry. Every step in the process from microbe isolation to licensing is laborious, expensive, and requires time. Collaboration among industrial, academic, and government research should become an important part of the product development process.

This topic has opened the door of a great field to study beneficial microorganisms and the mechanisms by which they act improving the crop yield and growth. A continued exploration of the natural biodiversity of soil microorganisms and the manipulation of microbial interactions in the rhizosphere of crops represent a prerequisite step to develop more efficient microbial inoculants. The study of the compounds that are secreted by beneficial microorganisms and the impact of them in plants or plant pathogens is a fundamental component. The future is exciting in this sense; the discovery of new strains with potential to apply in agriculture is an interesting challenge.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors.

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