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Biopesticides and sustainable agriculture: an overview

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Abstract

The rapid evolution of the world's population has led various countries to apply modern technologies in agricultural sector in order to meet local demands. These technologies include chemical pesticides. The use of these pesticides has later led to several effects on both the environment and human ecology. The production of healthy food through sustainable agriculture without polluting the environment has becomes a necessity. Biopesticides are emerging as the best alternative to fight chemical pesticides for sustainable agriculture. Biopesticides are pesticides that are extracted from plants, animals or microorganisms. They are non-toxic in nature and provide better integrated pest management. Ensuring food and nutritional security for a growing world population is a major concern, especially when the productivity factor is declining while the environmental pollution is increasing in limited natural resources. Sustainable agriculture in such situations appears to be a viable option. Sustainable agriculture systems are those systems that are economically viable and provide nutritious and safe food with the maintenance of natural resources for present and future generations. In this context, biopesticides appear to be the answer to all these expectations.

Keywords : Biospesticides, Sustainable agriculture, Chemical pesticides

Résumé

L'évolution rapide de la population mondiale a conduit divers pays à appliquer des technologies modernes dans le secteur agricole afin de répondre à la demande locale. Ces technologies incluent les pesticides chimiques. L'utilisation de ces pesticides a ensuite entraîné plusieurs effets néfastes sur l'environnement, l'écologie humaine et l'écologie tout entière. La production d'aliments sains par le biais d'une agriculture durable sans polluer l'environnement devient donc une nécessité. Les biopesticides apparaissent comme la meilleure alternative pour lutter contre les pesticides chimiques pour une agriculture durable. Les biopesticides sont des pesticides qui sont extraits de plantes, d'animaux ou de micro-organismes. Ils sont non toxiques par nature et permettent une meilleure gestion intégrée des nuisibles. Assurer la sécurité alimentaire et nutritionnelle d'une population mondiale croissante est une préoccupation majeure, surtout lorsque la pollution environnementale augmente et que les ressources naturelles sont limitées. Dans de telles situations, l'agriculture durable apparaît comme une option viable. Les systèmes d'agriculture durable sont ceux qui sont économiquement viables et qui fournissent des aliments nutritifs et sûrs tout en préservant les ressources naturelles pour les générations actuelles et futures. Dans ce contexte, les biopesticides semblent être la réponse à toutes ces attentes.

Mots clés : biopesticides, agriculture durable, pesticide chimique

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Introduction

The world population is likely to increase from 7.3 billion to 9.8 billion in 2050, with most of the increase coming from developing regions (FAO, 2017). The population of low-income countries could double to 1.4 billion. Feeding humanity will require a 50 per cent increase in the production of food and other agricultural commodities between 2012 and 2050 (FAO, 2017).

Agriculture is major to achieve food security, reducing poverty and conserving vital natural resources on which the world's current and future generations will depend entirely for their survival and well-being (Dhakal and Sing, 2019). Before 19th century, most of the world's food was produced organically using organic manure, human and animal potential. Agriculture and its related sectors represent a real economic driver for most developing countries and contributing more than 30% of their Gross Domestic Product (GDP) (FAO, 2017).

In some countries, such as India, agriculture represents the livelihood for more than 58% of the population (Kamat and Rajendra, 2016). However, the rapid increase in the human population has necessitated the use of modern technologies in the agricultural production system. Modern agriculture, which depends largely on the extensive use of external inputs such as hybrid seeds, fertilizers and pesticides for better production, has been of great help in alleviating world hunger over the last century (Kumar et al., 2019). This has led to the emergence of several second-generation problems such as declining productivity, increasing multiple nutrient deficiencies in the soil and increasing environmental pollution. The over use of chemical pesticides to improve agricultural productivity without taking into account their harmful effects has led to a lot of damage. These include insecticide resistance problems of some major crop pests (Kranthi et al., 2002; Mishra et al., 2015), resurgence of minor pests and high levels of pesticide residues in the environment and food, pesticide poisoning and death due to organ dysfunction, neurotoxicity, impaired reproductive function, carcinogenicity, paralysis and damage to flora and fauna (Dhakal and Singh, 2019). To solve this problem, several traditional chemical pesticides have been withdrawn from use as a result of environmental and health concerns (Damalas and Eleftherohorinos, 2011). In France for example, measures had been taken to control the use of plant protection products. Thus, the "Ecophyto 2018" plan discussed during the 2007 Grenelle Environment Round Table, aimed to reduce the quantity of chemical-based plant protection products by 50% until 2018 (Deravel et al., 2014). In October 2015, 32 pesticide active ingredients were forbidden from manufacture, import and use, 8 others withdrawn from the Indian market and 13 more restricted in their use (Kumar et al., 2019). In Belgium, a Pesticides and Biocides Reduction Programme (PRPB) was established in 2005. This programme should cover the period from 2005 to 2010 and would aim to reduce the environmental impact of agricultural pesticides by 25% by the year 2012 and the environmental impact of other pesticides and biocides by 50% (Deravel et al., 2014).

The need to promote environmentally exemplary agricultural activities is a prerequisite for a better future for agriculture (Bachelier, 2008). The effects of chemical pesticides have therefore encouraged research on alternatives for sustainable agriculture. Consequently, there is a great need to develop effective, biodegradable and ecological methods. Priority should be given to the use of other environmentally and human health-friendly control methods to avoid the adverse effects of chemical insecticides (Pathak et al., 2017), hence the concept of biopesticides. This literature review provides an overview of the use of biopesticides in agriculture, their benefits and prospects for sustainable agriculture.

Origin and diversification of biopesticides

Biopesticides are certain types of pesticides derived from natural materials such as microorganisms, plants, animals and certain minerals (Pathak et al., 2017). For example, canola oil, neem oil and baking soda have pesticidal applications and are considered biopesticides.

Biopesticides were originally designed to control crop pests. They are living organisms (natural enemies) or their products (phytochemicals/ botanical pesticides, microbials or by-products) that can be used for the management of pests that are harmful to crop through non-toxic mechanisms (Pathak et al., 2017). Today, the biopesticide concept goes beyond the limits of crop protection but concerned also with food security.

Microbial biopesticides

Microorganisms used as biocontrol agents and marketed as biopesticides include bacteria, fungi, viruses, nematodes and protozoa (Lengai and Muthomi, 2018). These microorganisms have efficacy and safety for humans and other non-target organisms. They are ecologically safe, leading to the preservation of natural enemies, and promoting the enhancement of biodiversity in the managed ecosystem (Pathak et al., 2017). Thus, the microbial agents are highly specific against the target pests and facilitate the survival of beneficial insects in treated crops. For this reason, microbial insecticides have been developed as biological control agents over the last three decades (Pathak et al., 2017). Until 2014, 175 microbial biopesticides have been identified for the control of pathogens, weeds, crop insect pests and nematodes (Singh, 2014).

Bacterial biopesticides

The bacteria used in the production of biopesticides include the genera Bacillus, Pseudomonas, Burkholderia, Xanthomonas, Enterobacter, Streptomyces and Serratia. Bacterial biopesticides represent 74% of the global market for microbial biopesticides (O'Brien et al., 2009). Those based on Bacillus thuringiensis are the most commercialized because of their insecticidal action (Deravel et al., 2014). Most bacteria use several mechanisms such as hyperparasitism, competition, production of volatile compounds, parasitism or by antibiosis to colonize their hosts. In the case of Gram-positive *B. thuringiensis* bacterium, the insecticidal activity of this bacterium relies on the biosynthesis of crystalline proteins called delta-endotoxins or protoxins (Cry and Cyt) associated with parasitic bodies produced during the sporulation phase and other toxins and virulence factors, some of which are produced and released by the vegetative growth phase cell (VIP) (Rosas-Garcia, 2009; Ruiu, 2018). Variation in toxin gene sequences results in different affinity with receptors in the midgut of insects, so that different strains are characterized by different insecticidal protein toxins and strain-specific insecticidal properties (Pigott and Ellar, 2007). Therefore, different strains of Bt are only effective against a narrow target. After ingestion, these toxins specifically bind to receptors in the midgut of insects, triggering a pore-forming process that determines the alteration of epithelial membrane permeability with consequent disruption of intestinal barrier functions and possible bacterial septicaemia leading to insect death (Ruiu, 2018). A similar mechanism is associated with the species *Lysinibacillus sphaericus* (formerly *Bacillus sphaericus*) which acts against mosquitoes and black flies through the production of complementary crystalline proteins BinA and BinB, and Mtx mosquito toxins (Ruiu, 2018). Bacterial species of the genus Bacillus with mechanisms of action other than that employed by B. thuringiensis can also protect plants. These include strains of Bacillus licheniformis, *Bacillus amyloliquefaciens* or *Bacillus subtilis*. *B. amyloliquefaciens* and *B. subtilis* are able to colonize plant roots and produce molecules of a lipopeptide nature, which are surfactins, iturins and fengycins (Deravel et al., 2014).

The latter can either activate plant defences or have a direct antibacterial or antifungal effect (Pérez-Garcia et al., 2011). Studies by Beric et al. (2012) reported that Bacillus isolates showed antagonistic activity against the rice pathogen, Xanthomonas oryzae p.v. oryzae, and the activity was attributed to the production of a bacteriocin by the bacterium. Bacteria belonging to genera other than Bacillus have

also been developed as biopesticides. This is the case of *Pseudomonas chlororaphis MA342*, which protects wheat and rye against fusarium and septoria. Several modes of action are proposed to justify its efficacy (Deravel et al., 2014). This bacterium could act against phytopathogenic fungi by direct antibiosis, by spatial and nutrient competition or by activating plant defences (Boulon, 2010).
Gammaproteobacteria represent a heterogeneous group of species including several entomopathogens such as endosymbiotes of insecticidal nematodes, Photorhabdus, Xenorhabdus and Serratia whose insecticidal action is a toxin-mediated process (French-Constant and Waterfield, 2006). The same group includes the non-spore-forming species *Yersinia entomophaga* producing the Yen-Tc complex toxin, containing toxins and chitinases, and *Pseudomonas entomophila* containing a toxin secretion system, both acting by ingestion (Landsberg et al., 2011).

Fungal biopesticides
In addition to bacteria and viruses, some fungi have activities against bio-aggressors and are exploited as biopesticides. Fungi used as biopesticides include species of the genera Trichoderma, Beauveria, Metarhizium, Paecilomyces, Fusarium, Pythium, Penicillim and Verticillium. Steinernama and Heterarhabditis are genera of nematodes used for biopesticide production (Ruiu, 2018). A study carried out by Adan et al. (2015) showed that a Trichoderma harzianum formulation prepared in black with gram bran, peat soil and water had a high level of activity against damping-off of garden eggs seedlings caused by Sclerotium rolsfii. This activity was attributed to the high number of spores produced by the fungus. Coniothyrium minitans is known to parasitize fungi of the genus Sclerotinia spp. This fungal genus is found in the soil and causes a disease called white rot that can affect many crops including carrots, beans, rapeseed and sunflowers (Deravel et al., 2014). C. minitans is known to enter Sclerotinia sclerotiorum either through cracks located on the outside of this form of the fungus or by entering through the outer bark following an intercellular pathway (Deravel et al., 2014). It then continues its intracellular way by penetrating the cortex and medullary. Treatment of wheat and rice crop with concentrations of Chaetomium globosum reduced the severity of wheat rust (Puccinia recondite) and rice blast (Magnaporthe grisea) by up to 80% (Park et al., 2005). Downy mildew (Phytophthora infestans) on tomato was also controlled by Chaetomium globosum by up to 50 % while the mycelial growth of Pythium ultimum was inhibited in vitro in well diffusion assays. The activity of the fungus was attributed to the production of two types of chaetoviridins A and B (Park et al., 2005). Several strains of the filamentous fungus of the genus Trichoderma spp. are used for biological plant protection. They generally have antifungal activity against several soil pathogens or against foliar pathogens. In particular, Trichoderma atroviride is used for the biological protection of grapevine (Longa et al., 2009). The biocontrol activity of this strain is attributed to several mechanisms of action that act synergistically. These mechanisms of action include competition for nutrients, antibiotics, or the production of specific cell wall degradation enzymes such as chitinases or proteases (Brunner et al., 2005). By causing total crop losses estimated at nearly 10%, nematodes of the genus Meloidogyne spp. are the most destructive in the world (Anastasiadis et al., 2008). The chemical nematicides most effective against them have been progressively withdrawn from the market because of their impact on the environment (Anastasiadis et al., 2008). The fungus Paecilomyces lilacinus is one of the most studied alternative products in biological control of these nematodes. It has the capacity to infest several stages of parasite development (Deravel et al., 2014). It is particularly known to have ovicidal properties. *P. lilacinus* in nematode eggs by secreting chitinases and proteases (Dong et al., 2007). According to Prasad and Syed (2010), exposure of Helicoverpa armigera to suspended conidia of Beauveria bassiana resulted in anti-

breeding habits, blackening of the body and the larvae becoming slow and morbid. The fungus finally consumes the entire larval tissue, resulting in its death.
The pathogenic action of fungal biopesticides depends on contact and, they infect and kill insect pests such as aphids, mealybugs, whiteflies, scale insects, mosquitoes and all types of mites (Koul, 2011). Some fungi, mainly streptomycetes, also produce toxins that act against insects (Dowd, 2002). Approximately 50 of these compounds have been reported to be active against various insect species belonging to lepidoptera, homoptera, beetles, orthoptera and mites (Dowd, 2002).
The most active toxins are actinomycin A, cycloheximide and novobiocin. Beauveria bassiana is one of the most widely used fungal bioinsecticides and was the first example of microbial control of insects in the late 19th century (Ruiu, 2018). In the same genus, B. bassiana and strains of B. brongniartii showing varying levels of virulence against various targets are now used as active ingredients in various formulations (Zimmermann, 2007). A limitation in the use of fungal biopesticides is their contact action and a strict range of conditions for conidia and spore germination (Vega et al., 2012).

Viral biopesticides

Insect-specific viruses can be very effective for the natural control of several caterpillar pests (Pathak et al., 2017). Insect viruses must be eaten by an insect to cause infection but can also spread from insect to insect during oviposition or mating (Pathak et al., 2017).
The group of viruses generally used in biopesticide formulations is baculoviruses. Species of the family Baculoviridae represent DNA viruses that establish pathogenic relationships with invertebrates and show potential for biological control (Haase et al., 2015). Viral infection is associated with the production of crystalline occlusion bodies, containing infectious particles, in the host cell. Based on the morphology of these inclusion bodies, baculoviruses are divided into two main groups: nucleopolyhedra (NPV), in which these bodies are polyhedral and develop into cell nuclei, and granuloviruses (GV), in which these bodies are granular (Ruiu, 2018). Inclusion bodies are composed of crystalline proteins that protect the virions from degradation by the environment, but are dissolved by the alkaline pH of the stomach of the larvae (Deravel et al., 2014). Once the crystalline proteins are dissolved, the virions are released. The primary infection that begins in the midgut produces budding forms that progress from the basement membrane to the host tissues. During this progression, budding and included virion forms are produced. Propagation takes about 4 days. Tissues die and liquefy.
Baculoviruses act orally against insects, and the first infection normally occurs after ingestion of contaminated food (Ruiu, 2018). Inclusion bodies ingested in the midgut environment are specific for the release of typical virions, called occlusion derived viruses (ODVs), which interact directly with the membrane of microvillar epithelial cells through the action of their envelope proteins (i.e., FIPs) (Ruiu, 2018). However, their efficacy can be enhanced by the use of formulations that include stilbene-derived optical brighteners, which increase susceptibility to NPV infection by disrupting the peritrophic membrane (Dougherty et al., 2006), by inhibiting by desquamation or virus-induced apoptosis in the midgut of insect cells (Koul, 2011). Infected nuclei can produce hundreds of polyhedra and thousands of granules per cell.
These can create enzymes to deplete the pest's population and ultimately have a significant impact on the economic threshold of the latter (Koul, 2011). Baculoviruses are specific rod-like viruses that can destroy and infect a number of important plant pests. They are effective against lepidopteran pests of cotton, rice and vegetables (Pathak et al., 2017).

Nematode-based biopesticides

Insect pathogenic nematodes normally enter the host through its natural openings (cavity, anus and spiracles) and release their symbiotic bacteria into the haemocele (Ruiu, 2018). The proliferation of bacteria is followed by the release of toxins and virulence factors that weaken the host, and by the production of metabolites that promote the creation of an environment conducive to nematode reproduction (Ruiu, 2018). Nematodes commonly used in pest management belong to the genera Steinernema and Heterorhabditis, which due to their mutual symbiosis with insect pathogenic bacteria attack hosts in the juvenile stage (Koul, 2011). Nematodes can live up to three generations within the host, after which they leave the body to find new hosts (Koul, 2011). Entomopathogenic nematodes (NEPs) can be mass-produced in vivo and in vitro by solid or liquid fermentation. Among other virulence factors, Photorhabdus and Xenorhabdus species produce a complex of insecticidal toxins (Tc), comprising different subunits that exhibit toxicity against insects by ingestion (Ffrench-Constant et al., 2007). A variety of improved in vivo and in vitro methods for small- and large-scale nematode production have been developed. The quality of the final formulation plays a major role in the efficacy of nematode-based biological control applications against pests (Shapiro-Ilan et al., 2012). However, further research is needed to optimize application parameters and develop effective strains to achieve significant pest control by nematodes.

Biopesticides based on protozoa

The use of protozoa as biopesticides has not been very effective although they naturally infect a wide range of pests by inducing chronic effects that reduce their target populations (Pathak et al., 2017). Microspore protozoa have been studied as extensively as possible as components of integrated pest management programmes. Ubiquitous microsporidia and obligate intracellular parasites are pathogens for several insect species (Koul, 2011). Two genera, Nosema and Vairimorpha, have potential when attacking lepidopterans and orthopterans and appear to cause hopper death more than any other insect (Lewis, 2002).

In the case of maize, spores from infected midgut cells are discharged into the lumen, and are eliminated with the excrement of the maize plant. The spores remain viable and are consumed during larval feeding, and the infection cycle is repeated for the next generation (Pathak et al., 2017). Vertical transmission occurs when a female larva (Nosema) is infected and transmitted to the filial generation.

As the infected larva matures to form an adult, ovarian tissue and developing oocytes become infected with Nosema pyrausta. The embryo is infected in the yolk, and when the larvae hatch, they are infected with N. pyrausta causing horizontal and vertical transmission in natural corn borer populations (Koul, 2011). The only protozoan that has been registered for use as a biopesticide is the microsporidian Nosema locustae. This organism is most effective when ingested by the pupal stages of grasshoppers and kills them within 3 to 6 weeks of infection (Pathak et al., 2017).

Plant biopesticides

Plants produce active substances with insecticidal, aseptic or plant and insect growth regulating properties. Most often, these active substances are secondary metabolites that originally protect plants from herbivores (Deravel et al., 2014). Plant biopesticides or botanical pesticides can be defined as plant extracts or essential oils depending on the method of extraction (Vidyasagar and Tabassum, 2013). They are obtained from plant parts such as leaves, bark, flowers, roots, rhizomes, bulbs, seeds, cloves or fruits that are fresh or dried. Dried plant parts are preferred as this reduces the water concentration resulting in a higher yield of active ingredient (Chougule and Andoji, 2016). Gas chromatography coupled with mass spectrometry (GC-MS) analysis on Citrus sinensis showed that d-limonene and myrcene were the main components of the oil (Lengai and Muthomi, 2018). The products were tested against a cereal beetle (Oulema melanopus) on wheat and mortality of up to 85% was reported on larvae observed within 48 h (Zarubova et al., 2018). Aqueous fruit extracts of Withania somnifera were tested for activity against Fusarium oxysporum f.sp. radicis-lycopersici, the causal agent of Fusarium disease and root rot in tomatoes. At a concentration of 2 %, extracts of this fruit inhibited the growth of the fungal pathogen by up to 56% in vitro (Lengai and Muthomi, 2018). Azarachtine, a mixture of seven isomers of tetranortritarpinoid, is the main active ingredient in neem oil and has the property of disrupting insect morphogenesis and embryonic development (Correia et al., 2013). Studies by Mboussi et al. (2018) reduced the incidence of cocoa mirids. Indeed, these authors showed that the activities of mirids were inhibited for eight (8) days after the application of aqueous extracts of Thevetia peruviana and Azadirachta indica. The plant Tanacetum (Chrysanthemum) cinerariaefolium, more commonly known as pyrethrum, is a perennial herbaceous plant, whose flowers contain active ingredients, called pyrethrins, which attack the nervous system of all insects (Sellami et al., 2015).

Turmeric (Curcuma longa) is thought to be the most effective with growth inhibition of up to 73% against Alternaria solani. Pseudomonas syringae p.v. tomato was effectively managed in vitro by Rhus coriaria, Eucalyptus globulus and Rosmarinus officinalis (Bastas, 2015). Eucalyptus globulus was effective in preventing bacterial spot of tomato (Pseudomonas syringae p.v. tomato) up to 65% in glasshouses (Lengai and Muthomi, 2018). At 5% concentration, mortality of up to 78% has been reported in juveniles of root-knot nematodes (Meloidogyne sp) by extracts of Nerium oleander. When the concentration was increased to 10 %, 65 % to 100 % mortality was observed in the second stage of juveniles treated with extracts of Eucalyptus sp, Cinnamomum verum, Nerium oleander, Azadirachta indica, Zingiber officinale and Allium sativum (Lengai and Muthomi, 2018).

Animal biopesticides

These biopesticides are based on animals such as predators or parasites, or molecules derived from animals, often invertebrates such as spider venoms, scorpions, insect hormones, pheromones (Saidemberg et al., 2009; Aquiloni et al., 2010). Studies by Laura and Francesca (2010) suggested that the use of sex pheromones to control invasive populations of the crayfish Procambarus clarkia showed that men were attracted to the sex of pheromone women. In India and Thailand, natural enemies (parasites and predators) had successfully transformed into plant protection tools for farmers (Leng et al., 2011). The ladybird beetle is the best known auxiliary insect. The Rodolia cardinalis ladybird collected in Australia is commonly used as a predator of the mealybug Icerya purchasi (Deravel et al., 2014). Although it was introduced as early as the 19th century in California to stop citrus destruction, the Galapagos Islands only allowed its introduction in 2002 (Calderón Alvarez et al., 2012). The effects of biopesticides of animal origin and especially auxiliary insects on local fauna are carefully studied before their use (Deravel et al., 2014).

Animal biopesticides that are chemical signals produced by an organism that change the behaviour of individuals of the same or different species are also referred to as "semiochemicals". Semiochemicals are not strictly speaking "pesticides". Indeed, they will not cause the death of pests, but rather create confusion among pests (Deravel et al., 2014). This confusion will prevent them from spreading in the treated area. Insect pheromones are good examples of semiochemical molecules used as an alternative to insecticides (Deravel et al., 2014). They are small molecules that are naturally produced by insects and are detected in the antennae of their congeners. These molecules may be ephemeral or persistent, but in all cases they carry a message. They can mark a territory, warn of the availability of food, or be a signal for mating. Insect pheromones are widely used both to control insect pests through trapping or mating disruption techniques and to monitor their numbers (Deravel et al., 2014).

Origin and role of bioactive ingredients in biopesticide effects

Phloroglucinols are secondary phenolic metabolites produced by plants, algae and bacteria. More than sixty derivatives have been described for their antimicrobial, antiviral, phytotoxic, cytotoxic and antioxidant activities (Dwivedi et Johri, 2003). Certain strains of bacteria are capable of exerting a variety of mechanisms of plant growth promotion and protection, including the production of the natural antibiotics such as 2,4-diacetylphloroglucinol (2,4-DAPG) and derivatives of phenazine (Phz) (Madrovi et al., 2012). These compounds are broadly active against plant pathogens and are produced by widely distributed taxonomically diverse Pseudomonas spp. that inhabit the rhizosphere of cereal crops and render certain soils naturally suppressive to soilborne plant diseases.

Other important compounds are Lipopeptides that are produced by microbes and have strong antimicrobial properties against different plant pathogens. Lipopeptides are low molecular weight compounds which havemultiple industrial roles apart from being usedas biosurfactants and antimicrobials (Malviya et al., 2020). Natural Bacillus strains play an important role in the production of different concentrations of each lipopeptide and thus are crucial for their interaction with plant as well as biofilm formation interaction with plants and the production of biofilms (Cawoy et al., 2014). It has been reported that lipopeptides have shown potential antagonistic activity against disease causing bacteria and fungi in vitro and in planta conditions (Makovitsky et al., 2007). Lipopeptides are a group of microbial surfactants such as surfactin, lichenycin, iturin and fengycin. The Figure 1 shown some compounds of the lipopeptide family.

Antibiotics also play a key role in biopesticide effect. That's the case of Pyrrolnitrin, a broad-spectrum antibiotic first isolated in the 1960s from Pseudomonas pyrrocinia. This compound has also been isolated from several other bacterial species including Myxococcus fluvus, Enterobacter agglomerans, Serratia sp, as well as several Pseudomonas and Burkholderia (Hammer et al., 1999). This very active metabolite has also been used medically for the treatment of cutaneous mycoses while a derivative of the molecule has been developed as an agricultural fungicide (fludoixonil) (Mc spadden et al., 2001). The production of this compound by P. fluorescens is involved in the control of certain root pathogens such as Fusarium oxysporum (Howell and Stipatovic, 1980).

Biopesticides produce several other metabolites such as siderophores, phenazines, pyoverdine, hydrocyanic acid, pyoluteorine (PLT)... Each compound played a important in plant protection and in the preservation of the environment by promoting sustainable and profitable agriculture.

Biopesticides and sustainable agriculture

From the mid-19th century to the present day, synthetic pesticides have been used as a pest control agent. There is no doubt that they have been a promising agent for pest control, but more than seven decades after their use, synthetic pesticides have been so well distributed in the animate and inanimate world that they occur virtually everywhere. Land that was productive 50 years ago is now showing a decline in yield (Dhakal and Singh, 2019). According to the latest revision of the UN population outlook, world population is likely to increase by 34%, from 6.8 billion today to 9.1 billion in 2050 (Dhakal and Singh, 2019). Feeding this growing population is a great challenge, especially when land productivity is declining day by day. Environmental pollution from agrochemical residues is increasing and eroding the natural resource base. Sustainability must be maintained in the production system to feed

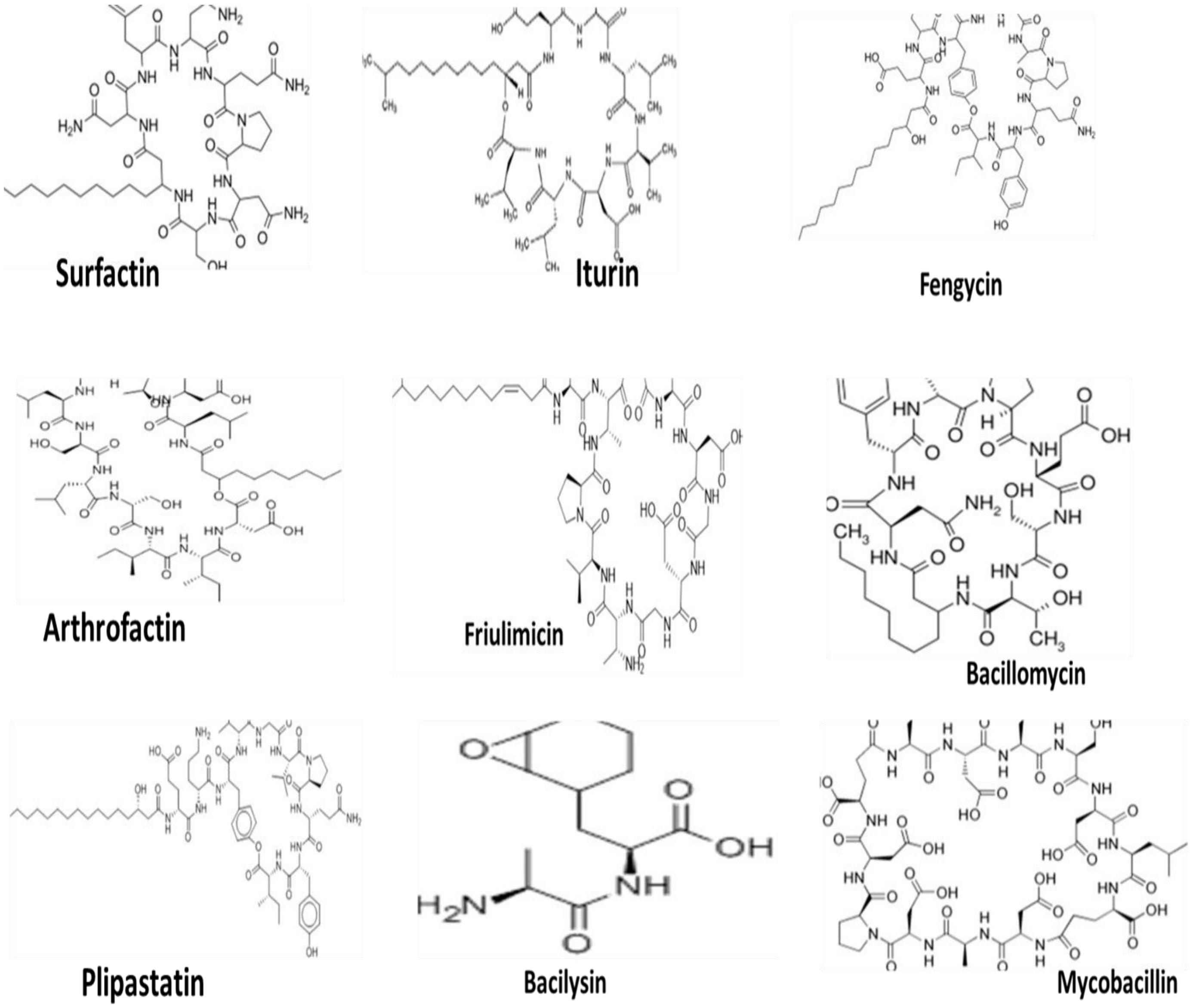

Figure 1: Some compounds and their chemical formula derived from lipopetides **Malviya *et al*. (2020)**

the world's burgeoning population.

Sustainable agricultural systems are those that are economically viable and meet society's need for safe and nutritious food while preserving or enhancing natural resources and environmental quality for future generations. It is in harmony with the environment while maintaining the buoyancy and dynamism of agricultural growth to meet basic human needs and conserve natural resources (Dhakal and Singh, 2019). It aims to produce food that is both nutritious and safe for human health. Since all materials are of natural or biological origin, it is very safe to use biopesticides as a potential source of pest control in sustainable agriculture.

The use of biological agents as a control strategy could have both preventive and curative effects, as the integration of microbial insecticides with other control agents to provide the desired level of protection. The inclusion of additional natural enemies would improve the sustainability and reliability of the biocontrol program, allowing WFT (Western Flower Thrip) to be managed at levels equal to or better than conventional pesticides (Brownbridge and Buitenhuis, 2019).

Not only have biological control strategies provided higher levels overall, their use has also mitigated highly resistant pests (Mishra et al., 2015).

Entomopathogenic fungi are important natural regulators of insect populations and have potential as mycoinsecticidal agents against various insects pests in agriculture. These fungi infect their hosts by penetrating through the cuticle, accessing the haemolymph, producing toxins, and growing by using nutrients present in the haemocele to avoid insect immune responses (Salma, 2011).

Entomopathogenic fungi may be applied in the form of conidia or mycelium that sporulate after application. The use of fungal entomopathogens as an alternative to insecticides or the combined application of insecticides with fungal entomopathogens could be very useful for the management of resistant insecticides (Sharma and Malik, 2011). The efficacy of seven strains of fungal entomopathogens against adult Ceratitis capitata was evaluated in the laboratory. The extract of M. anisopliae was the most toxic, causing about 90% mortality. The compatibility of the entomopathogenic fungus Beauveria bassiana (Balsamo) Vuillemin with neem was conducted against the sweet potato whitefly, Bemisia tabaci (Gennadius) (Hemiptera: Aleyrodidae) (Islam et al., 2010). The use of the insect pathogenic fungus Metarhizium anisopliae against the adult mosquitoes Aedes aegypti and Aedes albopictus was demonstrated. The lifespan of the fungi contaminated by mosquitoes of both species was significantly reduced compared to uninfected mosquitoes. The results indicated that both mosquito species are highly susceptible to infection by this entomopathogen (Scholte et al., 2010).

Bacterial bio-pesticides are probably the most widely used and cheaper than other pest bioregulation methods. Insects can be infected by many species of bacteria, but those belonging to the genus Bacillus are the most widely used as pesticides (Sharma and Malik, 2012). One Bacillus species, Bacillus thuringiensis, has developed numerous molecular mechanisms to produce pesticidal toxins, most of which are encoded by several cry genes 21.

Since its discovery in 1901 as a microbial insecticide, B. thuringiensis has been widely used to control important insect pests in agriculture, forestry and medicine. Its main characteristic is the synthesis, during sporulation, of a crystalline inclusion containing proteins called dendotoxins or Cry proteins, which have insecticidal properties (Sharma and Malik, 2012). To date, more than 100 bioinsecticides based on B. thuringiensis have been developed, and are mainly used against larvae of lepidoptera, diptera and beetles. In China B. thuringiensis is used to control diamond-backed butterflies and Helicoverpa on cotton, pigeon pea and tomato; Beauveria controls mango hoppers, mango mealybugs and coffee borer pod; Trichogramma controls sugar cane borer and trichogramma products control rots and wilt in various crops (Ruiu, 2018).

Management of plant diseases, namely dry root rot of chickpea and cotton (*Rhizoctonia bataticola*), stem rot of mustard (*Sclerotinia sclerotiorum*), Phytophthora root rot / gum disease (*Phytophthora spp*.), canker (*Xanthomonas axonopodis* pv. citri), post-harvest fruit drop and rot at Kinnow, was a formulation of the fungal bioagent Trichoderma (2 × 107 CFU / g), bacterial bioagent Pseudomonas fluorescens (1 × 109 CFU / g) or yeast bioagent *Sporidiobolus pararoseus* (109 CFU / mL) (Gaur and Sharma, 2012).

The biopesticide formulation containing onion (Allium cepa) and ginger (Zingiber officinale) was evaluated for its efficacy against tomato worm (Helicoverpa armigera) and recorded a control of 70 % - 80 % (Sumitra et al., 2014). The results of this study revealed an increase in yield of plants treated with the formulation. Muzemu et al. (2011) reported a reduction of more than 50 % of rape aphids (Brevicoryne brassicae) and tomato red mites (Tetranychus evansi) by powdered extracts of Lippia javanica and Solanum delaguense. Populations of Megalurothrips sjostedti were reduced by extracts of

Piper nigrum, *Cinnamomum zeylanium* and Cinnamomum cassia (Abtew et al., 2015). Larval and pupal numbers of Helicoverpa armigera were effectively reduced by extracts of Curcuma longa, Allium sativum and henge (Ferula assa-foetida) in a study by Shah et al. (2013). The extracts of Artemisia herbaalba, Eucalyptus camaldulensis and Rosmarin officinalis soaked in bean leaves (Vicia faba) caused 60 % to 100 % mortality of peach aphid (Myzus persicae) after 24 hours of exposure depending on the experimental dose in vitro (Nia et al., 2015).
Ngegba et al. (2018) reported that extracts of neem (Azadirachta indica) and Mexican sunflower (Tithonia diversifolia) inhibited the growth of tomato pathogen rot disease, Aspergillus niger, Fusarium oxysporum and *Geotrichum candidium* up to 100 %.
Castor seed extracts (*Ricinus communis*) effectively inhibited the growth of yam pathogens (Penicillium oxalicum and *Aspergillus niger*) after harvest (Patrice et al., 2017). Similar effects were reported by Devi et al. (2017) on post-harvest fungi, including *Fusarium solani*, *Rhizopus arrhizus* and *Sclerotium rolfsii* after using extracts of Duranta erecta and Lasonia ineruis. methanolic extracts of Chenopodium ambrosioides showed antifungal activity against *Fusarium oxysporum* f.sp. ciceris, a pathogen that causes wilt of chickpeas (Cicer arietinum) up to 50 % (Minz et al., 2012). In Côte d'Ivoire, several works have been carried out in the framework of the protection and conservation of agricultural products using bacterial biopesticides. Thus Bacillus subtilis GA1 was used to control mango spoilage germs (*Colletotrichum sp* and *Candida sp*) and allowed to preserve this seasonal fruit for more than ten days (Alloue-Boraud et al., 2015). The same species was used by Koffi et al. (2016) in the control of pineapple spoilage sprouts. The results of this study revealed that the main spoilage germs were inhibited by more than 57 % and the pineapple was preserved for more than 15 days without being spoilt. Ban Koffi et al. (2017) are used *B. subtilis* GA1 to enhance the preservation of mango fruit. Indeed, these authors found an 86.29% reduction in mango spoilage by *Colletotrichum sp* through in vivo testing of mango with B. subtilis GA1

Environmental impact of biopesticides

Microbial insecticidal organisms are non-toxic and non-pathogenic to humans, wildlife and other organisms that are not closely related to the target pest. The best strength of microbial pesticides is their safety. Microbial insecticides have a toxic mode of action that is specific to a single insect group or species. Most microbial insecticides do not usually directly affect beneficial insects (including predators or parasites of pests) in treated areas. Microbial insecticides can be used in conjunction with chemical insecticides as in most cases they are not deactivated or damaged by insecticide residues (Pathak et al., 2017). Microbial insecticide residues do not pose a hazard to humans or other beneficial organisms.
They can therefore be applied even when a crop is almost ready for harvest. In some cases, microbial pesticides become established in a pest population or its habitat, providing control during subsequent pest generations or seasons. They encourage beneficial soil microflora and improve root and plant growth. In this way, they help increase crop yields. Various examples are biofungicides (Trichoderma), bioherbicides (Phytophthora) and bioinsecticides (*Bacillus thuringiensis*).
Biopesticides are beneficial because of their lower toxicity, eco-security, specificity, reduced number of applications, no pest resistance, increased yields and quality and higher value of products for export and suitability for rural masses (Dakhal and Singh, 2019).
This includes crop losses, export losses, loss of labour hours and human lives, and losses of beneficial natural pests and predators. When used as a component of IPM, the efficacy of biopesticides can be equal to that of conventional pesticides, particularly for crops such as fruits, vegetables, nuts and flowers (Kumar, 2012). By combining performance and environmental safety, biopesticides work effectively

with the flexibility of minimum application restrictions and superior resistance management potential.

Although biopesticides offer benefits such as a safe and healthy food environment for human consumption, there are factors that limit their full adoption as a pest and disease control option. This is because only one microbial insecticide is specifically used for the target species or group of insects, so it can only control specific pests present in a field and garden. Other types of pests present in the treated area continue to cause damage. Similar limitations are observed with conventional insecticides which are not equally effective against all pests. Sometimes predators and chemicals can also be dangerous to other beneficial insects in the endangered area. Heat, low humidity or exposure to ultraviolet/intense sunlight could reduce the effectiveness of several types of microbial insecticides. Therefore, appropriate timing / storage conditions and application method are particularly important for some products (Pathak et al., 2017).

The adoption of biopesticides of a predatory nature requires careful consideration of host crop and dispersal capacity (Gerson, 2014). Crop coverage and duration of exposure are essential and for a small area, this could be costly as application can be manual (Lanzoni et al., 2017). Product registration requires chemistry, toxicity, packaging and formulation data that may not be readily available (Gupta and Dikshit, 2010). The cost of producing a new biopesticide is generally high and has many resource limitations (Lengai and Muthomi, 2018).

Special formulation and storage procedures are required for microbial pesticides. Since many microbial insecticides are specific to a pest or target, the market potential for these products may be limited. Therefore, some products are not commonly available or are relatively expensive (e.g. several insect viruses). Although, biopesticides are used as alternative strategies in pest management, there are several constraints such as the development of stable formulations, standardization of appropriate delivery methods, lack of biopesticides/microbial pesticides based on pathogenic microorganisms specific to a target pest (Pathak et al., 2017). High doses of constituent compounds are necessary for efficacy under field conditions (Shiberu and Getu, 2016). The concentration of bioactive compounds in plants is dictated by the environment in which they grow (Ghorbani et al., 2005). The active constituents are also dictated by the diversity of plants and their varieties resulting in differences in responses to pathogens (Sales et al., 2016). During formulation, it is sometimes difficult to obtain the right proportions of the necessary active and inert ingredients. There are also no standard preparation methods and guidelines for efficacy testing under practical application conditions (Okunlola and Akinrinnola, 2014).

Biopesticides also face strong competition from synthetic pesticides, and if the former were produced for small-scale farming, the costs may be relatively high and therefore difficult to achieve (Lengai and Muthomi, 2018). Awareness of biopesticides is insufficient, especially among small-scale producers, stakeholders and policy-makers. In the case of microbial biopesticides, there is generally a lack of trust in the value and use chain between producers, buyers and users, and given the risks of importation, synthetic pesticides appear to be reliable (Kumar and Singh, 2015).

Perspectives

Research on production, formulation and delivery can greatly assist in the commercialization of microbial pesticides. Greater emphasis should be placed on the integration of biological agents into the production system and the use of biopesticides in conjunction with chemical pesticides with an integrated approach. The management of populations of pests such as plant pathogens and insects is attracting global attention for the adoption of safer strategies that pose less risk to humans and the environment. The sustainability of the agricultural production system is essential to meet the growing demand for food with limited resource availability. Plant protection is one of the key factors in agricultural production and biopesticides appear to be the best alternatives to synthetic chemicals. Although there is increasing use of biopesticides on a daily basis, to maintain food availability for a growing population, the entire agricultural system worldwide should adopt biopesticides as a pest control agent (Pathak et al., 2017). Most of the time, farmers are affected by the problems of pesticide resistance and withdrawal of plant protection products. Therefore, a public-private partnership (PPP) for the development, manufacture and sale of biopesticides as an environmentally friendly alternative to chemical pesticides in developing countries should be developed. Data on toxicity levels, chemistry, active compounds and their compatibility with other pest and disease control methods are needed to assist in formulation and marketing.

Further research is recommended to fill gaps in biopesticide formulation. Products that are stable under field conditions will ensure that biopesticides are fully effective in controlling crop pests.

Researchers should therefore work with government and industry engineers as well as farmers to provide stable and sustainable biopesticide formulations. At the same time, there is also a need to encourage government-funded programs, commercial investors and companies in biopesticide management. Strict regulatory mechanisms are needed to maintain their quality and availability at affordable prices in developing countries. There is a need to strengthen the extension and supply chain management system to increase the use of biopesticides. At the molecular biology level, recombinant DNA technology is also being used to improve the efficacy of biopesticides. The fusion protein is designed to develop next-generation biopesticides. The technology makes it possible to combine selected toxins (non-toxic to higher animals) with a carrier protein that makes them toxic to insect pests when consumed orally, whereas they were only effective when injected into a prey organism by a predator (Dhakal and Singh, 2019). Innovative research is under way to increase the effectiveness of biopesticides and make them globally acceptable.

It is clear that biopesticides are the key to sustainable agriculture and there is an urgent need for increased scientific efforts to identify the preferred research area for the development of environmentally friendly production technologies with the use of biopesticides as a pest control agent.

Conclusion

Biopesticides can be an alternative to chemical pesticides because the indiscriminate use of pesticides is detrimental to the environment and human health and also increases insect resistance to pesticides. They are used as alternative pest management strategies. Although, when used alone, they are generally less effective in the short term than their chemical counterparts, they have many ecological advantages that cannot be ignored. The availability of biopesticides that control a variety of crop pests is essential to ensure that agro-ecosystems are managed in a way that is more respectful of the environment and human health. Growing farmer demand is followed by growing market supply and improving products that can be used alone and in rotation or in combination with conventional chemicals. However, several constraints such as the development of stable formulations, standardisation of appropriate administration methods, lack of registration procedures etc are associated with their introduction and promotion in most developing countries. It is likely that in the future, their role in agriculture and horticulture will be more fruitful, as they are able to conquer pests and limit the occurrence of resistance whether used alone or in combination with chemical pesticides in an IPM strategy.

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