Research and Development of Biopesticides: Challenges and Prospects

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RESEARCH AND DEVELOPMENT OF BIOPESTICIDES: CHALLENGES AND PROSPECTS

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This paper considers prospects and challenges to the use of biopesticides as part of Integrated Pest Management strategies

Keywords: Biopesticides, commercialisation, regulation, formulation, nanotechnology, microbials, botanicals

Introduction

Even though pesticides have greatly contributed to boosting agricultural productivity and farmer income over the years, there have been concerns about the safety of some of these pest control products. Besides, there has been a growing demand for good quality and safe food in the recent past – as reflected in the stringent regulations on pesticide residue levels in produce (Damalas & Koutrobas, 2018). Biopesticides in comparison with conventional synthetic chemical pesticides are usually less toxic, generally affect only the target pest and closely related organisms, are often effective in relatively small quantities and decompose faster, resulting in lower exposure. Consequently, over the last few years, biopesticides have attracted global attention as a safer pest control strategy (Arora *et al*., 2016) for incorporation into Integrated Pest Management (IPM) programmes. Besides, in the last decade, adoption of IPM programmes has significantly enhanced pest management practices and, in some cases, reduced pesticide use, consequently reducing the rise in demand for synthetic chemical pesticides. Also, the development of new synthetic chemical pesticides has declined considerably in the recent past, as regulations have become tighter, with products being withdrawn from the market, resulting in a more limited choice of chemical solutions (Damalas & Koutrobas, 2018) such that biopesticides have become a more feasible option. Many countries have also increasingly lowered chemical Maximum Residue Levels for agricultural imports which have made it increasingly necessary to explore pest control options which would ensure reduced reliance on the use of synthetic chemical pesticides (Damalas & Koutrobas, 2018).

In this paper, avenues of addressing challenges to biopesticide research and development are evaluated by seeking the inputs of a wide range of stakeholders, building on a recent international workshop with biopesticides practitioners from across the globe. Prospects for biopesticide application are detailed using a case study on the fall armyworm (*Spodoptera frugiperda*) in Africa.

The Biopesticides Market

Currently, biopesticides comprise a small share (5–6%) of the total global crop protection market, with a value of between $3 and $4 billion (Dunham & Trimmer, 2018). This is partly due to the efforts by various countries and regions to implement rules to adopt eco-friendly products for agriculture. Some promising products have recently been reported including *Clitoria ternatea* (butterfly pea) plant extracts (Mensah *et al*., 2014), *Trichoderma harzianum* fungus products (Kirk & Schafer, 2015), *Talaromyces flavus* fungus strains (Ishikawa, 2013), the alkaloid compound oxymatrine (Rao & Kumari, 2016), *Lactobacillus casei* strain LPT-111 bacterium fermentation products (Dubois *et al*. 2017), *Bacillus thuringiensis* var. *tenebrionis* strain Xd3 (Btt-Xd3) bacterium products (Eski *et al*. 2017), olive mill wastes (El-Abbassi *et al*. 2017), and stilbenes isolated from grapevines extracts (Pavela *et al*. 2017). Although promising, the effects of these substances on specific pest problems in various cropping systems are still unclear (Damalas & Koutrobas, 2018).

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Images from ICGEB workshop on 'Challenges to the adoption of biopesticides in agriculture: exploring solutions' held from 27–30 November 2018 in Cape Town, South Africa and upon which this manuscript is based.

The biopesticides market is rapidly expanding due to factors related to: greater environmental and health awareness, sustainability, regulatory pressure and retailer demands. In the past, biopesticides were produced exclusively by small local or regional companies who struggled to navigate the laborious regulatory process and hence were unable to grow their market share. Large multi-national agricultural chemical corporations are now investing heavily in this sector and continued growth in the biopesticide market is, therefore, expected – with projections showing that biopesticides may (arguably) catch up with chemical pesticides, in terms of market size in the next 20–30 years (Olson, 2015). Major uncertainties in the uptake rates, especially in developing countries, may however affect these estimates.

Regulatory, Research, Policy and Industry Perspectives and Challenges to the Development and Commercialisation of Biopesticides

The definition and categorisation of biopesticides as well as the stringency of biopesticides regulations varies in different countries, regions, regulatory bodies and even among the scientific community. For example, the United States Environmental Protection Agency (US-EPA) recognises plant-incorporated-protectants (PIPs) – pesticidal substances that plants produce from genetic material that has been added to the plant e.g. Bt gene – as biopesticides. On the other hand, in the European Union, the term 'biological control agents' is used instead of biopesticides; PIPs are not recognised as biopesticides. These divergencies which make it difficult for companies to navigate the regulatory processes easily have been discussed in several review papers including Arora *et al.* (2016) and Balog *et al.* (2017).

Even though very many biopesticide-active substances have been isolated and formulated, few have been registered due to lengthy and bureaucratic regulatory processes in many countries. These processes, with few exceptions like the USA, are generally similar to the model followed in registration of chemical pesticides and have not evolved sufficiently to regulate biopesticides.

Risk assessment is a key requirement for registration of biopesticides. However, even though this assessment should be done through scientific evidence-based processes, submission procedures in some countries are unnecessarily lengthy. Tailoring of registration requirements to facilitate effective assessment of biopesticide active substances is therefore required. The high cost related to the registration of new agents is another factor hindering the registration of biopesticides (Damalas & Koutrobas, 2018). It is recommended that regulatory authorities speed up the registration process of biopesticide products based on justifiable and appropriate regulations so that new products can reach the market quickly and hence generate income.

Much research is normally undertaken during the early stages of biopesticides' development leading to numerous articles on "potential" biopesticides. It is suggested that such substances should rather be referred to as biocontrol agents and only labeled as biopesticides once approved for commercial use.

The transition from a research project to the realisation of the product requires expertise in various fields. There is a need for coordination of biopesticide research leading to 'biopesticide innovation chains' and/or centralisation to research, develop, and deliver biopesticides. Biopesticide development, as with all other research and development efforts, requires skilled human resources, adequate physical infrastructure and the association with one or more small and medium enterprises to provide input at the early stages of research, and throughout the development process, to ensure that developed products have potential for commercialisation (Glare *et al.*, 2012).

Greater interaction with complementary sectors outside of the pesticide industries is also required. Equally important, especially for small companies, is patenting innovations to reap the benefits which is always done by larger companies. Patenting of naturally existing organisms is not possible but patent laws are able to distinguish between discovery and invention and the latter can be patented as long as they meet the patentability criteria (novelty, inventive step and industrial applicability) as stipulated in article 27 of Trade-Related Aspects of Intellectual Property Rights (TRIPS), a part of World Trade Agreement (Balachandra & Ramachandranna, 2010; Ravensberg, 2011). The main challenges associated with biopesticide usage, from a consumer perspective, are the intensified management required and acceptance of a generally lower or slower efficacy than with their chemical counterparts (Ash, 2009; Glare *et al*., 2016).

In a nutshell, the future of biopesticide development requires greater collaboration between various disciplines and ensuring the input of industry from very early in the process of selecting the agent to be taken through the research and development process all the way to determining the most appropriate business and funding models.

Opportunities for the Use of Viral Biopesticides – Present State and Future Perspectives

Several viruses are known to infect insects but only those belonging to the Baculoviridae family – a highly specialised group of viruses – have been developed into products for pest control (Rohrmann, 2011). This is because of their good safety profile and high specificity (Barrera *et al*., 2011). Their application as bioinsecticides was however limited until recently because of their slow killing action and technical difficulties for *in vitro* commercial production. Due to the immense efforts of Dr. Flavio Moscardi of the Brazilian Agricultural Research Corporation (EMBRAPA), this trend has changed. Many countries, e.g. India, China, Brazil, and South Africa have increased the area of crops protected by baculoviruses. A programme for the control of the velvet bean caterpillar (*Anticarsia gemmatalis*) was introduced in Brazil in the early 1980s. In the season 2003/2004, about 2 million ha of soybean plantations were protected with *Anticarsia gemmatalis* Multiple Nucleopolyhedrovirus (AgMNPV) (Moscardi *et al*., 2011). At present, soybean, corn, and cotton fields are protected in Brazil against *H. armigera* with *Helicoverpa zea* nuclear polyhedrosis virus (HzNPV) on about 1.3 million ha, while large areas of cassava fields are sprayed with *Erinnyis ello* granulovirus formulations. Two approaches for the wider application of baculoviruses as biopesticides are proposed for implementation in the future (Sosa-Gómez, 2017). First, in countries where the use of genetically modified organisms is restricted, the improvements will be mainly at the level of diagnostics, *in vitro* production and changes in biopesticide formulations. Secondly, it is proposed that the killing activity of baculoviruses be augmented by genetic modifications of the baculovirus genome with genes of another natural pathogen.

Botanical Pesticides – Present State of Research and Future Perspectives

Botanical pesticides are plant-derived organic pesticides used in defense against different pests. Botanicals control pests through mechanisms such as repellency, anti-feeding, anti-juvenile hormone activity, oviposition/hatching deterrence, and anti-fertility or growth disruption (Guleria & Tiku, 2009; Khater, 2012). These biopesticides are also effective against fungi, viruses, and bacteria (Prakash & Rao, 1997). Examples of anti-juvenile hormone activity are precocenes from the essential oil of *Matricaria recutita* which interferes with the functioning of insect glands involved in the production of juvenile hormones with the resultant effect of insect growth suppression at molting stage (Khater, 2012). The mode of action of antifeedants is mainly directed at the insects' taste cells either by stimulating a deterrent receptor in the gustatory sensillum or blocking the feeding stimulants and others are thought to cause erratic bursts of electrical impulses in the nervous system interfering with feeding behavior (Murray, 2002). Botanicals are often used inefficiently as pesticides hence their wild-scale adoption in Africa is limited. Therefore, there is a need for optimisation of their effectiveness as well as the production of data on their efficacy and safety (Sola *et al*., 2014). One key challenge is that crude plant extracts are a mixture of chemical molecules belonging to various chemical classes, all of which may not possess biological activity. Therefore, for botanical pesticides to be effective there should be chemical standardisation processes to identify and concentrate the chemical molecules possessing the active ingredients (Guleria & Tiku, 2009). On a more positive note, botanicals degrade very quickly within a few days or even hours, and so most are generally environmentally safe. Rapid degradation however makes them expensive to use, as more frequent applications are required. In a nutshell, very few botanical pesticides have been commercialised because of the several barriers to their commercialisation, including difficulties in large-scale production of plant materials, standardisation of chemically complex extracts, rigorous regulatory approval requirements, slow action of several botanicals, the lack of residual action and the availability of more cost-effective competing products (Khater, 2012). However, in view of the negative effects of some synthetic pesticides, there is a need for these challenges to be addressed so that botanicals can be commercialised and enter the market.

Bioherbicides – Constraints in Production and Field Application

Global food supply and the agricultural economy are threatened by the severe impact of weeds on crops. These weeds are primarily controlled by applying commercial chemical herbicides. However, overuse of chemical herbicides, improper application and management practices lead to pollution of the environment and harm to non-target organisms, including human beings. In response, researchers have developed bioherbicides which are weed control agents derived from living organisms and are thus less risky, and less persistent in the environment. In addition, they have multiple modes of action which reduces the risk of weed resistance development

(Bailey, 2014). At present, a few bioherbicides are successful in the market. This is attributable to a number of challenges including, limited host-specificity, incorrect formulation, and lack of field persistence. Strategies such as extending host ranges, improving formulation and field persistence, enhancing the weed suppressive nature and incorporating advanced techniques are needed to make bioherbicides a significant weed control agent (Radhakrishnan *et al*., 2018).

Fungal species are predominantly used in the control of weeds as mycoherbicides. Even though many fungal species are available as plant pathogens and are prospective biocontrol agents, only a very small percentage have been commercialised. Among the bacteria, *Xanthomonas campestris* and *Pseudomonas fluorescens* have shown potential to be developed as biocontrol agents. Viruses such as the tobacco mild green mosaic virus have also been investigated for use as bioherbicides. Around the World, about twenty-four bioherbicides based on microorganisms have been registered for commercial purposes and there are other microbial species under evaluation stages to be registered and developed as commercial products.

Host range is a complex issue in the development of a bioherbicide as most of these products are host specific. The choice of microbial species used in the host range test is difficult due to the lack of clear evidence in the relationship between plant phylogeny and pathogen specificity (Harding & Raizada, 2015). Crop plant colonisation by bioherbicide microbes creates risks which needs to be evaluated before the selection of a bioherbicide; as latent colonisation occurs in nature which interferes with the viability as commercial product (Casella *et al*., 2010). Competition among microorganisms for nutrition, space, and antagonism may reduce the microbial population and toxic substances from the plant leachate may negatively impact the effectiveness of bioherbicides. Environmental conditions also play a major role in determining the efficacy of any bioherbicides activity as initial infections, speed of infection development and spread to the weed, and rate of secondary infection on the target weed are controlled by the optimum environmental factors. Commercial development of bioherbicides majorly depends on the feasibility of mass production of a living, pathogenic and genetically stable propagules such as microbial spores, fragments, or pellets (Boyette & Hoagland, 2015). Specific technological and policy approaches are needed to make the bioherbicide economical and popular among the farmers. Researchers should consider the importance of overcoming the biological and environmental constraints of the pathogenesis of bioherbicides to make them potential commercial products (Aneja *et al*., 2017).

Clockwise from left: eggs, larva, pupa and moths of FAW at the ICGEB Cape Town insectary. The brown material in the images of the larval and pupal stages is artificial diet.

Prospects for Biopesticide Utilisation: A Case Study on the Fall Armyworm in Africa Using Microbials and Botanicals

The fall armyworm ((FAW) *Spodoptera frugiperda*) is a highly aggressive Lepidopteran pest native to the Americas. It feeds

Collection of FAW larvae from a farm in Thohoyandou, Limpopo province, South Africa.

mainly on grasses with a preference for maize crops; but is also known to feed on more than 80 additional species of crops, including rice, sorghum, millet, sugarcane, vegetable crops, and cotton. It was reported in Africa for the first time in 2016 and by 2018 had spread to Asia (Rwomushana *et al*., 2018).

FAW is susceptible to at least 16 species of entomopathogens including viruses (including Nuclear Polyhedrosis Viruses, NPVs), fungi (including *Metarhizium anisopliae, Metarhizium rileyi* and *Beauveria bassiana*), protozoa, nematodes, and bacteria (including *Bacillus thuringiensis, Bt*) (Bateman *et al*., 2018; Gardner & Fuxa, 1980). Many of these pathogens occur naturally in FAW populations with fungi, viruses, and bacteria being the most common and are recognised in other parts of the world as important natural control agents of FAW populations. In Africa, they are known to kill FAW larvae in the field. Among biological pesticides, virus (Nuclear Polyhedrosis Virus – NPV), bacteria (*Bacillus thuringiensis*-Bt), fungi (*Metarhizium* and *Beauveria* spp.), and the botanical insecticide (neem) have all shown promise for FAW control (FAO, 2017) and should be subjected to further investigation. Although not widely explored, entomopathogenic nematodes (EPNs), including *Heterorhabditis bacteriophora*, *H. indica*, and *Steinernema carpocapsae,* have proved promising as strategies for biological control, including for the FAW (Bateman *et al*., 2018; Prassana *et al*., 2018).

Virus-based insecticides are highly specific, virulent, non-toxic to vertebrates and have a significant potential for development as biopesticides (Barrera *et al*., 2011). Baculoviruses often play a significant role in keeping the populations of various insects in ecosystems under check (Rohrmann, 2011). Granuloviruses (SfGV) and multiple nucleopolyhedroviruses (SfMNPV) have been studied for the control of the FAW with SfGV showing greater potential (Sihler *et al*., 2018). However, although granuloviruses are slow acting on their own, their addition to SfMNPV formulations may improve nucleopolyhedrovirus performance as pointed out by Cuartas *et al.* (2015). The pest is infected orally through the ingestion of contaminated plant material. A caterpillar infected with NPV shows symptoms such as blemishes, yellowing of the skin and eats less than 10% of the food eaten by a healthy caterpillar (Gardner & Fuxa, 1980). Baculovirus infected caterpillars often move towards light and are therefore often found at the top of the plants. Upon death, they are often found hanging attached to the plant with head facing downwards. The dead larvae become soft, eventually oozing viroid particles and fluids which aid in further spreading the virus. Factors such as the age of FAW larva at infection, the amount of virus ingested, the virulence of the virus, prevailing climatic conditions – temperature, humidity, and solar radiation (UV light) – the formulations used, time of spraying and the type of equipment used are key in influencing the efficacy of the virus and pace of kill (Cisneros *et al*., 2002). It is, therefore, necessary to *inter alia* conduct research to determine the most appropriate formulation and application methods of these biopesticides. Addition of UV brighteners to baculovirus formulations has been shown to improve their performance (Li *et al*., 2015).

Entomopathogenic fungi (EPFs) are an important and widespread component of most ecosystems (Augustyniuk-Kram & Kram, 2012). Fungi are often an important natural mortality factor in insect populations. Even though more than 700 species of fungi from around 90 genera are pathogenic to insects (Hemasree, 2013), only a limited number have been investigated thoroughly for their use in agricultural management of insect pests (Khan & Ahmad, 2015). One advantage of fungi is that most species are obligate pathogens, and thus specific. Some species, including *Aspergillus* and *Fusarium,* are however facultative generalist pathogens (Driver *et al*., 2000). EPF can often cause epizootics under natural conditions and this has led to the isolation and identification of native fungal isolates from a wide range of hosts (Li *et al*., 2014). Fungal spores enter the insects through the integument and multiply in the insect hence destroying the tissues and often producing toxins resulting in host death. Diseased insects stop feeding, become discolored, and when dead often appear hard and calcareous with fungal growth commonly evident. *B. bassiana*, *M. anisopliae*, and *Nomurae arileyi* are common fungi with the potential for development into biopesticides. *B. bassiana* has been used for the control of FAW (Reinert *et al*., 1998); however, it only causes moderate mortality (Ramirez-Rodriguez & Sánchez-Peña, 2016). In comparison to other lepidopteran pests, studies have shown that FAW larvae may be the least susceptible to *B. bassiana* (Ramirez-Rodriguez & Sánchez-Peña 2016). There have been some studies at the International Centre for Insect Physiology and Ecology involving testing the efficacy of several fungal isolates from three different genera (*Metarhizium*, *Beauveria,* and *Isaria*) against second-instar larvae of *S. frugiperda*; the results, however, were not too promising (Prasanna *et al*., 2018). It is, therefore, necessary to identify and formulate other effective EPFs for FAW management.

Bacillus thuringiensis biopesticides are the most extensively used microbials for insect pest control. *Bacillus thuringiensis* is a commonly occurring, soil-dwelling, gram-positive spore-forming bacterium that produces insecticidal crystal proteins (commonly referred to as Cry proteins) (Schnepf *et al*., 1998). Susceptibility to the various toxins varies from one insect species to the next. Even though there are several commercially available Bt products for the management of lepidopteran pests, their effectiveness against FAW is still unclear. Among the different strains of Bt, laboratory studies have shown that the FAW is more susceptible to *Bt aizawai* and *Bt thuringiensis* (Polanczyk *et al*., 2000). Even though *Bt kurstaki*, is effective against several lepidopteran pests, the FAW is not as susceptible (Silva *et al*., 2004). Various research groups are currently working towards screening for effective Bt strains against the FAW. Populations of FAW may also have varying susceptibility to different Cry toxins (Monnerat *et al*., 2006), and this would, therefore, influence the choice of Bt-based biopesticides for FAW management in various regions. In addition to Cry toxins, FAW is also susceptible to various vegetative insecticidal proteins found in Bt cultures (Barreto *et al*., 1999). Commercial Bt biopesticides, especially those based on the strain *Bt aizawai* are registered and available to a limited extent in Africa. Studies to assess the effectiveness of these biopesticides against FAW in Africa have been recommended (Prassana *et al*., 2018).

Entomopathogenic nematodes (EPNs) present alternatives to synthetic chemical pesticides in the control of soil-dwelling insect pests which are safe to humans, animals, and the environment; hence are widely used in the horticultural industry.

Processing of plants at the ICGEB Biopesticides Laboratory for extraction of potential insecticidal compounds.

FAW has also been shown to be highly susceptible to these beneficial nematodes and especially to *Steinernema carpocapsae* and *S. riobravis* (Molina-Ochoa *et al*., 1999). The challenge with nematodes though is that they need to be applied at very specific times – usually early in the morning or late at night when FAW larvae are very active and can be easily accessed by the nematodes. These application periods also help to minimise exposure of the nematodes to UV which would otherwise kill them (Shapiro-Ilan *et al*., 2006). One advantage of EPNs is that they can be sprayed without dilution of their concentration or impacting their viability, with equipment that produces electrical charges to the spraying mix, and with those using hydraulic and rotary nozzle tips. Laboratory studies have shown that there are several commercial insecticides that are compatible with the three species of EPNs including *H. indica*, *S. carpocapsae*, and *S. glaseri* (Negrisoli *et al*., 2010a). In fact, some studies have shown enhanced efficacy of nematodes when mixed with insecticides; for example, *H. indica* efficacy against FAW is enhanced when mixed with lufenuron (Negrisoli *et al*., 2010b). It is, however, necessary to assess the compatibility of insecticides and EPNs comprehensively, as part of the programmes towards developing a FAW IPM programme for Africa. Even though there is great potential for developing EPNs for FAW control in Africa, only a few countries have been surveyed to date (Kaya *et al*., 2006). For example, there have been some promising studies in Egypt, investigating the potential of EPNs for incorporation into IPM programs in some cropping systems. Studies on EPNs for the control of the lepidopteran sugarcane stalk borer (*Eldana saccharina*) in South Africa showed limited success which was attributed to the fact that the pest is generally quite cryptic and that infested sites are normally filled with huge amounts of frass and sap (Prassana *et al*., 2018); a challenge that could also be faced in the application of EPNs for FAW control. Although commercial products have not yet been developed in Africa, there is a need to conduct extensive research on EPNs and explore their potential as biopesticides for use as part of IPM programs.

Several plants are known to have insecticidal properties and have great potential for development into botanical pesticides for FAW control. Some of these have been used for the management of FAW in other parts of the world. Most botanical pesticides are biodegradable and safe to humans, animals (including natural enemies) and hence amenable for use as biopesticides in IPM programs. Several plant extracts have insecticidal properties against stem borers infesting cereals in Africa. These include acacia (*Acacia* sp.), chillies (*Capsicum* sp.), Chrysanthemum (*Chrysanthemum* sp.), fish-poison bean (*Tephrosia vogelii*), jatropha (*Jatropha curcas*), lemongrass (*Cymbopogon citratus*), neem (*Azadirachta indica*), onion (*Allium sativum*, *Allium cepa*), persian lilac (*Melia azedarach*), pyrethrum (*Tanacetum cinerariifolium*), tobacco (*Nicotiana* sp.), West African pepper (*Piper guineense*), wild marigold (*Tagetes minuta*), wild sage (*Lantana camara*), and wild sunflower (*Tithonia diversifolia*) (Mugisha-Kamatenesi *et al*., 2008; Ogendo *et al*., 2013; Stevenson *et al*., 2017). The efficacy of these botanicals needs to be assessed against FAW and those found to be effective be promoted for dissemination among farmers in the region.

Recent Developments in Biopesticide Production and Formulation

Field use of biopesticide products can be enhanced using nanotechnology and micro-encapsulation to improve their stability, residual effects, and effectiveness (Damalas & Koutrobas, 2018; Vurro *et al*., 2019). Nanotechnology is the study of nanoscale (1–100 nm) materials known as nanoparticles

(NPs), exhibiting unique and novel physical, chemical and biological properties (Li *et al*., 2001). These NPs have flexible physical properties with a large surface area to volume ratio and a strong affinity for proteins (Sharon *et al*., 2010). Encapsulation of solid, liquid and gaseous substances into microparticles of 1–1000 µm through microencapsulation process is widely used in the fields of medicine, food, cosmetics and advanced materials (Campos *et al*., 2013; Dubey *et al*., 2009). Micro-encapsulation ensures that the core material is completely coated and isolated, and therefore protected, from the external environment. Products of nano-biotechnology can, therefore, provide controlled release of the molecules at the site of action, hence minimising potential toxic effects on non-target organisms and preventing degradation of the active agent by microorganisms. For this reason, products of nanotechnology would have reduced toxicity, enhanced efficacy, and a reduction of losses due to physical degradation (Barrera-Cubillos *et al*., 2017; Damalas & Koutrobas, 2018). For example, the use of nanoparticles is effective in protecting neem oil from rapid degradation, allowing a prolonged effect on target pests. Further nano-emulsions of neem oil extracted from the seeds of the plant significantly reduced the storage pest *Zabrotes subfasciatus* thus signifying the biopesticidal activity along with providing controlled release (da Costa *et al*., 2014). It has also been reported that various nanoparticles can encapsulate and protect the secondary metabolites containing active ingredients and these act on the attacking insects and behave as biopesticides (Lade *et al*., 2017; Nuruzzaman *et al*., 2016). Microencapsulation of the viral particles of *Spodoptera frugiperda* nucleopolyhedrovirus (SfNPV) protects them from UV-inactivation showing its potential for a biopesticide development (Villamizar *et al*., 2010). Nanotechnology could, therefore, contribute to the development of less toxic biopesticides with favorable safety profiles, increased stability of the active agents, enhanced activity on target pests, and hence enhance adoption by farmers. There are however possible risk factors associated with nanoparticle usage which need to be addressed through relevant research projects. Other concerns that still need to be addressed include the rates of release of active molecules from nano-particulate systems, stability in storage and cost-effectiveness of the technology.

Conclusion and Future Perspectives

There are several products with the potential to be developed further into biopesticides that have so far been identified, isolated and characterised. It is necessary that further research is carried out to ensure that the efforts that have so far gone into their identification and isolation are not in vain. The obstacles impacting the effectiveness of certain products have been identified and these need to be addressed, even as further research into new products continues. Collaboration between stakeholders remains crucial and it is, therefore, necessary that biopesticide researchers work closely with industry, farmers, policymakers, government and other relevant stakeholders. Methods for ensuring the integration of biopesticides into existing farming systems are also necessary. It is acknowledged that biopesticides cannot completely substitute chemical pesticides, so efforts and research should also focus on how to integrate biopesticides into integrated pest management strategies effectively. It is also important that biopesticides are provided to farmers – especially in developing countries – at costs which would ensure that it is profitable to the users of the technology. There is a need to sensitise and expose uninformed farmers, especially in developing countries, about the significance of biopesticides as a sustainable solution that could mitigate most of the adverse effects experienced with some synthetic pesticides. Regulations that promote the registration of biopesticides can also enhance commercialisation and market availability. While there are several new substances that have pest control potential more field research may be necessary to assess efficacy in specific cropping systems. Newer technologies such as nanotechnology show great promise in enhancing efficacy and residual action of biopesticides and their potential should be further explored. Most research institutes in developing countries lack minimal capacity in intellectual property rights (IPRs) management. Public research institutes will have to develop their independent IPRs policies and efficient management with a combination of legal, business and technical knowledge.

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Conflicts of Interest

The authors declare no conflict of interest.

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