Biopesticides in sustainable agriculture: current status and future prospects

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Abstract

Intensive application of synthetic pesticides was the routine practice of commercial agriculture during the Green Revolution to boost agricultural productivity to meet global food demand. Alongside this, the application of chemical pesticides caused adverse effects on the environment and its ecoreceptors including human health. Negative externalities arising from conventional farming instigated the call for sustainable development during the sixties to promote and balance the nexus between socially acceptable economic growth and environmental protection. Consequently, a blueprint of 17 Sustainable Development Goals (SDGs) and 169 targets including ecological stewardship and food security was drafted. Eight out of the 17 SDGs are directly linked to sustainable agriculture based on the direct impact of agriculture, judicious use of critical resources and conservation and the Principles of green chemistry. As a green chemical agent, biopesticides have been shown to have the potentials to substitute chemical pesticides with equal agricultural productivity. The adoption of bio-based pesticides via integrated pest management (IPM) has proven to be the most effective option to influence most dimensions of sustainable agriculture. Therefore, biopesticide-driven IPM if utilized with requisite education, skills and research would boost sustainable agriculture. This chapter reviews the prospects, importance, and limitations of biopesticides to sustainable agriculture and how sustainable agriculture is connected to sustainable development, Green Chemistry, and integrated pest management.

Keywords: Biopesticides; Green chemistry; IPM; SDGs; Sustainable agriculture; Sustainable development

1 Introduction

The quest for food production to satisfy the world's ever-growing population remains a conscious preoccupation dating as far as 300 AD to the present day (Alexandratos and Bruisma, 2012). According to the United Nations' projection, the world population has seen an increase of 0.8 billion per decade with 2020 seeing a population of approximately 7.7 billion. Interestingly, statistics showed sufficient agro production to sustain the global demand but with insignificant input from most of the third-world countries (Fan and Rosegrant, 2008). This leaves about a staggering 820 million global populace in ravaging hunger (WHO, 2018). The global and regional growth of aggregate production would have fared better in a world without crop pests. Pests are any species of living agents that cause damage to crops and their stored products. Some of these agents include fungi, bacteria, nematodes, weeds, rodents, and insects. According to Pandya (2018), pests account for 30% loss of potential yield (with major loss from developing countries) and 14% damage (Jankielsohn, 2018) in storage pests. Improving crop yield to an industrial-scale requires the deliberate application of conventional fertilizers and pesticides. The use of these synthetic chemicals, especially in the Green Revolution era, went along with attendant consequences such as poisoned foods, environmental degradation and health challenges. Later on, this scenario raised concern about sustainable development, considered as the judicious exploitation of the environment for the benefit of both the present and future generations (Burton, 1987). This consciousness of sustainable development was first reflected in the "Silent Spring", a book by Rachel Carson in 1963 and through a series of lectures and conventions. This resulted in the 2030 Agenda for Sustainable

Development Goal (SDGs) of the United Nations that was born in 2015. The SDGs spelt out a robust blueprint through which sustainable development can be achieved in all spheres of human endeavors.

The central message of sustainable development was to create a nexus between socially acceptable economic growth and environmental stewardship. However, during the green revolution, conventional agriculture, despite its success mounted huge pressure on the ecosystem through many facets including environmental pollution, land degradation, unsustainable use of natural resources, climate change, distortion of ecological services and biodiversity loss. Some of these negative impacts can be curtailed and controlled through changes in consumption patterns and the efficient use of natural resources. When these behavioral shifts, green technology and chemistry, and sustainability principles are factored into large-scale farming the three-dimensional concepts (Fig. 1) of sustainable development would be achieved. Within this framework, agriculture would be tied to achieve profitability, community well-being and environmental safety.

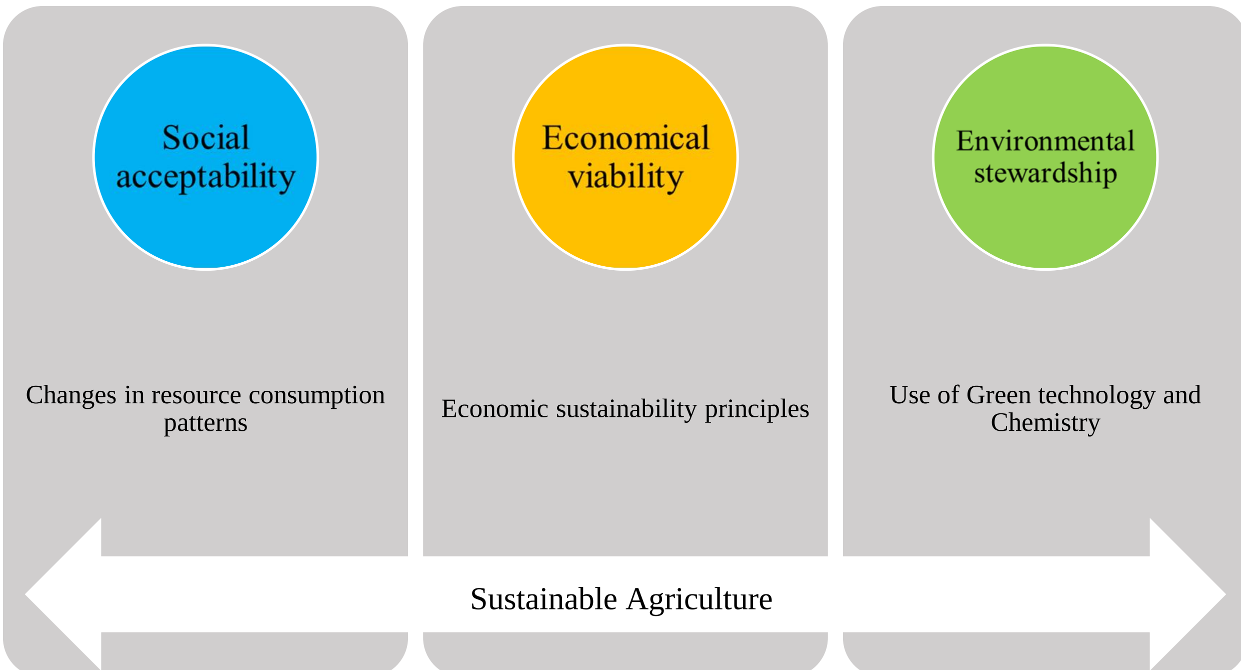

Figure 1. Three dimensional concepts of sustainable development in agriculture

Thus, agriculture that is directed to achieve economic viability, environmental objectives and social acceptability can be regarded as sustainable agriculture. Sustainable agriculture is directly or indirectly connected to all the various variants of sustainable development, including the 17 SDGs and Green Chemistry (Perlatti *et al*., 2014; Ganasen and Velaichamy, 2016; Saleh and Koller, 2018). Green Chemistry (processing, synthesis and use of innocuous chemicals) directly connects sustainable agriculture and the SDGs in eight areas based on the consumption of possible renewable chemicals and the associated green technologies. These eight goals are SDG15, SDG14, SDG12 and SDG6 (concerned with the environmental conservation and restoration which mostly require organic materials), SDG7 and SDG9 (concerned with green energy and technology respectively), and SDG1 and SDG2 (concerned with improving agro-outputs, which thus require biofertilizers and biopesticides).

Biopesticides are naturally occurring organisms and substances derived from plants and natural inorganic compounds that can control pests' populations by different mechanisms of action (Tijjani *et al*., 2016), excluding those that interfere with the nervous system of pests (Marrone, 2019). Biopesticides are of three categories: microbial biopesticides (microorganisms and their products that have pest controlling influences or compounds), biochemical biopesticides (natural substances with an active agent that control pests by non-toxic mechanisms) and plant-incorporated protectants (transgenic plants) (Kumar, 2012; Ibrahim and Shawer, 2014; Leahy *et al*., 2014). These bio-based pesticides exert their effects through different modes of action which, are classified into five groups: metabolic poison, growth regulators, gut disruptors, neuromuscular toxins and non-specific multi-site inhibitors (Spark and Nauen, 2015). Moreover, in most cases, biopesticides arm multiple modes of action against targeted pests making it difficult for the pest to develop resistance as is common with synthetic pesticides (Hassan and Gokce, 2014). Due to their eco-friendliness and low toxicity properties, they do not harm not-targeted organisms including humans and the environment. They are also specific, easily biodegradable, pose no post-harvest contamination problem, and are suitable in an integrated pest management system (Marrone, 2009). The effectiveness of biopesticides is made pronounced in integrated pest management (IPM). IPM is a multifaceted approach that combines all suitable control methods, including cultural practices into one management portfolio (James, *et al*., 2010; Barzman *et al*., 2015). IPM implementation aims to obtain the best result at the lowest cost while maintaining environmental safety. Several authors and commercial farmers have shown that biopesticide-driven IPM is a prerequisite for sustainable agriculture providing that awareness and skills associated with the IPM are given their right of place and time.

2 The global-view of conventional agriculture

2.1 Pests and their associated diseases

Food production to satisfy the world's ever-growing population remains a conscious preoccupation, right from the Tertullian era (300 AD) to this present age (Alexandratos and Bruisma, 2012). According to the United Nations projection, the global population will reach 9.15 billion in 2050. With a figure of 6.9 billion in 2010 and 2.25 billion in 1970, and presently the world population in 2020, is approximately 7.70 billion, there is seemingly a population expansion at a rate of 0.8 billion per decade. Current statistics hold that agro production's aggregate value is sufficient to sustain the global demand, but contribution from most third-world countries is abysmally low due to confluence of factors, including poverty, sectional and leadership failures to revamp agriculture (Fan and Rosegrant, 2008). And the result is widespread hunger amongst a great number (hundreds of millions) of the world population. WHO (2018) puts the number of those who suffer hunger worldwide at 820 million people, which ironically, is similar to the target number of people, the programme "world without hunger" hopes to reach by 2030. The regional and global increase in aggregate production of agro-yields would have fared better in the situations where there are no crop pests.

Phytopathogenic bacteria may cause the following symptoms, but are not limited to, galls, leafspots, blights, overgrowths, wilts, specks, soft rots, chlorotic halos, cankers and scabs (Cooper and Gardener, 2006). Relatedly, some of the diseases they cause can be described as crown gall, bacteria ring rot, fire blight, black rot of cabbage, bacterial soft rot, walnut bacterial blight, and brown rot (Sobiczewski, 2008). Phytoplasma can cause pear decline and aster yellows (Mergenthaler *et al*., 2020). However, sometimes not the case, plant diseases caused by fungi are recognized from the particular organ of the plant they affect and the type of symptom elicited. Based on these, the following fungal diseases are distinguished as follows: damping-off disease, powdery mildew, downy mildew, vascular wilts, root and foot rots, rusts, galls, dieback and anthracnoses (Brown and Ogle, 1997). Some notable plant viruses are tobacco mosaic virus, plum pox virus, yellow leaf curl virus, potato virus X, Africa cassava mosaic virus, brome mosaic virus, cauliflower mosaic virus, and potato virus Y (Scholthof *et al*., 2011). Nematodes are worm-like animals with some species known to parasitize plants. They are known to be the agents of root knots, yellow patches, yellow dwarfs, lesions, root-tip swelling, stem rot, flagging, cyst and stubby-root and corky ringspots (Lucas and Campbell, 2012; Mduma *et al*., 2015). Mistletoe and dodder are well-recognized plant parasites. Insects are known to be the most significant pests. Approximately 0.5% of the insect population are crop pests (Jankielsohn, 2018), although they also perform four major ecological services: nutrient cycling, decomposition, predation and pollination (Losey and Vaughan 2006). According to Gallai *et al*. (2009), insects' pollination accounts for 72% of crop reproduction worldwide with a 9.5% contribution to crop production yield. An active manifestation of pests is partly created by intentional human activities and clearing of vegetation to create space for crops and livestock production to ensure food security thereby compromising the ecosystem and its functions. An immediate cascade effect is witnessed in the distortion of biodiversity, causing insects to aggressively compete with humans in terms of space and nutrients. It is undeniable that the effects of pests are of economic significance from a global perspective. Summarily, the world has to contend with approximately 40 thousand pestilent species for the optimal production of food for the ever-increasing population of humans.

2.2 Global economic significance of insect pests

Top trans-continent insect pests cause huge global losses to crops. More than 180 host plants including cotton and chickpea are attacked by cotton bollworm (*Helicoverpa armigera*) with an economic loss of $2 billion on an annual basis (Tay *et al*., 2013) while onion thrips (*Trips tabaci*) ranked top as the most important pest of onion (Negash *et al*., 2020) and other plant hosts. More than 500 host plants belonging to 60 plant families suffer pestilent attack from tobacco whitefly (*Bemisia tabaci*) along with the potential of reducing crop yield up to 50% (Gangwar and Gangwar, 2018). More than 200 plants, including tomato and common bean, are destroyed by *Tetranychus urticae* commonly known as the two-spotted spider mite which has resulted in a control cost of $400 million per year (Litskas *et al*., 2019). An annual budget of between $4 and $5 billion has been estimated to cover weekly insecticide application and yield lost to the insecticide-resistant diamondback moth (Zalucki *et al*., 2012) which destroys more than 15 genera of plants (Willis, 2017), including *Brassica* (cabbage). *Spodoptera litura*, commonly known as taro caterpillar, has been reported to cause 0.85 million tonnes of loss per year in an arable field of 1.46 million hectares planted with soybean and cotton (Sharma *et al*., 2018). The polyphagous *S. litura* covers more than 120 species of plants as a pest (Bragard *et al*., 2019). The red flour beetle, a well-known secondary pest, feeds on stored food products such as dry fruits, cereals and cocoa beans.

Myzus persicae, the green peach aphid, is a resistant global pest and virus vector that feeds on more than 400 plant species (Silva *et al*., 2012). Their hosts are mostly essential crops such as oilseed rape, potato and tomato. They have the potential to reduce yield up to 30% in unprotected farmland (Alyokhin *et al*., 2020). A study conducted in 12 African countries demonstrated that in a year, losses incurred from maize cultivation and harvesting reach up to 4.1 to 17.7 million tonnes following an infestation of the fall armyworm *Spdoptera frugiperda* (Kassie *et al*., 2020). *S. frugiperda* is an invasive pest and can affect many crop types, especially maize and cotton (De Groote *et al*., 2020; Willis, 2017). Thrips (*Frankliniella occidentalis*), Mediterranean fruit fly (*Ceratitis capitate*) and codling moth (*Cydia pomonell*) attack pepper, citrus and apple, respectively with substantial damage done to more than 177 plant genera (Abdullah *et al*., 2015; Willis, 2017). The cowpea weevil is a pest that feeds on stored cowpea and legumes in the tropics with 10% to 50% storage loss (Tiroesele *et al*., 2015; Sanon *et al*., 2018). The infestation of cotton, maize and other plant species by the noctuid moth of the cotton leafworm (*Spodotera littoralis*) wildly occurs in Africa and Europe, thereby posing a threat to food security (Ahmed *et al*., 2019). Alfalfa and pea have been extensively attacked by *Acyrthosiphon pisum* (pea aphid) (Calevro *et al*., 2019). Citrus are attacked by the Asian citrus psyllid (*Dtaphorina citri*) (Monzo and Stansly, 2017) and tomato leafminer (*Tuta absoluta*) (Biondi and Desneux, 2019). Apart from the preference for the specific plants previously stated, these last three pestilent species have also affected more than 46 plant genera (Willis, 2017).

2.3 Application of synthetic pesticides and their significance

Industrial application of pesticides, which was accelerated in 1940, aimed at reducing the impact of pests, and marked the coming of age of the practice of modern agriculture and disease control (Unsworth, 2010). Broadly, pesticides can be classified as: synthetic or natural pesticides. Synthetic compounds used in modern agriculture as insecticides, herbicides, rodenticides, fungicides, and molluscicides are either from organochlorine, organophosphate, carbamate or pyrethroids (Mitra *et al*., 2011; Ndakidemi *et al*., 2016). Popular examples include Dichlorodiphenyltricholroethane (DDT), aldrin, toxaphene, endrin, chlordane, mirex, dieldrin, and heptachlor (Ritter *et al*., 1995). Pesticide's modes of action interfere with behavior, growth, reproduction and life cycle stages, development, and nervous system (Qi *et al*., 2001) of pests. Conventional pesticides have demonstrated broad-spectrum effects, quicker action, longer residual activity, convenience, and; highly effective against the target pests (Felsot and Rack, 2007; Maneepitak and Cochard, 2014). Pesticides improve the productivity of farm harvest, offer protection against crop losses and control vector-borne disease (Aktar *et al*., 2009). Furthermore, pesticides improve farm produce shelf life, marketability and profitability of these agricultural protects agricultural land and stored grain (Gill and Garg, 2014; Kumar and Kalita, 2017). Without crop protection, agricultural production losses would rise to between 48-83% (Glare *et al*., 2016). The global cost of pesticides has been estimated to be around $38 billion (Pan-Germany, 2012). The use of insecticides, molluscicides and herbicides in Thailand has maintained their rice exporting prowess despite reducing the number of farmers cultivating the plant (Maneepitak and Cochard, 2014). Conversely, a farming practice without pesticides would create lower productivity and a high food price (Damalas, 2009).

Despite the aforementioned benefits of synthetic pesticides, they have disadvantages such as high cost/long duration of development (Sanganyado *et al*., 2015); crop contamination, pest resistance, reduction, and a threat to the bird populations especially by DDT (Mitra *et al*., 2011); the depopulation of biological control agents and pollinators (Ndakidemi *et al*., 2016). Depopulation of biological control usually results in an eruption of secondary pests while reduced pollinators cause low productivity. Agrochemicals have also been confirmed as having serious health implications for humans and the connected ecosystem (Carvalho, 2017). Some of the identified health-related challenges caused by pesticides are irritation, enzyme inhibition, allergic sensitization, oxidative damage and neurotransmission inhibition (Hallenbeck and Cunningham-Burns, 2012). Residues of some synthetic pesticides, for example, toxaphene and DDT, remain persistent in the soil for years, and are washed off into water bodies with the attendant effect of contaminating groundwater and aquatic biota (Carvalho, 2017). Humans become intoxicated through bioaccumulating contaminants in food chains common in terrestrial and aquatic environments (Lushchak *et al*., 2018). Organochlorine and organophosphate compounds undergo the evaporation-condensation process and consequently are transported far and wide, with extensive effects felt at a considerable distance from the point of application. For instance, chlorpyrifos applied on a banana plantation in the intertropical region of Central America was detected in the ice pack in the Artic (Carvalho, 2017), essentially making the use of pesticides a global challenge. Pesticides as environmental pollutants disrupt microbial biomass and biodiversity, cause soil fertility losses, and adversely affect vital biochemical and enzymatic activities in soil (Gill and Garg, 2014) apart from causing unintended health challenges to humans. Thus, averting these negative consequences caused by synthetic pesticides has become a necessity, making the quest for alternatives to synthetic pesticides, an existential discussion in conventional agricultural practices. As such biopesticides are considered as a solution option to the challenge of pollution (Koul, 2011). Bio-based pesticides have been favoured in recent times, with a 2% drop annually of synthetic pesticides against a 10% growth rate of biopesticides (Damalas and Koutroubas, 2018). This trend reduced environmental pollution from synthetic pesticides, increased the production of wholesome crops, and improved biodiversity, thus addressing some of the dimensions of sustainable agriculture.

3 Sustainable agriculture: definition, concept and context

Sustainable agriculture employs the judicious and continuous use of critical resources in meeting both the needs of today but seeks to find a balance that does not compromise the need of future generation by integrating the understanding of the ecosystems in the exploitation of these natural resources (Burton, 1987). This idea of practicing sustainability predates most of the ancient civilizations, including countries like Greece, Rome and China (Cato, 1979; King, 1911). However, the sixties marked the development of global consciousness with the much publicized book authored by Rachel Carson titled, The Silent Spring (Carson, 1963), which emphasized the harm done to the environment by agriculture. Moreover, in the “Tragedy of the Commons”, written by Garret Hardin in 1968 posited that the rational drive of selfish interest would end up compromising common interest and would finally exhaust available natural resources (Hardin, 2009; Frischman *et al*., 2019). The profound computational simulation by Meadow *et al*. (1972) predicted economic and social collapse if a man fails to impose a limit to growth linked to the use of the inarguably limited natural resources. After 40 years, their predictions were confirmed in the visible signs of global pollution and its associated problems that threaten sustainable development. On the premise of depleting the natural resources reserve and pollution, the first UN Conference held in Stockholm in 1972 was to discuss human impact on the environment and its relatedness to economic development (Maurer and Bogner, 2019). Additionally, it was necessary to find a common ground to inspire and guide the global population to preserve the human environment. Progressively, the World Conference in 1979 focused on the influence and assessment of anthropogenic and natural causes and the contributions to climate change with its implications to human society. From the foregoing it is becoming evident that our planet has limited non-renewable resources and progress is not synonymous with economic growth alone. Consequently, the human development index came into the picture that encompasses economic and social achievements.

The Brundtland (“Our Common Future”) report (1987), provides, the simplest and most accepted meaning of sustainable development, as it stated that limitation is imposed on sustainable development by the collection of technology, social organization and the inefficient status of the biosphere to mitigate the impacts of human activities. Agenda 21, the draft document of the United Nation Conference of 1992 built a nexus between the socioeconomic sector and the environment. The document focused on explaining the deterioration of the environment and how it can be integrated into a sustainable development plans. Within this framework, sustainable development stands on the tripod of economics, social and the environment and if pursued with sincerity of purpose would certainly guarantee a more prosperous future through improved living standards and safe ecosystems. A chapter in the Agenda 21 document was dedicated to rural development and sustainable agriculture which require a major shift in agriculture, macroeconomic policies and the environment (Blandford, 2011). Beyond this tripod and the five domain concepts (economic, socio-cultural, technology, environment and public policy) of Steward W. C (Marteel-Parrish and Newcity, 2017), sustainable agriculture can also be looked at through the lens of the 12 Principle of Green Chemistry (Anastas and Warner, 1998) and the 17 Sustainable Development Goals (United Nations). Conceptualizing sustainable agriculture on the tripod dimensions means agro-practice that connects environmental soundness (efficient use of finite resources, prevention of air, land and water contamination; and reduction of health hazards), economic viability (reliable and profitable production activities) and social acceptability (self-sufficiency, improved quality of life and equality). Given this concept, equal emphasis will be placed on each of the dimensions of the Tripod over a long period (Zhen *et al*., 2005).

The Green Chemistry concept was enunciated in the Pollution Prevention Act of 1990 and developed by the trio of Joseph Breen, Tracy Williams and Paul Anastas in 1998 (Tundo and Griguol, 2018) and has gained prominence in theory, development and practice since then. The adjective "green" connotes benign solvent, catalyst/reagent and energy consumption components associated with a reaction (Ivankovic *et al*., 2017). This means adopting the safest innovative measures in line with some elements of chemical knowledge to protect the environment and its receptors including man. Green chemistry is considered as sustainable chemistry (Tundo and Griguol, 2018) when conventional chemistry is implicated in the area of economic consideration, efficient use of materials and waste reduction (Manahan, 2006). It covers areas such as efficient processes, renewable materials, green solvents and catalysts, and benign products (Song and Han, 2015). As a multidimensional concept, green chemistry encompasses processing, synthesis, and the use of chemicals (solvents, reagents, catalysts, products and feedstock) that reduce risks to the environment (its receptors) and humans (Verma *et al*., 2018). Its goal is to produce reduced wastes by using safer and better chemicals synthesized in the safest and most efficient process. Green chemistry has 12 Principles (PGC) which cover four concepts: (i) the design of processes in which all raw materials are incorporated in the final product (ii) the use of innocuous substances whenever possible (iii) energy-efficient process design and (iv) the choice of the best method of waste disposal (Ubuoh, 2016; Nnaji and Igbuku, 2019). Despite the lofty promises of green chemistry, it has its challenges embedded in time and cost (Ivankovic *et al*., 2017). Switching from the old and conventional process to green process is usually laced with a considerable time that covers for design, or redesigns as the case may be, for a new process. Robust design, required by green technology, requires a high cost of implementation. Lack of information and resources had also plagued the applications with negativity. For instance, ionic liquids seem to have a high prospect for green chemistry but if balanced against a strict definition of the 12 green chemistry principles, they are not considered green.

Green and sustainable agriculture holds a very strong position in the SDG agenda because it is directly and indirectly connected to the 17 SDGs such that no goal is left unlinked (Omilola and Robele, 2017). Sustainable agriculture is considered as an agro-practice that promises long-term productivity with minimal harmful effects due to the use of biofertilizers, biopesticides and organic manures. Sustainable agriculture is the outcome of farming that integrates green chemistry and sustainability principles to serve the economic, social and environmental interest. It holds the central position within the most recognized and acceptable sustainable development recipe.

4 Sustainable agriculture: its place in the tripod concept, SDGs and Green Chemistry

The Green Revolution intensified food production in Asia and other countries through technology, chemical inputs, irrigation, agricultural policies and strong institutional frameworks (Nelson *et al*., 2019). Interestingly, food prices decreased significantly, the income of rural dwellers increased, poverty declined by almost a double in Asia between 1970-1995, and conservation of marginal forest lands (Pinstrup-Andersen and Hazell, 1985; Evenson and Gollin, 2003; Pingali, 2012; Stevenson *et al*., 2017). Simultaneously, with some important exceptions, countries in the African continent performed below their agricultural potentials due to insignificant employment of external inputs (Shimeles *et al*., 2018). The resulting poor agricultural productivity and growth coupled with high population increase necessitated these countries to be net importers of food. The Green Revolution made significant economic progress but also created critical challenges such as pesticide impacts, pollution, land degradation, loss of biodiversity, unsustainable use of water and other resources. Naturally, agriculture is the highest user of natural resources such as water, land or nutrients, although the extent of their uses depends on a particular farming system. As noted by Mancosu *et al*. (2015) major land portions are used for agriculture, and the sector consumes 70% of the water used globally. Consequently, agricultural practices put huge pressure on greenhouse gas emissions and climate change, contribute majorly to the distortion of ecological services and functions. Moreover, with, the associated temperature increase due to climate change, it is expected that agro-yield levels, particularly in the third-world countries, will be reduced (Huang *et al*., 2015; Vetter *et al*., 2017; Perrone, 2018). Some of these occurrences can be curtailed and controlled through deliberate actions, changes in consumption patterns, efficient use of both renewable and non-renewable resources, the involvement of green technology, strategic positioning of institutional frameworks and implementation of salubrious policies for better agricultural regimes. The achievement of economic and environmental objectives of agriculture within the concept of sustainability would certainly influence the social construct through human development indices such as quality education, better health, well-being, and social infrastructure. Thus, the tripod dimension of sustainable development will receive a significant boost from sustainable agriculture since its achievement seeks three things: economic profitability, social well-being and environmental stewardship.

The scope of the (SDGs) UN 2030 Agenda of 2015 integrates the three-dimensional angle of sustainable development as its subset. The various variants of sustainable developments including the SDGs are connected directly or indirectly to the many dimensions of sustainable agriculture. Sustainable agriculture can address hunger (SDG2), drastically reduce poverty (SDG1), increase productivity where the agents of change (SDG5 and SDG10) are invested on, stewardship of the natural resources is upheld (SDG6, SDG12, SDG14 and SDG15); innovation and technology play their significant roles (SDG9), and appropriate responses are taken to address climate change (SDG13). Further, sustainable agriculture has the potentials to stimulate economic growth and improve livelihoods (SDG8). These SDGs are also linked with sustainable agriculture in different decrees. The remainder that are linked to sustainable agriculture are SDG3 (through inclusive economic growth, nutritious products), SDG4 (through a capacity building), SDG7 (inadequate alternative energy), SDG11 (value addition in agro-system, ecosystem resilience), SDG16 (peace and justice in tandem with economic growth), and SDG17 (government involvement).

However, government and private institution involvement through partnerships, policies, regulations, laws, and investment has an overriding influence on sustainable agriculture. Fig. 2 depicts how SDG1 and SDG2 (concerned directly with improved productivity of agro-outputs; with organic manure, biofertilizers and biopesticides), SDG6, SDG12, SDG14 and SDG15 (concerned with efficient use and restoration of natural resources; with organic materials) and SDG7 (concerned with the provision of green energy; using non-fossil sources) are directly linked to green chemistry based on the consumption of green chemicals and employment of associated technology (SDG9). Thus, sustainable agriculture is directly linked to eight of the 17 SDGs with green chemistry as the deciding factor. Within the context of sustainable agriculture, innocuous substances are not only meant to substitute conventional chemicals but can also reverse the consequences of synthetic chemicals.

Concerning the 12 Principle of green chemistry, an organic substance which is renewable and biodegradable will satisfy most of the conditions given in comparison to synthetic chemicals (Perlatti *et al*., 2014; Song and Han, 2015; Ganasen and Velaichamy, 2016; Gonzalez, 2017; Saleh and Koller, 2018). However, their production in commercial quantities is limited because of optimization bottlenecks (Hassan and Gokce, 2014). Apart from being renewable and biodegradable, these organic chemicals/substances should produce less residual chemicals, energy and solvent; be safe and their production process should be. One relevant group of compounds to green chemistry worthy of mentioning are biofertilisers, regarded as bioactive compounds derived from the activities of bacteria, fungi or algae. Biofertilisers are capable of causing plants to uptake nutrients by their interaction with the rhizosphere of the benefiting plant (CarvajalMunoz and Carmona-Garcia, 2012; Igiehon and Babalola, 2017; Itelima *et al*., 2018). Apart from nutrient uptake, other benefits associated with biofertilisers are reduction in fertilizer usage, soil fertility improvement, tolerance to (a)biotic stresses, and improvement in crop yield (Kumar, 2018). Most biofertilisers are either phosphorus solubilizing or nitrogen-fixing (Yimer, 2019). Phosphorus solubilizing microorganisms release organic acids which dissolve phosphate and tricalcium phosphate bearing rock particles thereby facilitating plant uptake of phosphorus (Saeid *et al*., 2018). Phosphorus solubilizing microorganisms are not selective nor specific to particular plants but have broad-spectrum action (Bhattacharya, 2019). The nitrogen-fixing candidates fix atmospheric nitrogen into forms which are biologically available to plants, easing uptake into cells. The microorganisms involved in this category are either symbiotic or free living. Examples of microorganism that fix nitrogen are *Azobacter* (for rice, vegetable, wheat), *Azospirillum* (for sugarcane, rice), *Azolla* (for rice), *Rhizobium* (for leguminous crops), and blue-green algae (for rice). There is quite a significant body of evidence that demonstrate the application of biofertilizers is efficient in different kinds of crops, including cotton, tomatoes, potatoes and others (Htwe *et al*., 2019; Khanna *et al*., 2019; Gortari *et al*., 2019). Some of these biofertilisers also exhibit biocontrol activities and in this context dually function as biopesticides (Gortari *et al*., 2019).

5 Biopesticides: definition and scope

Biopesticides are considered as a naturally occurring organisms or bio-based formulations that control pests through different mechanisms of action (Tijjani *et al*., 2016). They are products or byproducts derived from animals (nematode; *Heterorhabditis* spp.), insects (Trichogramma spp.) plant parts or extracts (example, a finely ground flower of *Chrysanthemum cinerariaefolium*) and microorganisms (*Bacillus thuringiensis*, *Verticillium*, *lecanii*, *Neodiprion sertifer*) (Pavela, 2014; Rodgers, 1993). However, there is a deviation in the generally accepted definition, as it is that natural products should be regarded as chemical pesticides, if they can have an impact on the pest nervous system (Marrone, 2019). For example, rotenone, as a plant-based pesticide, has the potency of killing and controlling insect pests by exerting its toxic effect primarily on nerve and muscle cells (Singh, 2014). Similarly, nicotine (a fast-acting nerve toxin), sabadilla (affects nerve cell membrane action), pyrethrins (interrupts the normal transmission of nerve impulses), and fluoroacetate (causes depletion of glutamic acid thereby affecting the nervous system) are all effective pesticides that interfere with the insect nervous system (Oguh *et al*., 2019). However, most literature classifies these compounds as botanical pesticides (Brudea *et al*., 2012; Chengala and Singh, 2017; Bateman *et al*., 2018; Arshad *et al*., 2019). A chemical homologue of a biopesticide can also be regarded as a biopesticide (Oguh *et al*., 2019). Biopeticides intended for the control of herbivorous insects or pests can be regarded as phytosanitory biocontrol agent or bioproduct.

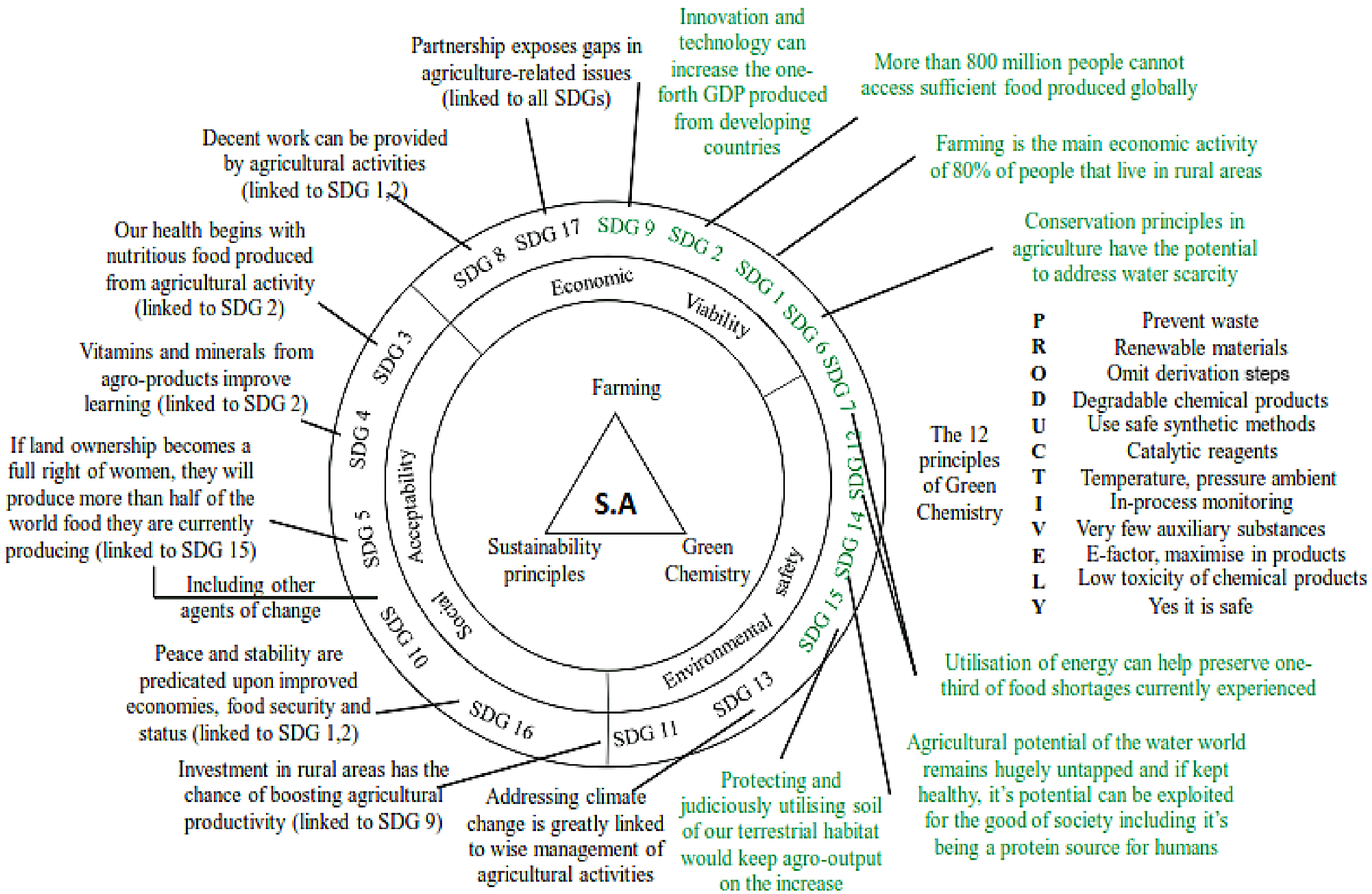

Figure 2. Connection of sustainable agriculture and 8 SDGs and green Chemistry (Adapted from Anastas and Warner, 1998; FAO, 2013)

5.2 Biopesticides' categories and their modes of action

Biopesticides are either microbial, biochemical or plant-incorporated protectant (PIP) biopesticides. Their modes of action come under five groups: neuromuscular toxins, metabolic poisons, gut disruptors, growth regulators, and non-specific multi-site inhibitors based on the physiological processes they affect (Spark and Nauen, 2015). However, some of the modes of action are still not specifically clear, especially with biochemical biopesticides. Microbial biopesticides exert their control through antagonism, predation, parasitism, and antibiosis (Mishra *et al*., 2018) For a natural substance to be considered as a biochemical biopesticide, its mechanism of action must be nontoxic (Ivase *et al*., 2017; Inam-ul-Hag *et al*., 2019). Plant-incorporated protectants are dependent on the incorporated molecule which may be derived from microorganisms or plants.

5.1.1 Microbial biopesticides

Microbial biopesticides could be bacteria, fungi, viruses, protozoa and nematodes, or compounds derived from these organisms that influence pest activities, through competition, pathogenicity or inhibitory toxins. These agents are broadly divided into multifactorial microbial generalists and hyperparasitic microbial specialists. The generalists control a wider range of pests whereas the specialists act against a particular pest. More than 3000 microbes have been recognized to cause diseases in insects implicating two major groups of nematodes (*Steinernema*; 55 species and Heterorhabditis; 12 species), more than 100 bacteria, 800 fungi, 1000 protozoa, and 1000 viruses (Sparks *et al*., 1999; Dowds and Peters, 2002; Casadevall, 2007; Mills and Kean, 2010; Ravensberg, 2011; Lewis and Clarke, 2012; Singh *et al*., 2015; Nawaz *et al*., 2016; Marche *et al*., 2018; Ruiu, 2018). Specific examples are *Bacillus thuringiensis*, *Paenibacillus* (bacteria), HearNPV (Baculovirus), *Metarhizium anisopliae*, *Verticillium* (fungi), *Heterorhabditis*, *Steinernema* (nematodes), *Nosema*, *Vairimorpha* (protozoa), *Chlorella*, *Anabaena* (microalgae; Costa *et al*., 2019). This category of biopesticides has the advantages of specificity (non-pathogenic to non-target), synergisms (can be used alongside synthetic pesticides), eco-friendliness (their residue has no negative impact on the ecosystem or eco-receptors), permanent effects (the microorganism becomes an integral component of the insect population or its habitat exhibiting the inhibitory effects) and growth improvement to plants (Nawaz *et al*., 2016). However, our understanding of microbial pesticides is hampered by challenges such as detailed scientific research, ecological study, and mass-production technologies (Haase *et al*., 2015). These challenges may differ from the known and common entomopathogenic microorganisms.

The bacteria *B. thuringiensis* is entomopathogenic, and produces Bt toxins. When insects ingest Bt toxins, the following sequence of events occurs: binding of the toxins to the midgut receptors, a pore-forming process is triggered, disruption of the intestinal barrier functions and finally infestation leading to the death of insects. A similar mechanism is confirmed in mosquito and blackfly control with *Lysinibacillus sphaericus* (formally *Bacillus sphaericus*) active agent. In this example, the complementary biosynthesis of crystal proteins (BinA and B) and Mtx (mosquitocidal toxin) act as the insecticidal toxins (Ruiu, 2018). In instances of fungal infection, the host cuticle serves as a point of contact to fungi, and when the environmental conditions are favourable, fungal spores and conidia germinate. The enzymatic and mechanical actions enhance the penetration of the fungi into the host body. Consequently, the mycelia develop internally giving rise to different types of spores, conidia, metabolites, toxins and virulence factors (Ruiu, 2018). Baculoviruses exert their effects via the production of crystalline occlusion bodies, possessing infectious particles, in the host cell. Once contaminated food is ingested, the occlusion bodies within the midgut release virions (occlusion derived viruses; ODVs) affecting the membranes of microvillar epithelial cells through the action of their envelope proteins (Townsend *et al*., 2010). The cadaver of the affected insects liquefies thereby dispersing the virus particle in the environment. Symbiotic nematodes, transport entomopathogenic bacteria to the internal host system via natural openings. The bacteria elicit their insecticidal toxins and virulence factors and metabolites that encourage the reproduction of the obligate nematodes.

5.1.2 Biochemical biopesticide

Biochemical biopesticides are substances of natural origin with active agents to control pests by mechanisms that are not toxic to the host, the environment and humans (Kumar, 2012; Leahy *et al*., 2014). By this definition, a natural chemical can be considered a biopesticide if it acts as an attractant, deterrents repellant, antifeedant, suffocant, confusants, arrestants, or desiccant (Stankovic *et al*., 2020). Being natural implies that such chemicals would be discrete or mixed bioactive substances from nature. However, a synthetic analogue that is identical to a natural compound, both structurally and functionally (exhibits the same mode of action). Certain factors have made some synthetic analogues of naturally occurring substances to dominate the commercial market (Dang *et al*., 2016). Although toxicity is a subjective term, a substance could be said to be nontoxic if direct lethality of the target host does not arise as a result of the chemical or biological interference of the substance active ingredients with the physiology of the target pest. This definition does not guarantee the absence of ill-fated biochemical and metabolic reactions in the target pest organism by the presumed nontoxic substance. Instead, the initiation of such ill-fated reactions is linked to one or more physical processes attributable to the substance. For instance, essential oil causes asphyxia (a physical process) which obstructs pest respiration leading to death. A substance still merits the nontoxic status if its active ingredients invoke biochemical reactions that interfere with the behavior or reproductive system of the target pests without resulting in death. A substance is environmentally safe if it is exogenous to that environment and has no impact on the physicochemical signature of the environment or affects the ecological services provided by that environment and causes no distortion or harm to ecological receptors including wildlife and humans. Chemicals that pass these criteria of naturalness, nontoxicity and eco-friendliness are semiochemicals (pheromones and allelochemicals), essential oil (from neem, sour orange), insect growth regulators (juvenile hormones, chitin synthesis inhibitors), plant growth-promoting regulators (Rhizobacteria) and natural minerals (diatomaceous earth, kaoline).

The semiochemical mode of action (MoA) is concerned with the disruption of hormones and neuropeptides associated with metamorphosis and insects' growth. The MoA of mineral-based insecticides (kaoline, insecticide soaps, diatomaceous earth) is mostly physical. The abrasive nature and sorption properties of diatomaceous earth, and the waxy layer of insects are damaged giving way for desiccation and eventual death (Nukenine *et al*., 2010; Sousa *et al*., 2013). Similarly, kaoline exerts its insecticidal effect through its sorption property, which causes desiccation in insects. Besides, surface activity, the coating property of kaoline can cause reduced sublethal effects, repellence and oviposition deterrence (Yee, 2008). The mode of action of insecticidal soap is expressed through cuticle dissolution leading to suffocation and desiccation. Bioactive compounds in botanical extracts can cause inhibition of hyphal growth, structural modifications of mycelia, changes in the cell wall, partitioning of cell membranes, and separation of the cytoplasmic membrane in entomopathogenic fungi (Lengai and Muthomi, 2018). Plant extracts apart from inducing behavioral changes (as it concerns feeding habit, oviposition and mating behaviour) in insect pests also inhibit insect reproduction, growth and development. Essential oils act as antifeedants, repellants, and oviposition deterrents. Besides, they possess active ingredients that make them larvicidal, ovicidal and insecticidal thereby displaying properties that interfere in all stages of insect metamorphosis (Sarma *et al*., 2019). The MoA of semiochemicals acts by inhibiting lipid biosynthesis resulting in a significant decrease in total lipids in immature insects (Linda *et al*., 2010), disruption and prevention of metamorphosis caused by the binding of juvenile hormone analogues to the receptor of juvenile hormone in insects (Jindra and Bittova, 2020), and inhibition of moulting and chitin synthesis which determines growth and development of insects (Cohen, 2001; Ullah *et al*., 2019).

5.1.3 Plant-incorporated protectants

A plant-incorporated protectant (PIP) is a biopesticide produced by a gene inserted into a plant through transgenesis (Ibrahim and Shawer, 2014). PIP does not require killing the pest but renders the plant unsuitable for an attack. In some cases, the protected plant may act as a repellant or disrupt the normal physiology of the insect pests when insects ingest PIPs. Once the PIP is ingested it overcomes the digestive and physical barriers and then gets to the target site where it acts. The digestive system has been confirmed as a strong determinant of insect vulnerability and susceptibility therefore, gut function disruption has been a common theme in the development and discovery of PIPs (Nelson and Alves, 2014). Insecticidal proteins, particularly Bt, are suitable for application in PIPs and are thus being explored in pest control (Koch *et al*., 2015). The insecticidal property of *Bacillus thuringiensis* was first discovered in

1902 against silkworm (*Bombyx mori*) and from then the search for Bt strains as an insect control agent has continued (Jisha *et al*., 2013). The insecticidal proteins from Bt are effective, diverse and specific thus they are widely used as a model in PIP biotechnology, however, Schwnek *et al*. (2020) has demonstrated that Bt shows non-negligible pathogenic potentials. The insecticidal crystal protein produced by Bt is known as Cry proteins (δ-endotoxins) but they are diverse thus, they exhibit insect selectivity. For instance, there are those that are selective for Lepidoptera, Coleoptera and those for Diptera (Maciel *et al*., 2014). Currently, no less than 70 classes (based on sequence homologies and target selectivity) of Cry proteins have been used to protect corn, cotton, potato, soybean and other crops (Pardo-Lopez *et al*., 2013). The Cry proteins are toxins produced during the sporulation period but toxins produced during the vegetative phase are called vegetative insecticidal proteins (Vips) and are commonly used in PIPs. More than 50 Vips proteins, including Vips 1, Vips 2 and Vips 3, have been reported (Shingote *et al*., 2013; Chakroun *et al*., 2016; Sopko *et al*., 2019). Other insecticidal proteins from other bacteria proved to be effective in transgenic control are toxic complex (Tc) proteins expressed by *Photprhabdus* and *Xenorhabdus* (Shingote *et al*., 2013). Also, plants possess transgenic enzyme inhibitors that have been explored in PIP technology, for example, α-amylase inhibitors (Franco *et al*., 2002). Mir1-CP protease from maize, enhancing protease from Baculovirus has also shown potency in protecting plants via the PIP technology (Mohan *et al*., 2006; Wei *et al*., 2018). Besides, double-stranded ribonucleic acids (dsRNAs) are commonly used as approved PIPs (Parker and Sander, 2017) due to the rapid progress in ascertaining RNAi biological processes (Liu *et al*., 2020). The dsRNA triggers host-induced gene silencing and protein synthesis inhibition which improves endogenous gene expression in plants while causing increased pest mortality within the plants (Raruang *et al*., 2020).

The Bt mode of action could be explained based on the correlation of the Cry protein ingestion and insect susceptibility. Once the Cry protein reaches the midgut after ingestion it attacks the “brush border” epithelium with the attendant manifestation of feeding cessation (Lee *et al*., 2003) With the right concentration of the toxin, ATPases concerned with active transport, become inhibited, followed by modulation of endogenous potassium channels and pore formation that occasionally leads to uncontrolled ionic flux, the collapse of normal cellular function and death (Knaak *et al*., 2010). As noted earlier, the Cry proteins exist in different classes and structures with structure-dependent toxicities specific to particular insect orders. For instance, Cry 3 and Cry 1 proteins are toxic to Coleoptera and Lepidoptera respectively (Chakroun *et al*., 2016). In the case of the dsRNA, after ingestion, it becomes biochemically cleaved by dicer into small molecules of interfering RNA (siRNA of ca. 20 nucleotides) after getting in contact with a target cell in the gut of insects (Sopko *et al*., 2019). The machinery of the RNA interference (RNAi) aids siRNA targeting mRNA for destruction (Zhou and Rana 2013). The destruction of the targeted mRNA inhibits its translation into proteins, essential for the insect pest thus leading to reduced growth or death (Rodrigues and Figueira, 2016). The dsRNA PIP, the regulatory approved in this class was used against corn rootworm by inhibiting the synthesis of SnF7 proteins necessary for vacuolar sorting protein (Ramaseshadri *et al*., 2013; USEPA, 2017). The prospects of RNAi PIP are higher in insects with long dsRNA because of the higher number of siRNAs. The three different categories of biopesticides are illustrated in Fig. 3.

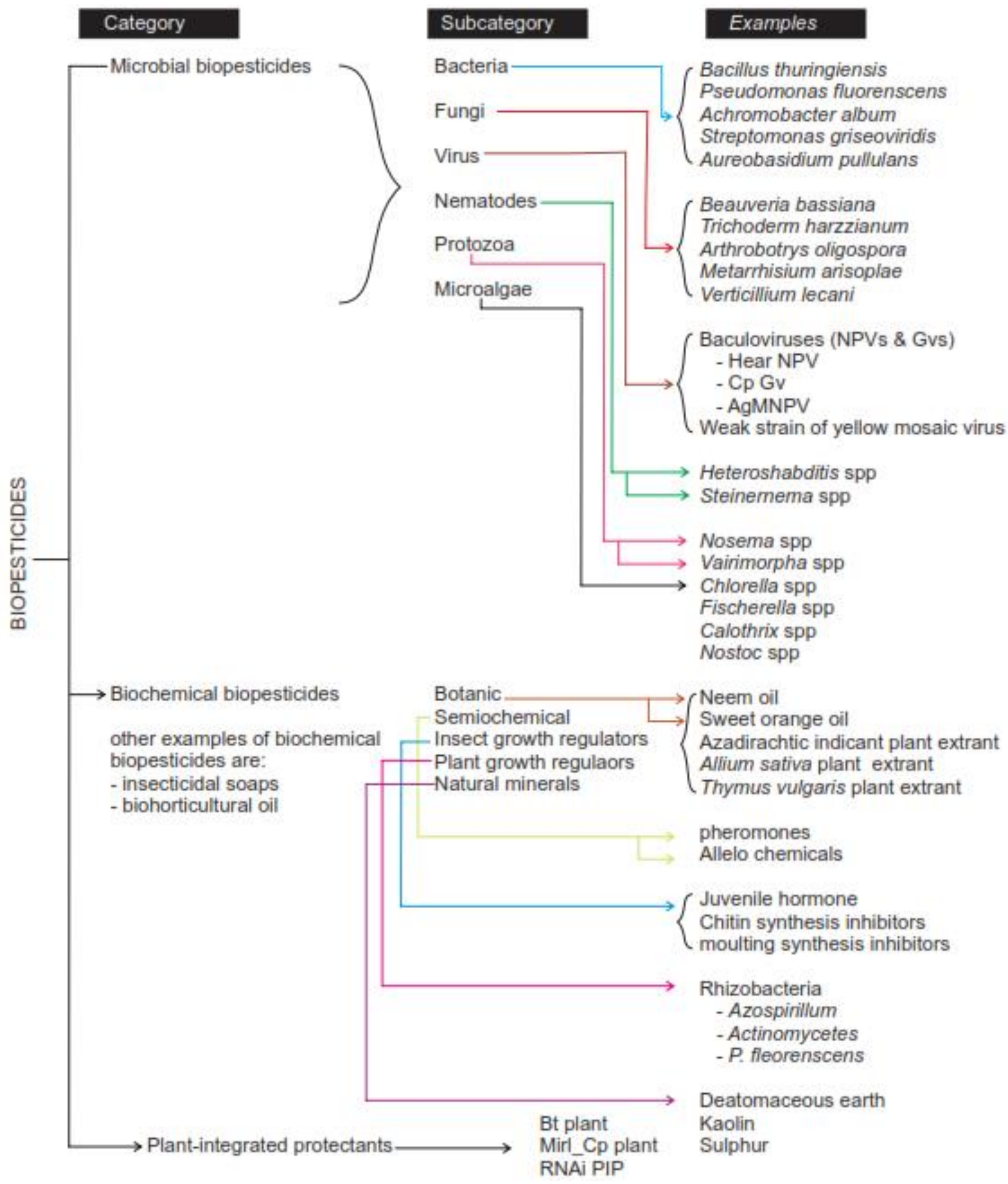

Figure 3. The three different categories of biopesticides and some selected examples

5.2 Production, commercialization and market prospect of biopesticides

Biopesticide production starts with bioprospecting from the natural environment, screening (*in vitro*), *in vivo* experiments, purification, formulation and registration (Fig. 4) (Lengai and Muthomi, 2018). Botanical pesticides are obtained from plants in the natural environment while microbial bioprospecting can be obtained from compost, manure or rhizosphere. Botanicals are first cleaned of impurities, extracted and the extracts are then screened *in vitro* against pest of interest using different methods (Altemimi *et al*. (2017). From the screened plants, the most effective plant can be evaluated through field-trials, and from these plant extract the most active constituents can be identified and ascertained for optimum formulation (Khot *et al*., 2012) The active compounds are usually identified with either or in a combination of different spectrometric techniques including high-performance liquid chromatography (HPLC). The active ingredients are further combined with carriers, surfactants, emulsifiers and other components, followed by intensive *in vitro* and laboratory trials and optimization until such a product is ascertained to be efficacious. Once the efficacy trial is confirmed to be successful, the product can be registered with concerned regulatory body or bodies. For microbial biopesticides, isolated pure cultures are maintained in agar slants. *In vitro* efficacy trials are conducted through culture and diffusion methods (Oikeh *et al*., 2016). Suitable substrate medium for the active microbial agents is prepared in the lab and mixed with other components (that will not inhibit microbial growth) such as enhancers, carrier materials and stabilizers. The fficacy of the product is ascertained after repeated laboratory and field trials against the target pest(s). The stability and efficacy of active compounds of biopesticides lie in the formulation of the active compounds. Formulation of pesticides, in general, is a necessity for effective control of pests however for a particular application method.

Formulation of the active ingredients of bio-based pesticides are in principle the same as that of the formulation required for synthetic pesticides. Usually, the formulation consists of the active ingredients, adjuvants and carriers that will guarantee sustained bioactivity of the active agent, protection of the products from environmental conditions, storage stability, easier handling, and interaction with the target pests when applied in field settings (Gasic and Tanovic, 2013; Sharma *et al*., 2019). Based on the physical state, biopesticide commercial products are divided into dry and liquid formulations. Liquid formulations come as emulsions, oil dispersions, suspension concentrates. Dry formulations come in the forms of dust, powder, granules, wettable powders, and water dispersible granules (Knowles 2005). Emulsions are liquid droplets dispersed in a different immiscible liquid with phase droplet size of between 0.1 and 10 μm. Emulsions are usually regarded as oil in water but can also be in the inverted form (water in oil as in essential oils). Suspension concentrate consists of an insoluble finely ground active compound in a liquid (water) phase (Vimala and Vineela, 2015; Seaman, 1990). Their particle size distribution is between 1-10 μm. Oil dispersions are solid active ingredients dispersed in non-aqueous liquids, especially in plant oil. Biopesticide dusts are formulations made of an active ingredient and finely ground solid mineral powder with a particle size of between 50-100 μm. Powder formulations are produced by mixing an active ingredient, carrier and adjuvant that will facilitate adherence of the product to seed coats (Chen *et al*., 2013). Granules formulation are similar to dust formulations except that the granular particles are heavier and larger (100-1000 μm). Wettable powders are formulations made up of finely active ingredients (5 μm), surfactants, dispersing agents and inert fillers which are used after suspension in aqueous medium (Tadros, 2005). Water dispersible granules are a powder formulation to be used when dispersed in water.

Currently, biopesticides command a 5% pesticide market, with a corresponding value of approximately $3billion globally (Damalas and Koutroubas, 2018) and are increasing at an annual growth rate of between 10-15% (Marrone, 2014). The likely pressures behind this increase are demands for organic vegetables, tree crops and vineyards; and the need for improved food safety. Thus far, the average product number of registered biopesticide products in India is 970; in the US they are 452 and 86 in Europe (Hassan and Gokce, 2014; Mishra *et al*., 2020). Microbial biopesticides share 63% of the global biopesticide market (Hassan and Gokce, 2014), with *Bacillus thuringiensis* derived products accounting for 90% (Kumar and Singh, 2015). Other microbial biopesticides that have made significant in-roads in market penetration are *Trichoderma gamsii*, *Trichoderma harzianum*, and *Beauveria bassiana* (Mishra *et al*., 2020). Botanical biopesticides, on the other hand, are dominated by the essential oil, pyrethrins, rotenone, and azadirachtin.

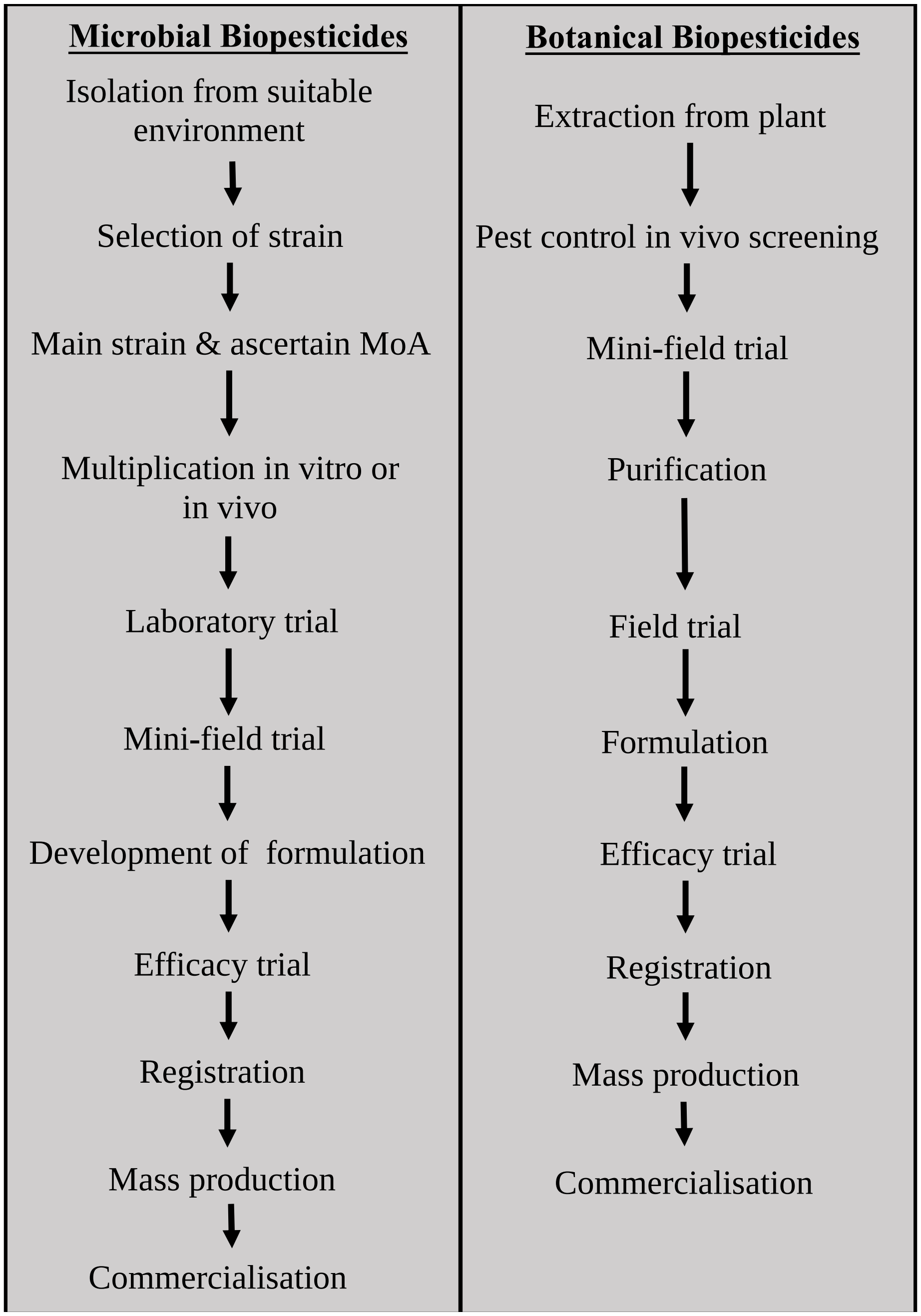

Figure 4. Commercial production chart of microbial and biochemical biopesticides (Adapted from Lengai and Muthomi, 2018)

Table 1, 2 and 3 display a few selected commercial products and their manufacturers. It was projected that biopesticides would have equal utility in plant protection by 2050 in comparison to the role currently played by chemical pesticides. This would become a reality if Africa and Southeast Asia, make a sincere and concerted effort in bringing about changes in farming practices (Olson, 2015) as well as investing in research in this direction. However, biopesticide production and consumption is hindered and will continue to be so unless all stakeholder, including, end-users, marketers, regulators and researchers involved in the development and commercialization chain, align to the same objectives. For instance, marketers often disagree with researchers and regulators to such an extent that the end-users get dissuaded about the potency of the final products (Kumar and Singh 2014). Furthermore, researchers are discouraged due to the daunting procedure of documentation, submission procedures and registration required for a product to enter the market. Often, the process takes several years, coupled with the high cost involved in the registration of new pest controlling agents. These factors, as well as others that are unique to various regions of the world, contribute to higher cost of biopesticide products. Moreover, the social acceptability of biopesticides compared to the conventional and long-accepted synthetic chemical pesticides, as well as the end-users' perception of biopesticide "slow action" are strong aggravating factors. To maximally exploit the prospects of biopesticides, regulatory authorities should have a fast and flexible but not-quality-compromising requirements that consider the morally relevant differences that mitigate their use compared to synthetic pesticides especially in the registration process. Additionally, special concessions should be provided for organizations, institutions and individuals to encourage them during biopesticide production and registration. It is expected that more efficacious biopesticides would be produced in the future.

5.3 Biopesticide prospects and limitations

A close examination of biopesticides and conventional synthetic pesticides demonstrates parallel similarities, particularly in potency. Conventional pesticides have a broad-spectrum effect, are quicker in action, have longer residual activity, are highly effective against target pests, and are convenient (Felsot and Rack, 2007; McCoy and Frank, 2020). The negative effects of synthetic pesticides have prompted the placement restrictions on a significant number of them. Approximately 1000 active ingredients of conventional pesticides were authorized in 2001, but there has been a decline, to as low as 250 in 2009 (Jensen, 2015) and the entrance of new chemical pesticides has also reduced from 70 in 2000 to 28 in 2012 (McDougall, 2013). This new perspective has given impetus to the increased demand for alternative pesticides that must counteract the negative effects that are leading to the slow demise of questionable practice of chemical pesticide applications. Biopesticide usage tends to have little or no harmful effects on nontarget organisms, humans, and the environment due to its specificity and low toxicity compared to synthetic pesticides. It has been hypothesized that in the near future biopesticides can replace synthetic pesticides without significantly affecting crop yield (Leng *et al*., 2011; Arora *et al*., 2016; Mishra *et al*., 2020). At present an operational compromise appears to be in the utilization of biopesticides in conjunction with synthetic pesticides, which has also proven effective both quantitatively and qualitatively (Ujagir and Byrne, 2009). It is not an ideal solution but has its merits in the reduction of pollution and deleterious effects that would otherwise be the case with sole use of these synthetic pesticides. One of the outstanding benefits of the use of biopesticides is their eco-friendliness. They are easily biodegradable and produce minimal residues thus, their presence in the air, water and terrestrial ecosystems is absent or minimal. The high specificity of biopesticides guarantees that they only harm the target pests and encourage the proliferation of beneficial organisms such as pollinators, predators and parasitoids for the overall benefits to protected crops. Further, biopesticides have proven to be effective against insect pests that have developed resistance to conventional pesticides. By extension, the insurgence of secondary pests will be limited if not completely obliterated. In this sense, the continued use of conventional pesticides would mean spending more for the poor results, increasing environmental impacts and health challenges.

Table 1. Commercial examples of biopesticides (adapted from Mondal and Parween, 2001; Kabaluk *et al*., 2010)

Product name	Active ingredient	Plant species	Company
Botanical insecticides			
Prentox Pyrethrum	Pyrethrins	*Chrysanthenum cinerariaefolium*	Prentiss
Py-rin Growere	Pyethrins	*Chrysanthenum cinerariaefolium*	Wilbur-Ellis
Pycon	Pyrethrins	*Chrysanthenum cinerariaefolium*	Agropharm
Premim Pyganic	Pyrethrins	*Chrysanthenum cinerariaefolium*	MGK
Neemx 90 EC	Azadirachtin	*Azadirachta indica*	Thermo Trilogy
NeemAzal	Azadirachtin	*Azadirachta indica*	Trifolio-M
Trineem	Azadirachtin	*Azadirachta indica*	Tagros
Vironone	Rotenone	*Derris* spp.	Vipesco
Rotenone-Copper	Rotenone	*Lonchocarpus* spp.	Bonide
PBNox	Rotenone	*Tephrosia* spp	Penick
Stalwart	Nicotine	*Nicotiana tabacum*	United Phosphorus Ltd
Nicotine 40%	Nicotine	*Nicotiana tabacum*	Dow AgroScience
Natur Gro R-50	Ryania	*Ryania speciose*	AgriSystems International
Veratran D	Sabadilla	*Schoenocaulon officinale*	Dunhill Chemical
Nemguard	Garlic extract	*Allium sativa*	ECOSpray Ltd
Botanical fungicides and	bactericides		
Bioxeda	Clove oil	*Syzygium aromaticum*	Xeda International
Iodux 40	Laminarin	*Laminaria digitata*	Geomar
Vertigo	Cinnamaldehyde	*Cassiatora* spp.	Monterey
Milsana	Milsana	*Reynoutria sachalinensis*	Geomar
Botanical herbicides			
Interceptor	Pine oil	*Pinus* spp.	Certified Organics Ltd
Barrier H	Citronella oil	*Cymbopogon* spp.	Barrier Biotech Ltd
Hinder	Pelagonic acid	*Geraniaceae* family members	Amvac
IGR commercial products			
Applaud	Buprofezin	Protects rice against homopteran pests	Nihon Nohyaku
Logic	Fenoxycarb	Protects apples from worms	Ciba-Geigy
Atabron	Chlorfluazuron	Protects vegetables, cottons against lepidopteran pests	Trigard

Table 2. Commercial products of different microbial pesticides

Microbial biopesticide	Insect.	Fungi.	Bacteri.	Others	Commercial product	Company	Reference
Bt and sub species	*				Dipel	Valent BioScience	Li *et al*. (2007)
		*			BT Sulfur 15-50	Loveland Products Inc	www.greenbook.com
			*		Defender	Arbico Organics	Mishra *et al*. (2015)
				1	Thurisav-3	Agrochem	Kabaluk *et al*. (2010)
Bacillus subtilis				1	Sting	Stanes Company	Berlitz *et al*. (2014)
Pseudomonas fluorenscens				1	Bio-Cure-B	Stanes Sompany	Khalil *et al*. (2012)
Aureobasidium pullulans			*		Blossom Protect	Bio-Ferm	Rosello *et al*. (2013)
Salmonella enteriditis subsp. danysz				3	Biorat G	LabioFam	Kabaluk *et al*. (2010)
Streptomyces griseoviridis K61		*			Mycostop	Arbico Organics	Bailey *et al*. (2010)
Lactobacillus spp				2	Organo-Sol	Organica	Kremer (2019)
Beauveria bassiana	*				Mycotrol	Mycotech Corp.	Steinkraus and Tugwell (1997)
Trichoderma harzzianum		*		1	Plant Guard	Ajay Bio Tech	Radwan *et al*. (2018)
Sclerotina minor IMI 344141				2	Sarritor	Redox Industry Limited	Abu-Dieyeh and Watson (2007)
Baculovirus	*				Cyd-X	Certis USA	Quarles (2013)
AgNPV	*				Baculovirus Nitral		Haase *et al*. (2015)
Yellow Mosaic Virus (weak strain)				4	AgroGuard-Z		Urek *et al*. (2017)
Nematode	*				Nemabact		Ilyashenka and Ivaniuk (2008)

Insect. = Insecticide, Fungi. = Fungicide, Bacteri. = Bactericide, 1= Nematicides, 2= Herbicides, 3= Rodenticides, 4= Viruside

Table 3. Latest commercial phytosanitory bioproducts, their target pest and protected plants

S/No	Product (Manufacturers)	Active ingredients	Disease/pest controlled (Host)	Remarks	References
1	Grandevo DF 2 (Marrone Bio Innovations)	*Chrombacterium subtsugae* sp. PRAA4-1	*Tetranychus urticae* (Tomato + more than 150 plant species)	The bioproduct significantly reduces fecundity of adult pest and nymphal mortality	Golec *et al.* (2020)
2	Agree WG (Cetis USA)	*Bacillus thuringiensis*	Lepidopterous larva	Controls both resistant and non-resistant diamondback moth larvae	Sterk *et al.* (2020)
3	Nogall (Bio-Care Technology)	*Agrobacterium radiobacter* sp. K1026	Crown gall (Grapes plus thousands of plant species)	Strain K1026 produces toxic compounds that inhibits other *Agrobacterium* spp. that cause the disease	Kerr and Bullard (2020).
4	Biogard (CBC and Intrachem Bio)	*Bacillus* thuringiensis	Glassy clover land snail (Cotton field)	The product causes luminal secretion and hemocyte infiltration causing molluscicidal activity in the *Munacha*. *cartusiana* snail pest	El-Atti *et al.* (2020)
5	Tricotop (Biotop)	*Trichoderma* spp.	Fungal pathogens of vegetables	The product is a cold adaptive biocontrol agent active with 0C	Morel *et al.* (2020)
6	Zequanox (Marrone Bio Innovations)	Dead cells of *Pseudomonas fluorescens*	Mussels	Mussels ingest the product as food and once consumed, the mussel stomach lining becomes ruptured with consequent death	scr.zacks.com (2020)
7	Aflasafe SN01 (BAMTAARE-IITA)	*Aspergillus flavus* genotype native to Senegal	Aflotoxin (Ground nut, maize)	Effective bioagent for aflatoxin mitigation	Senghor *et al.* (2020)
8	BotaniGard ES (BioWorks)	*Beauveria bassiana*	Aphids (Banana plus host of other plant species)	BotaniGard act by contact enabling the active agent to grow on the cuticle of the insect pests	Prince and Chandler (2020)
9		Protease inhibitors (PIs)	Diverse pests	PIs are legumes' proteins that inhibit protease activity of phytopathogens	Roddriguez-Sifuentes *et al.* (2020)
10	Spray-induced gene silencing (SIGS)	Interference RNA (RNAi)	Diverse pests	dsRNA is an emerging biopesticides in which RNAi influence the degradation of target pest mRNA causing gene silencing and subsequent synthesis of vital protein	Zhang et al. (2020) Biedenkopf *et al.* (2020)
11	Metarril E9 (Koppert)	*Metarhizium anisopliae*	Asian longhorned beetle	The active agent produced more conidia on the surface of pest cadavars and on a wider thermotolerance with optimum ranges of 25-30 ºC.	Clifton *et al.* (2020)

Table 3. Continued

S/No	Product (Manufacturers)	Active ingredients	Disease/pest controlled (Host)	.Remarks	References
12	Nemastim (Pheronym)	Nematodes	Insect pests	The product results in a 5X insect kill in comparison to EPN	Fatma Kaplan (2020).
13		*Beauveria bassiana*	wheat weevils (Grain silos)	The active agent is an highly resistant microsclerotia used against insect in grain silos	Trejo *et al*. (2020)
14	Not provided	*Bacillus thuringiensis* sp. JXBT-0296	Root and butt rot of Cassia nodosa (+ hundred species of trees)	Strain JXBT act as an excellent insecticide of Ganoderma lucidum (moths) that causes the root and butt rot disease	Fenshan, W. (2020).
15	*Antifungal	Crucifalexins	Grey mould (Wine grapes + more than 200 plant species)	Potent antifungals synthesized from brassinin through engineered metabolic pathways	Calgaro-Kozina *et al*. (2020)
16	*EPN	*Heterorhabdits* spp	Pod borer (Beans)	Efficacy comparable to commercial H. indica	Thakur *et al*. (2020) Vashisth *et al*. (2019)
17	*EO	Polyphenolic extracts	Mediterranean Fruit fly	Active ingredient extracted from olive mill wastewater	Ilio and Cristofaro (2020)
18	*Fumigant	Monoterpenes	*Drosophila suzukii* (soft-skinned fruit crops)	Monoterpenes interact with Drosophila suzukii type 1 tyramine receptor thus having an inhibitory effect on the target pest	Finetti *et al*. (2020)
19		*Aspergillus flavus* F3	*Elasmolomus pallens* (Groundnut)	The strain F3 is active against *E. pallens*, a post-harvest pest of groundnut	Umaru and Simarani (2020)

Note: 1-11 (Recently registered biopesticides or existing biopesticides whose proof of efficacy has been recently proven); 12-14 (Patented biopesticides); 15-19 (Recent research backing a positive proof of concept). *Potential formulation

Furthermore, biopesticides would greatly reduce the effect of bioaccumulation of toxic compounds in the food chain that are likely affecting humans, especially infants and adults (Kumar, 2012). The use of crudely extracted plant insecticides, has been demonstrated to be more economically attractive and successful in agro-dependent rural areas in controlling insect pests in comparison to synthetic compounds (Tulipa and De, 2019). For example, *Tephrosia vogelii* is a pesticidal plant used by 80% of farmers in southeastern Africa. Commercial cultivation relies heavily on pesticidal plants (Stevenson *et al*., 2017). Thus, cultivation of pesticidal plants can provide an opportunity for acquiring additional income through entrepreneurial ventures. These advantages of using biopesticides (see Table 4) ranging from environmental stewardship to healthy foods and feeds for animal consumption and the lessening of health issues have not been fully achieved due to certain challenges. These challenges are responsible for limiting the full adoption of biopesticides as pest and disease control options. One such constraints in relation to the application is dose determination of the active ingredients from biopesticide sources under real-life conditions (Shiberu and Getu, 2016). This limitation is compounded because of the bioactive compounds' concentration, as it is influenced by the environment under which these pesticidal plants grow and also by their varieties. The diversity of these pesticidal plants results in differences in their responses to pathogens and herbivores (Ghorbani *et al*., 2005; Sale *et al*., 2016). Moreover, dose inaccuracy may be affected by the method of extraction, which may reduce the concentration or processing methods (Sesan *et al*., 2015). The disparity of efficacy determination during laboratory tests versus field tests is also a source of limitation. Additionally, the rapid development process and production of pesticides in different regions around the world implies that there are few, if any, standard preparation methods and guidelines for the determination of field efficacy of most of the active components of these new or modified biopesticides. The susceptibility of biopesticides to several environmental conditions including moisture and temperature tends to reduce the product shelf-life. This is made worse in uncontrolled environments such as those found in the field (Koul, 2011). Microbial biopesticide formulations especially those of fungi and viruses display limited activity spectra against pest complexes; and their effectiveness is a function of the dynamic interaction between the environment, pathogens and the hosts (Ansari *et al*., 2012).

Some of the recognized limitations for microbial biopesticides are the need for highly virulent strains, complex handling requirements, intricate life cycles of candidates, and the phenomenon of slow biochemical activity, often a consequence of microbial lag phase and time needed for acclimatization and production of enzymes in response to identified threat (Glare *et al*., 2016). The combination of these limitations results in variable effects, which are considered significant challenges to research and development. In addition, there is a significant cost during product development. For example, cost incurred from substantial product feasibility studies, data gathering, and chemical analyses, such as toxicity testing, characterization of active ingredients and formulation as well as label articulation and packaging, are all tedious processes required from a regulatory standpoint for product acceptability and registration. These processes often serve as a deterrent for most innovators and researchers, preventing the product from reaching commercialization, due to resource limitations (Stoneman, 2010). Consideration of the initial substantial investment requirements versus turnover and profit margins for potential biopesticide start-up companies, particularly with limited product lines, provides little encouragement or incentives to investors. In most instances, these fledging companies must also include capital finances for the construction of new facilities and initial production costs. However, a possible solution to the latter, especially with a single product line, will be from government investments into facilities and infrastructural development which these researchers may employ in product development and commercial production, but are charged a fee, which significantly reduces the financial burden. Additionally, Kumar and Singh (2014) highlight the resistance to broad applications of biopesticides by farmers in developing countries and the lack of trust, which they attribute to insufficient information and a lack of awareness of the efficacy of these biopesticides and the misunderstanding, especially, with microbial pesticides within the value chain. It is also important to note, that currently available biopesticides have been shown to have increased effectiveness when complemented with varieties of pest control methods using the integrated pest management approach (Grasswitz, 2019).

Table 4. Merits and demerits of biopesticide (Adapted from Hassan and Gokce, 2014; Marrone, 2009)

Factor	Advantages	Disadvantages
Eco-friendliness	Biopesticides have low toxicity against humans and the environment	Due to their low toxicity, biopesticides exhibit slow action against target pest
Environmental persistence	Biopesticides when applied leave little or no residues thus have no pre-harvest interval. This factor is key in export crops	
Multi-mode of action	Due to their multiple mode of action, pest hardly develop resistance or cross-resistance to biopesticides	
Biodegradability	Biopesticides are characteristically low volatile compounds does pose risks to the environment and its receptors	Poor stability is often between 2-4 days which necessitate frequent and repeated application for effective eradication
Specificity	Biopesticides have little or no adverse effect on non-target organisms	Biopesticides limit actions against broad range of pests thereby would require diverse plant protection strategies
Safety profile	Safety during application, makes it convenient for workers to complete agro-assignment on timely basis, including harvest operation	
Suitability in IPM	Biopesticides has the potential of surpassing conventional control agents when used in IPM programme and reduce the use of classical pesticides	
Usefulness of co-wastes	Wastes from biopesticides production are used as fertilizers	
Improving productivity	Use of biopesticides lead to increased yield and in complete sense defines organic farming producing and wholesome and toxin-free food and crops	
Cost	Cost to develop biopesticides is cost effective	Cost of production of a certified biopesticide product is comparatively higher
Standardization		Standardization of the quality of biopesticides remains a limitation

6 Biopesticides as a component in integrated pest management (IPM)

6.1 Definition and purpose of IPM

One unavoidable long-term outcome of using pesticides is the inevitable development of resistance and the outbreaks of secondary pests. Moreover, the understanding that there are often a myriad of pests that can attack a cultivation site has meant that any approach that will offer a lasting solution must use several approaches to tackle each of the problems. Apart from being science-based and sustainable, it is also a decision-making process that fosters the integration of cultural, physical, biological and chemical tools to identify and reduce the risk associated with pests for economic viability, social acceptability and environmental safety (USDA-ARS, 2018). Some practitioners see IPM as alternating chemical compounds with different mechanisms of action groups to establish pest control efficacy and reduce pesticide resistance (Dara, 2019). Elimination of pests, minimal consumption of chemical, promotion of environmental stewardship and human health preservation are overarching objectives with the IPM approach. There are at least 77 variances to the definition of IPM, most of which are based on operational interpretation, strategies and objectives, yet there is a core philosophy within the practice of IPM that is constant to most of its advocates (Dufour, 2001). The implementation of IPM is aimed at obtaining the best result at the lowest cost, generating the least hazard to humans and the environment and avoiding the development of resistant pest strains. Moreover, IPM generates positive externalities, including lasting effects on farmers' health (Naranjo *et al*., 2015). Reports from diverse literary resources have indicated that the implementation of IPM requires, to varying degrees, education, tools, consumer preference, regulation, governance, moral values, socio-cultural and economic conditions, environmental awareness and retail marketing (Parsa *et al*., 2014; Jayasooriya and Alheeyar, 2016; Rezaei *et al*., 2019). The intellectual buy-in of these factors in the implementation of IPM must be robust and represent a modern model of pest control management systems. This modern model of IPM underscores the science, art and enterprise components of sustainable crop production with four major components: knowledge and resources; planning and organization; communication and pest management (Dara, 2019).

6.2 The key components of IPM

Knowledge and resources, planning and organization, and communication are different elements that are crucial to the IPM scheme. Knowledge of pest biology and ecology, their potential risk to plants, various control strategies and options, and their suitability are key for farmers to make informed decisions regarding pest control (Asante *et al*., 2001). A lack of sufficient knowledge remains one contributing key factor limiting IPM implementation including the meaning and understanding of IPM (Adam *et al*., 2010). The identification of an effective control strategy also requires knowledge about the specific stages in the insect pest life cycle that are most damaging to the plant, their niches, the nature of the damage and their economic significance, seasonal population trends and vulnerability of each stage to control options (Lefebvre *et al*., 2015). The effectiveness of control options in IPM is critical because one effective option for a particular circumstance may not be effective in another different situation. Planting date adjustment is an effective control strategy for pests known to follow seasonal patterns, and during the favourable season, it can be controlled with natural enemies (Heimpel and Cock, 2018). While entomopathogenic nematodes have been confirmed to be effective against soil pests, viruses and bacteria can be effective against insect pests using chewing mouthparts and fungi against different kinds of pests (Zalom *et al*., 2018). The planning and organization component of IPM is concerned with data collection, raw data processing and informed decision making. It is important to know that regular monitoring of fields for pest spread precedes data collection. As a basic step of crop protection, early detection of pests of economic interest can allow for curbing them with minimal cost and less intricate control tactics and prevent intensification of damage. Drones in recent times have been employed in detecting and locating areas exposed to (a)biotic stressors through aerial imagery (Santesteban *et al*., 2017; Dara 2019). The partnership between plant science industries and IPM practitioners would have a great influence on these aspects through the integration of IPM principles and awareness of product development strategies and business plans thereby facilitating the offering of ideal marketing materials and sales services for the safest pest control products.

Profound recordkeeping that factor cultural practices, pest identity, their damages, seasonal fluctuations, the influence of environmental factors, and effective treatment strategies will help build institutional knowledge on improving crop production management (Stenberg, 2017). When vital information concerning pest management is communicated among growers and within groups through traditional and modern communication channels, this would not only spread appropriate knowledge but can also help the whole circle of crop production and sustainable crop production. Most information shared through outreaches is obtained through research and outreach, considered to be an integral part of IPM. Research in IPM aims at detecting and anticipating pests, their characteristics, associated problems, factors that are favourable to injurious pests and development of strategies that can lead to the development of prophylaxis and treatment of possible (a)biotic stressors (USEPA, 2017). A study conducted by Parsa *et al*. (2014) identified inadequate technical support and training as critical barriers to IPM implementation. This assertion was based on information extracted from IPM practitioners and professionals around 96 countries. Extension services and science-based solutions were shown to play a positive role in the IPM success of fruits and vegetables in New Zealand (Cameron, 2007). Information gathered through scientific findings when disseminated through effective outreach to the end receivers involving extension educators and researchers would certainly play an important role in IPM implementation and management.

6.3 Pest Management approach and its principles

Pest management terminology evolved from integrated control (a combination of biological and chemical control) when it became obvious that integrated control can accommodate more than chemical and biological controls (Ruiu, 2015; Hajek and Eilenberg, 2018). With time pest management became a preferable term to pest control even though the contextual description of both may be regarded as similar. The IPM principles are geared towards the prevention of possible pest problems. Some of the recommended practices may not be effective in all situations thus, practitioners and professionals must choose one or more strategies appropriate for their given situation to manage pest populations to a tolerable low-level with preferably, minimum economic damage (Dara, 2019). The additive effect of the different control options (cultural control, host plant resistance, biological control, behavioral control, physical control, microbial control and chemical control) which in themselves can be employed individually to provide a certain degree of control level, can provide significant results in reducing pest damage (FAO, 2013; Grasswitz, 2019). However, it is important to consider the IPM as a systemic approach in reducing pests below their damaging economic threshold (population density cut-off above which control action should be initiated). The adoption of IPM based on general principles, rather than reliance on a single pest control method, entails sustainable pest management integrated with a variety of farming situations (Dara, 2019). The holistic IPM approach will be better served through the adoption of eight implementation principles shown in Table 5 which follows a logical order with Principles 4-7 involving the application of biopesticides. Table 6 and 7 display the roles played by the different categories of biopesticides.

Table 5. The eight principles of IPM adapted from ANNEX III of Framework Directive 2009/128/EC (Barzman *et al*., 2013)

Principle 1: **Prevention and Suppression**	**Principle 2**: **Monitoring**	**Principle 3: Decision-making**	**Principle 4: Non-Chemical Methods**	**Principle 5**: **Pesticide Selection**	**Principle 6**: **Reduced Pesticide Use**	**Principle 7**: **Anti-Resistance Strategies**	**Principle 8**: **Evaluation**
Potential injurious organisms should be targeted, prevented and suppressed through combination of: ○ Crop rotation and intercropping ○ Adequate use of cultivation techniques ○ Use of resistant cultivars and certified seeds and planting resources where appropriate ○ Relying on balanced nutrient supply and germ-free/optimal water management ○ Preventing spread of pests through sanitation ○ Protecting/enhancing beneficial organisms ○ Preserving biodiversity near farmland	Where possible use adequate techniques and tools to monitor pests, including field observation, warnings, early diagnosis system, forecasting and the making use of reliable advice from experts	Based on the outcome of Principle 2, practitioners decide on when and what plant protection measures to take. Threshold values from reliable research are key component for decision-making in the area of timing, need for, and methods of pest control	If satisfactory results can be possible, non-chemical methods (physical, mechanical and biological methods) should be used instead of chemical pesticides	When pesticides are applied, they should be specific and possess the list side effects so that the environment and non-target organisms are not harmed including humans	As low as reasonable possible dose of effective pesticides should be used to control pest of interest. Alongside, reduced application frequency or partial application in line with allowable level of risk in crops; and limit risk for resistance development of pests	Apply the strategy of rotating (or multiple) pesticides to protect crops or plant where the risk of resistance against a particular treatment option is evident	The success of the applied plant protection option should be checked based on the monitored pests and the records on the use of pesticides

Table 6. Field application of the different categories of biopesticides

Category and sub-category		Pest being controlled and plant being protected	Applicable principle(s)	Reference
Plant-incorporated protectant (PIP)				
	Transgenic plants	Pea weevil larvae, peach potato aphid, *Heliothis virescens*, *Agrotis* spp, *Spodoptera frugiperda* Corn, cotton, potatoes, tobaco	Principle 1: Prevention and suppression	Stevens *et al*. (2012)
Microbial biopesticide				
Bacterial:	Bt formulations	Lepidoptera, coleopterans, dipterans, mosquito larva *P. xylostella*, *H. armigera*, *S. litura* Cotton, cruciferous vegetables, corn, tomato, cabbage	Principle 4: Non-chemical methods	Ansari *et al*. (2012)
Fungal:	*Beauveria bassiana*	Whiteflies, termites, beetles, mosquitoes *Cydia pomonnella*, *Leptinotarsa decenmlineata* Rice, maize crop, potato plant, banana tree, sugarcane	Principle 4: Non-chemical methods	Bhattachaya *et al*. (2003)
Nematodes:	*Steinernema* spp.	White grub, mole crickets, *P. xylostella*, *Delia radicum*, *P. japonicum*, *A. aegyptii* Cabbage	Principle 4: Non-chemical methods	Ansari *et al*. (2012)
Protozoa:	Microsporida	Lepidoptera, Orthoptera, corn borer, hoppers,	Principle 4: Non-chemical methods	
Viral:	Baculoviruses	Codling moth, tobacco budworm, alfalfa looper, gypsy moth *S. exigua*, *P. xylostella*, *H. armigera*, *S. litura*, Apple, cotton, alfalfa, corn, sorghum, tomatoes, plum	Principle 4: Non-chemical methods	Granados and Williams (1986); Rai *et al*. (2001)
Biochemicals				
	Natural minerals	German Cockroach, pulse beetles, rice weevil, onion thrips *Sitophilus* spp., *Ceratitis capitate*, *D. suzukii*, *R. dominica* Wheat, maize plant, rice, grains	Principle 6 and 7	Pierattini *et al*. (2019)
	Plant extract/oil	Two-spotted mite, cabbage root flies, cowpea weevil, *Sitophilus oryzae*, *Tribolium castanum*, *Aedes albopictus*, Rice grain, cowpea, tobacco plant, potato,	Principle 6 and 7	Grdisa and Grsic (2013), Erdogan *et al*. (2012)
	Semiochemicals	Silkworm moth, gypsy moth, caterpillars, bark beetle, aphids *Rhagoletis* spp, *Helicoverpa armigera*, *Poillia japonica* Tomato, maize plant, *Allium porrum*, pine trees,	Principle 6 and 7	Gebrezier (2018)

Table 7. Strategic application of semiochemicals

Control strategy	Principle	Purpose or Important information	Reference
Monitoring	Employs kairomone- and pheromone-baited traps	Detection of pest invasion, Population density and fluctuation, Detection of first peak flight activity	Abd El-Ghany *et al*. (2019), Piccardi, (1980)
Mass tapping	Host attractant mechanism in a baited traps	Catching and removal of attracted insect from the population	Pinero and Dudenhoeffer (2018)
Attract and kill	Use of attractants on a substrate to attract pest and kill later on	Used in both field and stored products	Sonenshine (2004), Nandagopal *et al*. (2008)
Matting disruption	Synthetic sex pheromones are employed to cause: False trail following, Camouflage, Desensitization and sensory imbalance	Disruption of chemical communication is the weapon of use in this strategy	El-shafie and Faleiro (2017) Benelli *et al*. (2019)
Push-pull strategy	Deterring of insects from protected crops with simultaneous attraction of the pests in order areas and killed subsequently	Use of alarm pheromones as deterrent	Heuskin *et al*. (2011), Kumari and Kaushik (2016)
Biological control	Use of kairomonal substances to attract natural enemies: predators and parasitoids	HIPVs, OIPVs and insect host semiochemicals	Renou and Guerrero (2000), Mensah and Moore, (2011)
Mono-control strategy			
Arrestment	Semiochemical induces formation of clusters	Matting enhancement and host scouting success	Sonenshine (2004)
Attractant	Luring of insects by semiochemicals and HIPVs to sources that containing inhibiting or killing agent	Matting enhancement Location of habitat and hosts	El-Shafie and Faleiro (2017)
Antifeedants	Disallowing insects from entering a microhabitat for feeding on a particular surface	Provide surplus food for unaffected insects	Deutsch and Guedot (2017)
Confusant	Silencing of one semiochemical by another due to higher concentration	Spacing in reproduction	Knipling (1976)

6.4 Biopesticides in IPM implementation

When prevention and suppression stages of IPM fail and are confirmed by monitoring, a decision should be promptly made to put in place a non-chemical option. It is noteworthy that PIP-cultivars, an example of biopesticides, have been advised for this stage of IPM implementation (Hodson and Lampinen, 2018). The first non-chemical option to take is a mechanical approach, which may include a sticky trap (pheromone traps) alongside augmentation (with natural enemies) biological control. These natural enemies are either predators (insects that feed on pests; e.g. lady beetle, ground beetle, lacewings, centipedes) or parasitoids (wasps, *Trichogramma*) (Naranjo *et al*., 2014). A strategy in which microbial biopesticides are integrated into IPM to boost the effect of augmented natural enemies is known as biointensive pest management (BIPM). However, if, BIPM is not able to reduce the population density or the effect of the pest, it is advised that least-toxic pesticides be used. This category of pesticides includes insecticidal soaps (active against whiteflies, aphids, and other soft-bodied insects), horticultural oils (smother aphids, scales, mites), botanicals (neem oil, garlic oil, excluding pyrethrum), and insect growth regulators (chitin synthesis inhibitors, moulting synthesis disruptors). Insect growth regulators are also grouped under least-toxic pesticides but they are not allowed to be used in organic farming (Rahman *et al*., 2016). Although biopesticide usage as plant protection compounds is intensified in Principles 4 to 7, their utility is also reflected in all the different stages of the IPM pyramid shown in Fig. 4. For instance, the pheromone bait trap is used in monitoring the population density of insect pests (FAO, 2013). Garlic oil as a repellant to certain insects serves a purpose under physical means of controlling pests. Likewise, insecticidal soap affecting soft-bodied insects (Curkovic, 2016) is a typical example of a mechanical mode of action. Diatomaceous earth and kaolin also serve the same physical control. As a principle, toxic pesticides are used as the last resort and are unavoidable in certain critical situations. Normally, WHO classes III and IV are preferred due to the lesser danger they pose in comparison to Classes I and II. Classes III and IV which are used in some IPM implementations are pyrethroids, carbamates and organophosphate in increasing order of toxicity (Chandler *et al*., 2011).

The optimal performance of biopesticides in the IPM portfolio scheme is contingent upon compatibility between agents, delivery precision, application frequency and timing (Chandler *et al*., 2011). Equally, the effectiveness of IPM implementation lies to some extent on result evaluation. This can be done by determining whether IPM results were achieved, and, if there are no other possibilities of improvements. A programme of an IPM can be evaluated through:

i. Taking cognizance of any changes and prophylactic measures that avoid future problems
ii. Changing economic thresholds with respect to experience

Thresholds are levels of pest populations that require taking control action to prevent health, economic or esthetic losses representing different action thresholds. When an action threshold is set based on economic consideration, such threshold is regarded as an economic threshold (ET). Most thresholds in the IPM programme are set on ET.

iii. Tracking the benefits and costs of an IPM programme
iv. Visual monitoring and counting of pests and nontarget organisms during treatment and before treatment
v. Treatment records: methods, cost, rate, dates, time, etc.
vi. Feedback from site users and clients
vii. Increased productivity, healthy environment and improved biodiversity
viii. Where need be, implement improvement actions after deep knowledge of what treatment to take

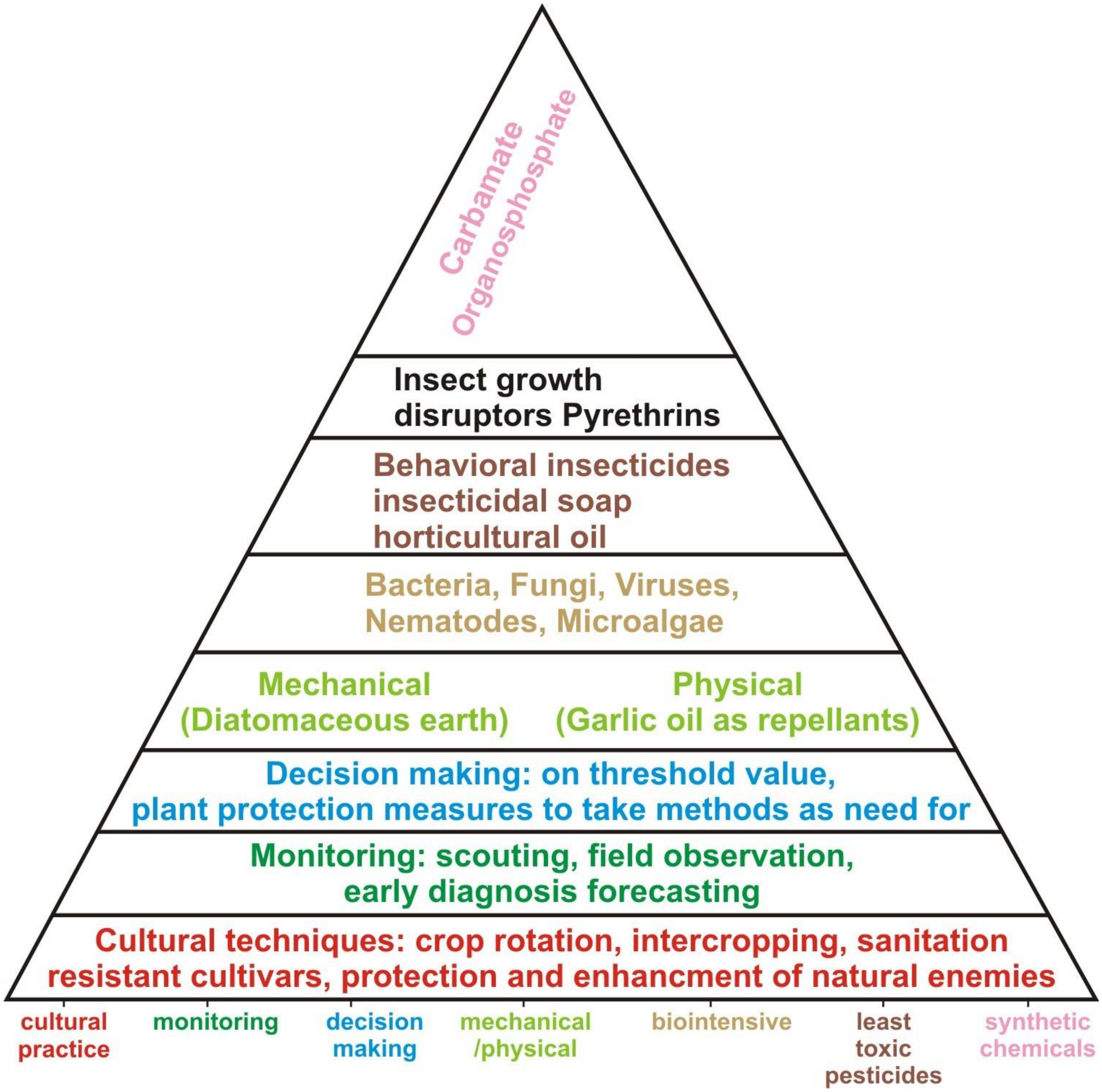

Fig. 4. Pyramid of biopesticide driven integrated pest management (adapted from James *et al*., 2010)

7 Current research and future direction

Biopesticides have the potential to completely replace synthetic chemicals used in pest control. Consequently, it has attracted global attention in recent times for several positive reasons highlighted previously in this chapter. Apart from being green molecules, more active substances are discovered through research thereby raising the stake of their potential as innovative pest control agents. Currently, there are more than 175 registered bio-based pesticides globally and the commonly used biopesticides are from neem and Bt derivatives (Moosavi and Zare, 2018; Raza *et al*., 2019; Samada *et al*., 2020). Bt pesticides are the most popular and diversified biopesticides. They are components of most PIPs, biochemical and microbial biopesticides. Most recent statistics holds that 75% of biopesticides used consist of Bt-based products (Samada *et al*., 2020). Neem has proven to be the most widely used botanical biopesticide (Rodgers, 1993; Leng *et al*., 2011; Pavela, 2014; George *et al*., 2014; Pavela and Benelli, 2016; Huang *et al*., 2020). Moreover, neem has demonstrated multiple modes of action by acting as an antifeedant, sterilant, ovicidal and insecticide. However, owing to its instability in environmental conditions, such as sunlight, its effectiveness is short-lived. Pesticidal plants are preferentially used in less developed countries to control pests. However, the determination of the active ingredients of these pesticidal plants remains credible research gap. Efforts are ongoing to improve the characterization of effective phytochemicals and their concentration in finished products but precision and standardization are still current issues. Interest should be devoted to phytochemicals and their production to control pests. This however, will require knowledge of natural product chemistry.

The instability of neem products under ultraviolet light is also worthy of investigation in the pest control systems. Neem efficacy can be enhanced through the use of synergists such as piperonyl butoxide (Dar *et al*., 2014). Additionally, the new branch of science, nanotechnology could be used to address the limitations experienced with pesticide formulations especially concerning storage stability, release rate and effectiveness as it relates to biopesticides (Perlatti *et al*., 2013; Chaudhary *et al*., 2017). Nanopesticides in agriculture have been demonstrated to play roles in controlled release, enhanced dosage reduction, genetic material delivery into crops and detection of pathogens (Manchikanti, 2019). Although, some misgivings have been expressed for nanopesticide applications, pertaining to resistance by the target pests, deleterious impact on humans, interference with genetic codes among others (Ganguli, 2019). Emerging technologies such as fusion protein and recombinant DNA are currently used to enhance the efficacy of biopesticides. Moreover, omics technologies are expected to be applied in the environment of Bt and its Cry protein delivery to target pests as well as in the elucidation of novel toxin discovery. This is likely to be achieved with optimization studies that exploit both recombinant DNA techniques and proteomics (Nakasu *et al*., 2014). Strain selection during bioprocessing of active microbial agents can be aided using sequencing technology to directly target genes found to be associated with insecticidal traits (Glare *et al*., 2016). Baculovirus application in many cropping systems has shown its effectiveness and reliability especially in the control of soybean fields. Thus, on this premise, a projection was made for the application of Baculovirus to protect two million hectares of a farm from the velvet bean caterpillar cost-effectively (Sun, 2015). Moreover, the success in the use of Baculovirus can be improved through *in vitro* culturing processes, changes in formulations and genetic engineering. It was further proposed that such an approach will not only necessitate the use of foreign genes but this may improve reaction times (Szewczyk *et al*., 2006).

An important prerequisite for the success of commonplace applications of biopesticides is the research breakthrough that ensures efficiency in the production, formulation and delivery of the formulated products; these are essentially critical to biopesticide commercialization. In order to facilitate the market penetration of biopesticides, there is a need for cooperation among researchers, venture capitalists, investors, producing companies and farmers with greater considerations placed on long term gains (Rezaei *et al*., 2019). Public-funded agro-programmes must also prioritize assistance in research and development of these biopesticides. Additionally, the amelioration of the bottleneck of regulatory protocols, will guarantee business feasibility and affordability that will encourage bioentrepreneurs towards these bio-based commercial products. This will play a significant role in driving the agenda of economic sustainability. One major hurdle that is standing on the way of an adequate supply of biopesticides is regulatory protocols that will guarantee the affordability of bio-based commercial products (Rao *et al*., 2007). It is acknowledged that there is a need for regulatory processes in developing countries; however, there is a need that these tools of governance must not become a hindrance to credible advances that will improve the environmental management provided by these eco-friendly products.

Researchers should also consider ways of using available technologies at the production scale-up with objectives focused on cost reduction, efficiency and reliability of commercial biopesticides. This will positively affect the efficacy and reliability of biopesticides when integrated into a flexible IPM programme. The latter will ensure the protection of the ecosystem through the use of minimal synthetic pesticides at the most reasonable cost. A pest management system in which IPM is connected to computer-based system support can offer improved stored grain protection (Samada *et al*., 2020). It should be acknowledged that strict compliance with biological control has more chances to fail and thus should be supported with other variants of pest control options. In line with the concept of the "green consumerism" biopesticides are exclusively used in organic farming to produce chemical-free foods and crops (El-Shafie, 2017). Upholding organic farming as a tradition will improve and conserve valuable natural resources such as nutrient loss, topsoil, erosion, compaction and improvement of higher economic value for farm crops (Umar, 2013). The full adoption of biopesticides and their variant forms including their roles in IPM requires awareness and training among the different stakeholders to sustainably control insect pests and vectors.

8 Conclusion

Conventional agriculture has been relied upon to satisfy the food needs of the global population which is growing at a rate of 0.8 billion per decade. The application of synthetic pesticides has contributed immensely to mitigating the negative effects of more than 40,000 extant crop pests leading to the high productivity of farm yields. On an average basis, pests are responsible for 30% crop yield loss and 14% damage to stored food products. These pesticides cause health challenges to humans, environmental pollution, development of pest resistance, and narrowing of biodiversity among others. For these reasons the need to significantly reduce the continuous reliance on synthetic pest controlling agents is pertinent. This can be achieved through the adoption of bio-based pesticides. The use of alternative pesticides in crop cultivation reduces environmental pollution and solves pest resistance problems and improves biodiversity, including natural enemies. Crop cultivation practices that ensure environmental conservation, economic viability and social acceptability will result in sustainable agriculture. Sustainable agriculture is directly or indirectly linked to the 17 SDGs. The 12 Green Chemistry Principles have shown that sustainable agriculture is directly connected to eight out of the 17 SDGs. As green compounds, biopesticides have shown to substitute classical pesticides with a possible increase in crop productivity. In order to achieve an optimum increase in crops' productivity, biopesticides are used in an integrated pest management (IPM) scheme, which goes in tandem to achieve minimal use of chemical pesticides at the lowest cost. With the right education, skill, research on how to improve shelf life and stability problems, and partnerships among stakeholders, biopesticide-driven IPM can make chemical pesticide-free agriculture a reality and create a nexus between socially acceptable economic viability and environmental safety.

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