Production and Consumption of Biopesticides

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Errol Hassan and Ayhan Gökçe

Abstract

The intensive use of synthetic pesticides in pest control activities can cause resistance and therefore resurgence of target pests. Undesirable effects on the environment, including reduction in natural enemies (predators and parasitoids) and beneficial insects, are also possible. A major concern is the effects of synthetic pesticides on human health. In the last few decades, biopesticides have emerged as a potential alternative to synthetic insecticides. Currently, biopesticides share only a small portion of global pesticide market, but growth is faster in this area than in synthetic insecticides. This growth is mainly driven by a rising interest in the demand for organic agricultural products that is most pronounced in western countries. This review will discuss biopesticide history, categories, advantages, disadvantages, conventional and nonconventional extraction technology, and consumption.

Keywords

Essential oils • Environment friendly • Biopesticide history • Extraction technology • Biopesticide global consumption • Biopesticides advantages • Pest management • Biopesticide categories • Botanical pesticides • Natural products • Friendly to natural enemies

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E. Hassan, Ph.D. (✉)
School of Agriculture and Food Sciences,
The University of Queensland Gatton,
Gatton, QLD 4343, Australia
e-mail: e.hassan@uq.edu.au

A. Gökçe, Ph.D.
Plant Production and Technologies Department,
Faculty of Agricultural Sciences and Technologies,
University of Nigde, Nigde, Turkey

D. Singh (ed.), *Advances in Plant Biopesticides*,
DOI 10.1007/978-81-322-2006-0_18, © Springer India 2014

1 Introduction

Synthetic pesticides are most commonly used for controlling insect pests, diseases, and weeds. Many farmers prefer synthetic pesticides over other pest control products because of their efficacy and rapidity of action. However, repeated application of synthetic pesticides can result in pest resistance. According to Pedigo (1989), insect pest populations may develop resistance after exposure to an insecticide for several generations, but this is dependent on the insects' life cycle. Insects with a shorter life cycle are more likely to develop resistance to insecticides. Repeated use of synthetic insecticides has frequently disrupted natural biological control systems and led to resurgence of target insect species. This has been due to causing undesirable effects on nontarget organisms, such as important insect predators and (Epstein et al. 2000; Van Hamburg and Guest 1997; Papachristos and Milonas 2008) parasitoids (Borgemeister et al. 1993). Beneficial insects such as earthworms (Reddy and Rao 2008) and pollinators (Nderitu et al. 2007; Loucif-Ayad et al. 2008) have also been affected by application of synthetic pesticides to the detriment of crop species. These effects on nontarget insect species occur mainly because many synthetic insecticides have a broad spectrum of action and long residual activity.

In addition, the large-scale use of chemical pesticides in agriculture may cause adverse effects on humans (Hayes and Laws 1991; Lopez et al. 2005). Besides degrading slowly, many synthetic pesticides are also fat soluble which means they can accumulate in animals, plants, and humans. Consequently, the prolonged use and application of synthetic chemical insecticides has detrimental impacts on the environment and can negatively affect human health (Nayak and Chhibber 2002; Wheeler 2002; Lopez et al. 2005).

Insect pests are notorious for their ability to adapt to control methods. Thus, implementation of an integrated pest management (IPM) system is the best strategy for controlling them. A combination of strategies including crop rotation, cultivar resistance, and biological control helps to keep insect pest populations below economic thresholds. Biopesticides which generally have slow-acting activity when applied independently can be integrated into an IPM system with other techniques to enhance their efficacies (Bailey et al. 2010).

2 History of Biopesticides

For thousands of years, humans have been using various crop protection products to control insects, diseases, and weeds that harm or destroy food crops. Before the invention of synthetic insecticides in the twentieth century, the most likely primary source of pesticides was of natural origin. The first generation of pesticides was probably derived from inorganic materials (sulfur, copper, mercury, arsenic, etc.). The Sumerians were the first recorded using sulfur compounds to kill insects and mites around 2500 BC (Dent 2000). The oldest documentation of the use of plant-based pesticides was found in India and is dated as 2000 BC (Ignacimuthu 2012). In 1200 BC, the Chinese applied mercury and arsenical compounds to control body lice (Dent 2000). At this time, the Chinese also applied insecticides of plant origin for seed treatments (Dent 2000). History records that farmers in the seventeenth century used nicotine in an effort to control plum beetles (Lopez et al. 2011). More recently, extensive uses of botanical insecticides were recorded between the late 1800s and 1940s (Henn and Weinzierl 1989).

The use of botanical insecticides dropped sharply in commercial agriculture following the introduction of synthetic insecticides in the mid-1940s which were less expensive, more effective, and more persistent than their botanical predecessors (Henn and Weinzierl 1989). At the time of World War II, one of the first organochlorine insecticides to be used widely in insect pest control was dichlorodiphenyltrichloroethane, commonly known as DDT. Between 1945 and the 1970s, pyrethrins were used only for household and industrial sprays, whereas nicotine was used for greenhouse/orchards, and rotenone was in limited use for home gardens (Henn and Weinzierl 1989).

The interest in using pesticides of plant origin for crop protection was renewed when the potential negative effects of synthetic insecticides on target and nontarget organisms were revealed. The publication of a book entitled *Silent Spring* by Rachel Carson in 1962 became the most defining moment that led to the banning of a number of synthetic insecticides that were mainly organochlorines such as DDT (McKinlay et al. 2012). It is not surprising that, in the time since this publication, there has been a marked increase in the study of pesticides of plant origin. A rapid increase in the number of studies relating to the development of insecticides of natural, and particularly organic, origin was observed during the 1990s. Studies of plant ecology have led to the identification of various biochemical compounds that act as insect repellents and insect antifeedants. Among the most widely studied plant products are neem oil/extract (Schmutterer 1995) and essential oils (Isman 2000).

There are currently a considerable number of plant-based crop protection products that are available commercially (Cloyd et al. 2009). In addition to plant materials that have a long history of traditional use such as neem, rotenone, and pyrethrum, more recently developed botanical pesticides contain vegetable oils and/or essential oils. Although botanical pesticides are generally lower in efficacy than the synthetic ones, their demands are expected to increase. Organic agricultural products continue to gain popularity, especially in developed countries, indicating that food safety is a major concern for consumers and this has driven the development of biopesticides.

3 Category of Biopesticides

The US Environmental Protection Agency (EPA) categorizes biopesticides into biochemical pesticides, microbial pesticides, and plants containing added genetic material. However, the most common categories of biopesticides are botanicals and microbial pesticides. Botanical pesticides refer to pesticides of plant origin, whereas microbial pesticides refer to pesticides that include microorganisms such as bacteria, fungi, and viruses.

3.1 Microbial Pesticides

Plant insects and pathogens are often naturally infected (for insects) or antagonized (for pathogens) by various kinds of microorganisms. Some common fungi in nature such as *Trichoderma* spp. have the ability to antagonize plant pathogens either through parasitization, antibiosis, or competition, while other fungi, such as *Beauveria bassiana*, act as entomopathogens against a number of insect species. These two fungi are used commercially in plant nurseries, forestry plantations, and field crops for insect pest control (Quarles 2011). A report suggested that *Beauveria bassiana* accounted for about one third of the 171 mycoinsecticides and mycoacaricides available commercially (Faria and Wraight 2007). A number of fungi have also been developed for weed control although only a few of them are available commercially (Chutia et al. 2007).

Other microbial pesticides include those products based on bacteria. These products are developed for the management and control of plant diseases, nematodes, insects, and weeds. The most well-known and widely used microbial pesticide is *Bacillus thuringiensis*, or Bt. It produces insecticidal proteins that are harmful to the larvae of lepidoptera, coleoptera, and diptera. The proteins cause insect pests to stop feeding and finally die. Bt has been proven to be so effective that it has been in commercial use in the agricultural sector for more than 50 years. It was reported that the majority of biopesticides sales involved *B. thuringiensis* (Sanchis and Bourguet 2008).

There are a number of virus formulations available for insect control (Quarles 2011). The most common viruses in use are granulosis virus (GV) and nuclear polyhedrosis virus (NPV). Both are baculoviruses, a family of large rod-shaped viruses. These viruses are active against a number of insect pests. To be active, these viruses must be ingested by target insects. When a susceptible caterpillar, for example, ingests the viruses, the microcapsule dissolves and the virus begins to infect the cells lining the midgut. After a significant buildup of the virus inside the insect's body, symptoms will be noticed such as refusal to eat, and in later developmental stages the cuticle

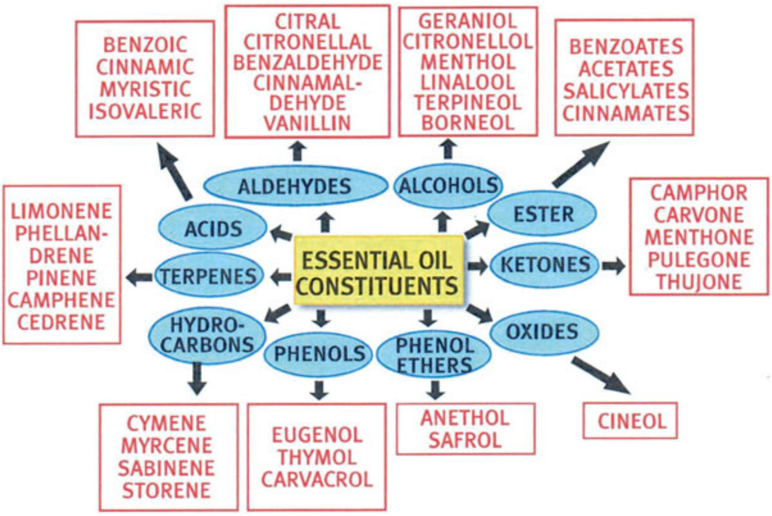

Fig. 18.1 Diverse chemical groups present in essential oils adapted from (Handa 2008)

ruptures easily. It will take 3–8 days for a virus to cause death. An example of a commercially successful viral insecticide is the granulovirus of the codling moth *Cydia pomonella*.

3.2 Botanical Pesticides

In addition to producing primary metabolites such as carbohydrates, proteins, and lipids, plants are known to produce secondary metabolites. A plant secondary metabolite is not directly involved in normal growth, development, and reproduction, but it usually performs an ecological role to govern the relation between plants and other organisms. Some compounds may have bitter taste that act to repel or deter herbivorous insects while other compounds can be toxic. There are three major classes of plant secondary metabolites: terpenes, phenolics, and alkaloids. Azadirachtins, the most active compounds of neem extract/oil, are triterpenoids. Terpenes are made up of carbon and hydrogen. Oxidation of terpenes results in terpenoids. Monoterpenoids and sesquterpenoids are the primary components of plant essential oils. Figure 18.1 shows the different chemical groups found in plants.

Plant secondary metabolites can be extracted as valuable sources of botanical pesticides. Grainge et al (1984) provided a list of plants that have pest control properties such as attractant, antifeedant, repellent, growth inhibitor, and insecticidal. Among those plants, 1,053 are insecticidal, 384 are antifeedants, 297 are repellents, and 32 are growth inhibitors (Ignacimuthu 2012). Of the many plants that have been identified as having insect control properties, only about 30 have commercial potential, and these include neem (*Azadirachta indica* A. Juss), tobacco (*Nicotiana tabacum* L.), pyrethrum (*Tanacetum cinerariaefolium* (Trevir.) Sch.), sabadilla (*Sabdilla officinarum* Brandt Ratzeb), derris (*Derris chinensis* Benth), basil (*Ocimum tenuiflorum* L.), jatropha (*Jatropha curcas* L.), spearmint (*Mentha spicata* L. and *M. arvensis*), garlic (*Allium sativum* L.), and eucalyptus (*Eucalyptus globulus* Labill) (Ignacimuthu 2012).

One of the most widely used phytochemicals is azadirachtin which is derived from the neem tree (*Azadirachta indica*). This bioactive compound affects the reproductive and digestive processes of a number of important pests. Azadirachtin's structure is similar to the natural insect-molting hormone ecdysone. Azadirachtin interrupts the ability of the insect pest to undergo metamorphosis (Hassan 1999; Bhuiyan, et al. 2001) and can cause sterility of emerged adults. Immature insects that ingest azadirachtin may molt prematurely or die. Deformation of adults often occurs due to hormonal disturbance.

4 Advantages and Disadvantages of Biopesticides

4.1 Advantages

When exposed to sunlight, plant-based compounds breakdown easily into nontoxic substances within hours or days. Therefore, food contamination by biopesticides is less likely to happen. Contamination of soil and groundwater is a rare case except for in rotenone-based botanical insecticides.

Insect resistance to biopesticides is less likely to occur because the complexity of mixtures in the plant extracts and oils can act to disrupt the selection process (Berenbaum and Zangerl 1996; Scott et al. 2003). A number of plant products are fast acting, thereby preventing insect feeding and ultimately avoiding further crop damage. Furthermore, because many plant-based biopesticides act on the insect's gut enzymes and breakdown faster in the environment, they can be selectively applied to insect pests and are therefore safer to nontarget organisms (Hedin and Hollingworth 1997; Krishnamoorthy and Atmakuri 1999; Schmutterer 1997).

Biopesticides typically have multiple modes of action and do not rely on a single target site for efficacy. This situation causes insects to have a low tolerance to botanical insecticides as their detoxification enzymes can have difficulty in metabolizing the mixture (Berenbaum and Zangerl 1996; Scott et al. 2003). For example, azadirachtin (from neem) has been in long-term use as an insecticide for controlling crop and storage pests with no evidence of tolerance in target organisms found to date (Kraiss and Cullen 2008; Rharrabe et al. 2008). The responsible and safe use of biopesticides has the potential to extend the effective field life of products by curtailing the development of resistant insect pest populations.

Biopesticides provide growers with valuable tools to manage insect pests in an environmentally friendly manner. Generally, biopesticides have been shown to have limited adverse effects on the environment, flora and fauna, and the wider public (Brown 1978; Georghiou and Saito 1983; Hayes and Laws 1991; Lopez et al. 2005). Other positive aspects of using biopesticides are their ability to help maintain beneficial insect populations, their nonhazardous application, and their effective use in resistance management programs.

Today's consumers are more aware and knowledgeable about their health and the foods that they eat. To meet the growing demand for producing high-quality fruit and vegetables year-round, growers are mindful that consumers view produce grown with less or no synthetic chemical inputs as safer to eat, healthier, and friendlier to the environment. Consequently, organic farming has expanded greatly in the USA, Europe, and other countries.

Most biopesticides worldwide are exempt from residue limits on fresh and processed foods. When growers use biopesticides, either alone or together with reduced application of conventional pesticides, consumer exposure to regulated pesticide residues is reduced. This provides benefits to food producers, grocery retailers, and consumers. Essentially, these factors provide a solid foundation for the provision of wholesome food and vegetables to meet the supply and demand of today's sophisticated consumers.

Insecticides of plant origin include different compounds that provide various modes of action that can be targeted toward specific insect pests. Biopesticides generally do not act or harm against beneficial insect populations. It is important to protect beneficial insects and animals as they help pollinate plants and can be natural predators of the insects infesting the crop. For example, bees, ladybird beetles, butterflies, birds, and parasitic wasps fall into this category. Maintaining natural enemy populations against insect pests, biopesticides play a significant role in integrated pest management (IPM) programs. This approach in combination with cultural and biological controls keeps beneficial insects healthy and helps keep insect pest populations below economic threshold.

4.2 Disadvantages

Rapid degradation of most botanical insecticides can be considered as an advantage, but consequently more frequent application is required. Commercial formulations of botanical insecticides are often more expensive than the synthetics mainly due to the high cost of raw materials (labor intensive in collecting neem seeds) and extraction processes in order to optimize the quantity of active compounds. Therefore, investigation of the insecticidal properties of cheap and readily available natural products such as vegetable oils is strongly encouraged. It is important to note that crop protection products must be readily available with assured continuity of the supply before they are adopted on a broad scale. The quantity of plant secondary metabolites often varies between seasons and locations so it is not easy to standardize the quality of botanical pesticides.

5 Extraction Techniques for Biopesticides

Plant extraction is the separation or isolation of particular chemicals from plant tissue using selective solvents in a range of procedures. Extraction techniques separate the soluble plant metabolites and leave behind the insoluble cellular material. Extraction is a critical step in exploring bioactivity of phytochemicals. Plants produce complex mixtures of metabolites including alkaloids, glycosides, terpenoids, flavonoids, and lignans. Various techniques are available to further isolate fractions or individual compounds from the crude extracts. Essential oils are plant products usually obtained by distillation or other extraction methods. Figure 18.2 shows plant organs containing essential oils.

The quality of a plant extract is determined by the plant parts, extraction solvents, extraction techniques (extraction technology), and type of equipment used. Figure 18.3 shows special structure of the plant tissue where essential oils are usually available. A number of methods are available for phytochemical extraction, and the

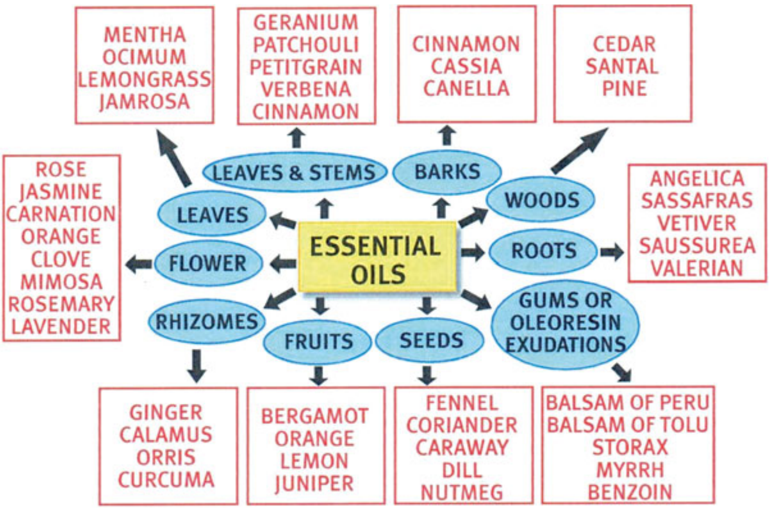

Fig. 18.2 Plant organs containing essential oils (Handa 2008)

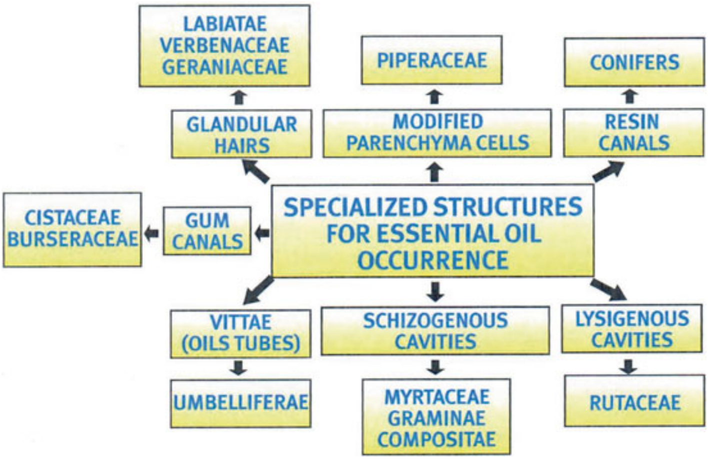

Fig. 18.3 Family-specific plant tissues responsible for producing essential oils (Handa 2008)

choice among them is determined by the physicochemical properties and stability of the phytoconstituents to be obtained. Figure 18.4 shows general methods for producing essential oils from plant materials. For the extraction of volatile compounds such as essential oils, the simplest methods are hydro-distillation and steam distillation, while for nonvolatile compounds, they are cold fat extraction, expression, maceration, and solvent extraction. More advanced extraction technologies are available including supercritical fluid extraction.

5.1 Maceration

Maceration is an inexpensive way to extract essential oils and other bioactive compounds. This extraction technique involves several steps (Azmir et al. 2013; Handa 2008): Firstly, plant materials are ground into small particles to increase surface areas for optimal mixing with solvents and then an appropriate solvent is added in a closed vessel. The vessel is kept at room temperature for at least three days or until the soluble matter has dissolved (constant shaking is often needed). Following this, the liquid is strained off and the marc (solid material) is pressed and then the combined liquid is filtered. To increase solvent efficiency, gentle heat may be used during the extraction process if this is not destructive to the bioactive compounds (Handa 2008).

There are several factors that need to be considered when performing extractions with maceration techniques (Singh 2008):

1. Continuous hot extraction should be avoided when phytochemicals are susceptible to high temperature.
2. Solvent selection depends on the solubility of the phytochemicals.
3. Solvent can be recovered under reduced pressure to minimize evaporation temperatures so that thermolabile compounds can be retained.
4. For a large-scale extraction, it is very important to improve the efficiency of extraction to minimize solvent requirements.

Circulatory extraction is an example of an improved maceration procedure (Singh 2008). In circulatory extraction, the solvent is circulated continuously through plant materials by pumping it from the bottom of the vessel (through an outlet) and then redistributing it over the surface of the plant materials.

5.2 Hydro-distillation

Hydro-distillation is a common method to isolate essential oils from plant materials. Three types of hydro-distillation are available: water distillation,

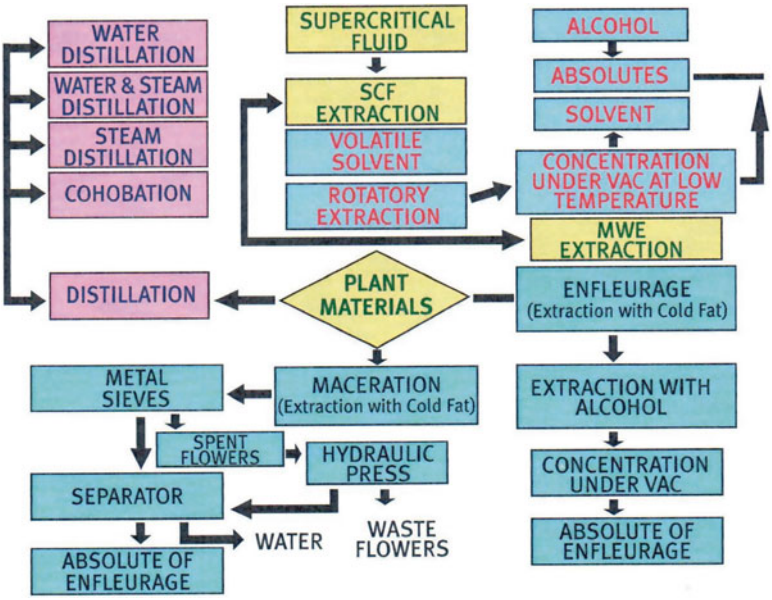

Fig. 18.4 Methods of extraction of essential oils from plants (Handa 2008)

water and steam distillation, and direct steam distillation (Handa 2008).

5.2.1 Water Distillation

In water distillation, the plant material is placed inside a still compartment and immersed in water that is then brought to boil by heating. This process frees plant biochemicals, particularly volatile compounds (essential oils), from the plant tissue. The vapor is then condensed by indirect cooling with water. The distillate is then filtered through a separator to separate oil from distillate water. The advantages of this type of distillation are as follows: it can be used for finely powdered material or plant materials that normally form lumps when contacted with steam, and the still compartments are inexpensive, easy to build, and suitable for field operations. The disadvantages of water distillation are as follows: it is impossible to extract all of the essential oils and constituent chemicals may be hydrolyzed (certain esters) or polymerized (aldehydes). This process is higher in cost than other distillation techniques as a larger volume of material must be processed to extract a similar volume of essential oils making this technique time and resource intensive. Therefore, water distillation is used only when other hydro-distillation techniques (water and steam distillation and direct steam distillation) are unsuitable.

5.2.2 Water and Steam Distillation

The equipment used for water and steam distillation is similar to that used for water distillation. The difference is that the plant material is placed above the boiling water on a perforated grid in water and steam distillation. When compared with water distillation, this method produces a higher yield of oil with less hydrolysis and polymerization while being faster and more energy efficient. However, this distillation technique reduces the capacity of the still.

5.2.3 Direct Steam Distillation

In direct steam distillation, the steam used to distil plant materials is generated from a boiler placed outside the still. This distillation method is advantageous because the released steam can easily be controlled and the temperature generated will not exceed 100 °C so thermal degradation of phytochemicals is less likely to occur. The disadvantage is that the equipment required is more expensive than the other two distillation techniques. However, as it can accommodate a large-scale oil production, this distillation technique is most widely utilized.

5.3 Expression

Expression refers to a physical process, usually achieved by a combination of crushing and pressing, that forces the plant material to release its oil. This method works well for plant materials that contain high quantity of oil such as seeds. Neem oil and many vegetable oils can be extracted by this method. Citrus or lemon essential oils can also be extracted from fruit peel using expression. The expression method often generates heat through friction that may damage the quality of oil.

5.4 Cold Pressing

Cold pressing is a process of expression in which temperatures are kept as low as possible to maintain the natural structure of the oil and therefore preserve quality. There is still no global agreement in the standard maximum temperature of cold pressing. Some suggest that it should be no more than 27 °C, but the others have a standard of no more than 49 °C. In this extraction method, stainless steel presses are commonly used for pressing and grinding.

5.5 Hot Continuous Extraction (Soxhlet)

Soxhlet extraction has been widely used to isolate phytochemicals. The general procedures are described in Azmir et al. (2013) and Handa (2008) as follows: (1) a small amount of powdered plant material is placed in a thimble (a porous bag), which is placed in a designated chamber of the soxhlet apparatus; (2) solvent is placed in a glass flask at the bottom of soxhlet apparatus that is heated; (3) the vapor that is produced is then condensed so that the solvent drips into thimble; (4) when the chamber of the thimble becomes full, the solvent flows back into the solvent flask; and (5) this process continues until the plant material is fully extracted.

5.6 Microwave-Assisted Extraction (MAE)

In microwave-assisted extraction, the following process occurs (Pangarkar 2008): (1) there is a direct transfer of heat to plant material that causes instantaneous heating of moisture in the solid; (2) the heated moisture evaporates and creates a high vapor pressure; and (3) the vapor pressure breaks cell walls causing them to release oils. The advantages of MAE are reduced heat degradation, reduced processing cost, reduced extraction time, much lower energy usage, and much lower solvent usage (Pangarkar 2008).

5.7 Supercritical Fluid Extraction (SFE)

Supercritical fluid extraction (SFE) is a new important alternative to conventional extraction methods such as hydro-distillation and organic solvent extraction. This new extraction method does not cause hydrolysis or degradation of thermolabile compounds as often occurs with hydro-distillation or conventional solvent extraction. With SFE, there is no need to remove expensive solvent via evaporation.

A supercritical fluid refers to any substance in a stage where distinct liquid and gas phases do not exist. This occurs when the substance's temperature and pressure are above its critical point. The most commonly used supercritical fluid is CO_2. The critical temperature of CO_2 is 31 °C and the critical pressure is 73.825 bars.

Supercritical fluid extraction results in extracts with low viscosities and high diffusiveness that are easily recovered as the supercritical fluid can return to gas phase by simply depressurizing, leaving little or no solvent residue. The main disadvantage is that the investment cost for SFE is higher than the traditional atmospheric extraction techniques (Martin et al. 2012). Another disadvantage is that CO_2 has low polarity and is more effective for extraction of nonpolar substances. However, this limitation has been addressed by the use of chemical modifiers that can increase polarity (Azmir et al. 2013). The common modifiers are alcohols (1–10 % of the supercritical fluid), which allow the mixtures to dissolve into more polar compounds (Martin et al. 2012). SFE is applicable for the extraction of numerous important phytochemicals such as pyrethrins, azadirachtins, rotenone, and also essential oils (Martin et al. 2012).

5.8 Pressurized Liquid Extraction (PLE)

Pressurized liquid extraction or PLE is a new extraction method conducted under elevated temperature and pressure. This method was first reported by Richter et al. (1996). PLE is less time intensive and requires less solvent when compared with traditional solvent extraction techniques (Richter et al. 1996). PLE also provides a potential alternative to supercritical fluid extraction for the extraction of polar compounds (Kaufmann and Christen 2002).

A study by Sae-Yun et al. (2006) revealed that PLE had higher extraction efficiency in extracting rotenone (from *Derris elliptica* Benth and *Derris malaccensis* Prain) compared with the conventional maceration method. Time and solvent consumption during extraction was reduced from 72 h and 10 ml/g of dried sample using maceration to only 30 min and 3 ml/g of dried sample via PLE.

5.9 Enzyme-Assisted Extraction (EAE)

Enzyme-assisted extraction (EAE) can be used to extract oils from plant parts such as seeds. Cellulase, amylase, and pectinase are among the enzymes that are most frequently used for oil extraction (Rosenthal et al. 1996). Two common approaches are available for this extraction method, namely, enzyme-assisted aqueous extraction (EAAE) and enzyme-assisted cold pressing (EACP) (Latif and Anwar 2009). In EAAE, the enzymes help to degrade the seed cell walls and rupturing the polysaccharide-protein colloid; however, in EACP, the enzymes only facilitate the hydrolysis (Latif and Anwar 2009). Little is known on the use of enzyme-assisted extraction for phytochemicals with pest control properties. However, these extraction methods are expected to have a role in the near future since many plant vegetable and essential oils are currently used as biopesticides. Several studies revealed that enzyme-assisted extraction methods can increase the yield of oil with only little change on the quality (Latif and Anwar 2009; Sowbhagya et al. 2009).

6 Production of Biopesticides

Agriculture sectors face many obstacles in producing profitable crops. One of the primary obstacles is pest pressure in agroecosystems. High pest control standards in crop production have led the industry to rely on conventional pesticides that result in increased chemical residues at harvest, increased development of resistance, and consequently, increased cost to growers. The Food Quality Protection Act (1996) encouraged the reduction in the use of conventional pesticides in food production for human consumption and also encouraged farmers to use more environmentally friendly pesticides, such as biopesticides.

The global biopesticides market has been growing since the mid-1990s and is expected to reach $3.2 billion by 2017 (Global Biopesticides Market – Trends and Forecasts (2012–2017)) and Thakore (2006). In this growth, organic farming and chemical-free crops are the key factors encouraging international companies to add more biopesticides to their product ranges. This trend is reflected in the recent increase in biopesticide product registrations in the USA from 175 registered in 1998 to 452 in 2009 (Regnault-Roger 2012). In Canada, 86 products were registered for controlling agricultural and domestic pests in 2010 (Agriculture and Agri-Food Canada 2010). In recent years, more biopesticides have been approved compared to conventional pesticides by authorities. For instance, the US Environmental Protection Agency approved eight biopesticides in 2011 of which half were microbial and the other half botanical (Agropages.com 2012). In China, insecticidal microbial biopesticides are the leading group with 13 registrations, followed by 6 fungicides and 2 nematicides (Agrow 2013; Zhang et al. 2011).

Microbial pesticides include bacteria, fungi, viruses, protozoa, and nematodes and are the leading category in production and consumption of biopesticides. The major companies that dominate the microbial biopesticides market include: AG Biotech Australia Pty Ltd., AgraQuest Inc., Bayer Crop Protection Gmbh, BioWorks Inc., BionTech Inc., Certis USA LLC, Greeneem, Isagro SpA, Kumiai Chemical Industry Co. Ltd., Marrone Bio Innovations, Koppert B.V., Prophyta Biologischer Pflanzenschutz GmbH, San Jacinto Environmental Supplies, Sumitomo Chemical Co. Ltd., Syngenta International AG, Troy Biosciences Inc., and Valent Biosciences Corporation. Microbial pesticides accounted for approximately 63 % of the global biopesticide market with *Bacillus thuringiensis* and its subspecies being the most widely used (marketsandmarkets.com 2012). The USA, China, Russia, and India are the leading producers of microbial pesticides (Leng et al. 2011). *Bacillus subtilis*, *Trichoderma gamsii*, and *Trichoderma harzianum* are the most popular microbial biopesticides in the USA, and their market share significantly increased in recent years (Agropages.com 2013a). In China, a total of 23 registered microbial pesticides (9 bacteria, 7 fungi, and 7 viruses) are sold, and these are manufactured by 134 different companies (Agrow 2013). Chinese biopesticides companies' cumulative sales were 6.2 billion yuan, and this amount accounted for 12 % of the total pesticide sales in 2010 (Agropages.com 2011). While in India, the total registered biopesticide products numbered 12. Leng et al. (2011) assert that there are 410 Indian companies manufacturing biopesticides, with 130 of these operated by private sector (Leng et al. 2011).

Several botanical biopesticides, such as pyrethrins, azadirachtin, rotenone, and essential oils, are already widely used in specialty crop production, particularly for organic production. These compounds are usually considered relatively safe for humans and the environment. The unique mode of action of botanical biopesticides promises potential for their use in rotation with other reduced-risk pesticides. Microbial biopesticides are dominating the biopesticide market, but new active compounds are expected to contribute to the growth of botanical biopesticide sales.

Pyrethrum, azadirachtin (neem), rotenone, and essential oils are four major types of botanical biopesticide that dominate the world biopesticide market. Kenya and Australia are the leading pyrethrum-producing countries, with Kenya alone producing 70 % of pyrethrum world production (Cavoski et al. 2011). Pyrethrum is also grown in Tanzania and Ecuador but their productions are small quantities (Attia et al. 2013). There are many formulations of pyrethrum used in agricultural pest management, public health, and structural pest control (Table 18.1). Pyrethrum sales account for 80 % of total global botanical insecticides (Isman 2005).

Azadirachtin is the active compound of neem oil that is extracted from the seeds of the neem tree (*Azadirachta indica*). The neem tree is native to India and Burma and has also been planted widely in Asia, Africa, and Australia. India has the largest neem tree plantations with 20 million rootstocks and accounting for 60 % of the entire neem tree population (Agropages.com 2013b). The total neem oil production of India is approximately 2.5 lakh (Indian measurement) tonnes. However, this number may rise to 7 lakh tonnes with some development programs. India exported US$ 5.73 million neem-based products in 2012 to the leading importers USA, Italy, Japan, and Spain (Agropages.com 2013b).

Traditionally, aromatic plants were used in pest control. Mint, thyme, clove, and rosemary oils and their constituents are very effective against stored product insects and some important plant diseases and weeds. Tables 18.2 and 18.3 show lists of selected, commercially available essential

Table 18.1 Examples of commercially available botanical insecticides and nematicides[a]

Active ingredient	Plant species	Company	Product name
Azadirachtin	*Azadirachta indica*	ThermoTrilogy	Neemix 90 EC, Neemazid, Trilogy 90 EC, Triact 90 EC, Bioneem, Margosan-O, Azalin Align, Turplex, Bollwhim
		Fortune	Fortune Aza, Fortune Biotech
		Agridyne	Azatin
		Karapur Agro	Neem Suraksha, Proneem, Neem Wave, Aza Technical
		Trifolio-M	NeemAzal
		Krishi Rasayan	Kayneem
		Rallis	Neemolin
		Consep	Surefire Neemachtin
		Stanes and PBT International	Nimbecidine
		EID Parry and Andermatt	NeemAzad
		Cyclo	Neememulsion
		Rallis	Neemitox, Neemolin
		RPG	Blockade
		Agro Logistics	Neem Cake Agroneem
		Gowan	AZA-Direct
		PBI/Gordon	EI-783, EI-791, Azatrol EC
		JB Chemicals	Jawan
		Biostadt	Neemactin
		Agri Life	Margosom
		Tagros	Trineem
		Biocontrol Network and Safer	Bioneem
		Biocontrol Network	NeemPlus Liquid
		Organica	K+ Neem
		SOM Phytopharma	AquaNeem
		Vipesco	Vineem
Nicotine	*Nicotiana tabacum*	United Phosphorus Ltd	Stalwart
		Hortichem	No-Fid
		Vitax	XL-All Nicotine
		Dow AgroSciences	Nicotine 40 % Shreds
		Bonide	Tobacco Dust
		United Phosphorus Ltd	Nico Soap
Plant pelargonic and related fatty acids		Dow AgroSciences	M-Pede, De-Moss, Scythe I, Akzo-Nobel, Thinex

(continued)

Table 18.1 (continued)

Active ingredient	Plant species	Company	Product name
Pyrethrins	*Chrysanthemum cinerariaefolium*	Prentiss	Prentox Pyrethrum Extract, ExciteR
		Syngenta	Alfadex
		MGK	Pyrocide, Evergreen, Premium Pyganic 175, Pyganic Crop Protection EC 1.4, Pyganic Crop Protection EC 5.0
		Frunol Delicia	Milon
		Agropharm	Pycon
		Consep	CheckOut
		Kemio	Hash
		Wilbur-Ellis	Py-rin Growers Spray
		Diatect	Diatect II, Diatect III, Diatect V
		Bonide	Bonide Liquid Rotenone-Pyrethrin Spray, Garden Dust, Earth Friendly Fruit Tree Spray/Dust
		Woodstream	Safer Yard
			Garden Insect Killer
		Natural Animal Health Products	Ecozone Pyrethrum Insect Powder
Rotenone	*Derris* spp., *Lonchocarpus* spp., *Tephrosia* spp.	Tifa	Chem Sect, Cube Root, Chem-Fish, Rotenone Extract
		Vipesco	Vironone
		Penick	PBNox
		Wright Webb	Pyrellin
		Prentiss	Prenfish, Noxfish, Nusyn-Noxfish, Synpren Fish
		Bonide	Rotenone 5 %, Bonide Liquid Rotenone-Pyrethrin Spray, Garden Dust, Rotenone-Copper Dust
Sabadilla	*Schoenocaulon officinale*	Dunhill Chemical	Veratran D, Veratran
Ryania	*Ryania speciosa*	AgriSystems International	Natur Gro R-50, Natur Gro Triple Plus
		Dunhill Chemical	Ryan50
Starch syrup		Kyoyu Agri	YE-621
Capsaicin	*Capsicum frutescens*	Soil Technologies	Armorex, Nemastroy, Valoram
		Bonide	Bonide Hot Pepper Wax
		Champon	Dazitol
		Hot Pepper Wax	Hot Pepper Wax
		Biocontrol Network	Hot Pepper Wax Animal Repellent

(continued)

Table 18.1 (continued)

Active ingredient	Plant species	Company	Product name
Cinnamaldehyde	*Cassia tora*	Monterey	Vertigo
		Proguard	Cinnacure
Phenethyl propionate	*Mentha piperita*	Spectrum	Bag-a-Bug Japanese Beetle Trap, Japanese Beetle Combo Bait
		Bioganic	Ecozap WaspHornet Insecticide, Ecozap Crawling and Flying Insecticide, Bioganic Flying Insect Killer
		EcoSmart	EcoExempt HC, Matran, Ecopco D Dust Insecticide, Ecopco AC, Ecopco Jet
		Arbico	Ecosafe
		Trece	Japanese Beetle Bait II, Trece Japanese Beetle Trap
		Woodstream	Ringer Japanese Beetle Bait
		Suterra	Surefire Japanese Beetle Trap
		Vipesco	Vizubon-D
Garlic extract	*Allium sativum*	ECOSpray Ltd	Nemguard
Saponin			Nema-Q
Plant-derived porphyrin derivative	*Quassia amara*		Nemastop

[a]Data adapted from Cooping and Duke (2007) and Dayan et al. (2009)

oil-based fungicides and herbicides. Definitive lists are difficult to compile as aromatic plants are grown all over the world and there is no accurate total harvest of these crops.

7 Consumption of Biopesticides

Biopesticides contribute only a small percentage of the total pesticide market in the world; however, it is expected their use will rise faster than synthetic insecticides. In 2011, the global biopesticide market was valued at US$1.3 billion (Marketsandmarkets.com 2012), whereas the total pesticide market (biopesticides and synthetic pesticides) was valued at US$37.5 billion (BCC Research 2012). The global market value of biopesticides is predicted to reach US$2.1 billion in 2012 and US$3.7 billion in 2017, giving a compounded annual growth rate (CAGR) of 12 % (BCC Research 2012). On the other hand, the global synthetic pesticide market value was predicted to reach US$44 billion in 2012 and US$61.5 billion in 2017, giving a CAGR of only 7 % (BCC Research 2012). Increasing demand for biopesticides from the USA and European countries is expected to continue because of market growth in organic vineyards, vegetables, and tree crops. For example, Table 18.4 shows the biopesticides usage in California from 2012 to 2013. It is interesting to see that the use of vegetable oils increased every year. This growth is reflected in the world with areas devoted to organic farming estimated to be at around 22 million hectares with 7.287 million hectares in Europe (Regnault-Roger 2012).

Table 18.2 Commercially available botanical herbicides[a]

Active ingredient	Plant species	Company	Product name
Clove oil	*Syzygium aromaticum*	EcoSmart	Matran EC
		St. Gabriel Laboratories	BurnOut II concentrate
		St. Gabriel Laboratories	Poison Ivy Defoliant
Fatty acids	Several plant species	Monterey	M-Pede
Pelargonic acid	Geraniaceae family members	Amvac	Hinder
		Neudorff	Quik-RTU
		Nufarm	Neo-Fat
		Russell	Naturell WK herbicide
		Otsuka	Oleate
		Koppert	Savona
		Neudorff	Neu 1128
		Dow Agrosciences	Scythe I
Phenethyl propionate	*Mentha piperita*	EcoSmart	EcoSmart HC
		EcoExempt	EcoExempt HC
		Bioganic	Bioganic Weed and Grass Killer
Pine oil	*Pinus* spp.	Certified Organics Ltd	Interceptor
Citronella oil	*Cymbopogon* spp.	Barrier Biotech Ltd	Barrier H

[a] The data in the table gathered from Cooping and Duke (2007) and Dayan et al. (2009)

Table 18.3 Commercially available botanical fungicides and bactericides

Active ingredient	Plant species	Company	Product
Cinnamaldehyde	*Cassia tora*	Monterey	Vertigo
		Proguard	Cinnacure
L-Glutamic acid plus γ-aminobutyric acid	Many plants	Auxein Corporation	AuxiGro
Jojoba oil	*Simmondsia californica*	IJO Products	E-Race
	S. chinensis		Eco E-Race
		Soil Technologies	Permatrol
Laminarin	*Laminaria digitata*	Goemar	Iodus 40
Milsana	*Reynoutria sachalinensis*	KHH BioScience	Milsana
Pink plume poppy extract	*Macleaya cordata*	Camas	Qwel
Giant knotweed extract	*Reynoutria sachalinensis*	Marrone Bio Innovations	Regalia
Tea tree oil	*Melaleuca alternifolia*	SIA "Biomor Latvija"	Timorex
Clove oil	*Syzygium aromaticum*	Xeda International	Bioxeda
Fenugreek seed powder	*Trigonella foenum-graecum*		Stimulia

Data adapted from Cooping and Duke (2007) and Dayan et al. (2009)

In the USA and Europe, the *Cydia pomonella* granulovirus is applied to combat codling moth on apples (Chandler et al. 2011). For example, in Washington State, the biggest apple producer in the USA, it is used on 13 % of the apple crop (Chandler et al. 2011). In Brazil, 4 million ha (approximately 35 %) of soybean crops have been sprayed with *Nucleopolyhedrovirus* in order to control the soybean caterpillar *Anticarsia gemmatalis* in the mid-1990s (Moscardi 1999). Also in Brazil, the entomopathogenic fungus *Metarhizium anisopliae* is used against spittlebugs in approximately 750,000 ha of sugarcane and 250,000 ha of grassland annually (Lomer et al. 2001).

Table 18.4 The total usage of biopesticide in California between 2002–2011

	Total usage (%)									
Active ingredient	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Acetic acid	–	–	–	–	–	–	–	0.01	0.12	–
Agrobacterium radiobacter	0.01	0.02	0.02	–	0.03	0.06	–	0.01	0.01	–
Azadirachtin	0,10	0.11	0.29	0,10	0.20	0.24	0.21	0.23	0.13	0.13
Bacillus pumilus	–	–	–	0.26	0.48	0.74	0.77	0.64	0.48	0.47
Bacillus sphaericus	0.25	0.81	1.41	2.52	3.83	2.13	2.04	1.66	0.92	0.63
Bacillus subtilis	1.01	1.38	1.67	1.04	1.45	1.83	1.59	1.48	1.5	1.53
Bacillus thuringiensis	7.37	10.58	15.59	17.24	20.61	27.96	27.05	27.56	21.8	16.15
Beauveria bassiana	0.06	0.06	0.09	0.06	0.05	0.07	0.05	0.03	0.03	0.04
Buffalo gourd root powder	–	–	–	–	–	0.01	0.03	–	–	–
Canola oil	–	–	–	–	–	–	–	–	0.01	–
Castor oil	0.03	0.10	0.04	0.01	–	–	–	–	–	–
Chenopodium ambrosiodes near *ambrosiodes*	–	–	–	–	–	–	–	1.86	0.73	0.49
Neem oil	16.09	4.83	8.65	8.65	8.15	11.68	9.97	9.71	8.16	4.39
Coniothyrium minitans	0.01	0.01	0.02	–	–	–	–	0.01	0.01	0.01
Gamma-aminobutyric acid	7.08	0.54	0.86	0.64	0.36	0.20	0.09	0.02	–	–
Garlic	0.04	0.02	0.02	0.01	0.01	0.01	0.02	0.00	0.30	–
Lavandulyl senecioate	–	–	–	–	–	–	–	0.04	0.03	0.38
Limonene	4.64	2.26	1.44	3.39	2.77	7.27	4.33	5.16	3.97	3.78
Linalool	0.01	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.08	0.01
Margosa oil	–	–	–	–	–	–	–	–	0.04	0.48
Menthol	–	–	–	0.01	–	–	–	–	–	–
Myrothecium verrucaria	1.93	3.75	3.98	2.06	2.11	3.16	2.27	2.13	1.61	1.73
Oil of citronella	–	–	–	–	–	–	–	–	–	0.02
Oil of jojoba	0.07	0.11	0.30	0.26	0.81	0.76	1.15	0.31	0.29	0.08
Oil of lemon eucalyptus	–	–	–	–	–	–	–	–	–	–
Paecilomyces lilacinus	–	–	–	–	–	–	–	–	0.02	0.03
Pseudomonas fluorescens	0.07	0.16	0.09	0.07	0.08	0.06	0.04	0.03	0.02	0.02
Quillaja	–	–	–	–	0.01	0.03	0.11	0.04	0.05	0.07
Reynoutria sachalinensis	–	–	–	–	–	–	–	0.02	0.63	0.92
S-abscisic acid	–	–	–	–	–	–	–	0.01	0.06	0.12
Sesame oil	–	–	–	–	–	0.09	0.05	0.08	0.09	0.08
Soybean oil	1.77	2.63	5.02	3.41	5.94	1.55	1.14	2.59	1.68	1.50
Sucrose octanoate	–	–	–	–	–	–	0.16	0.37	0.08	0.01
Thyme	–	–	–	–	0.01	0.05	0.06	0.07	0.09	0.04
Trichoderma harzianum	–	–	–	–	–	–	–	–	0.04	0.01
Vegetable oil	5.89	11.23	24.80	15.41	21.66	16.24	25.72	17.92	22.75	32.17
Yucca schidigera	–	–	–	–	–	–	–	0.01	0.03	0.10

Data was obtained from the Summary of Pesticide Use Report Data 2011 published by California Department of Pesticide Regulation

Biopesticides decompose in nature without bioaccumulation. Additionally, as these products often exist in the agroecosystem with few negative effects on nontarget organisms, they are regarded as environmentally friendly. Successful implementation of biopesticides will result in residue reduction, thereby producing a potentially safer product for the consumer. With the development and implementation of biopesticide control strategies, farmers and growers can decrease their reliance on the use of conventional pesticides against insect pests while at the same time, decreasing insect resistance to conventional pesticides.

8 Biopesticide Solutions

In essence, biopesticides are an innovative and safe solution for crop protection and management. The global biopesticide market is expanding rapidly in response to a demand for more environmentally friendly products. Biopesticide products exist on the market for the management of a wide range of important agricultural pests and diseases.

For agricultural growers, using cost-effective production methods is only part of the equation to harvesting and storing crops. The grower's income is determined on crop quality and yield. In an effort to achieve this output, biopesticide products can help growers improve crop quality and yield under challenging conditions. Microbial and biochemical products can be used in weed management and crop protection against pathogens, harmful insects, and numerous plant diseases that may otherwise divert or restrict a crop's access to valuable resources such as water, sunlight, or nutrients. Therefore, biopesticides promote crop health therefore increasing its salability. With organic farming systems becoming more popular due to consumer demand, biopesticide products provide growers with a means by which to produce higher-quality crops and larger yields that conform to consumer requirements.

9 Conclusion

World agricultural sectors face many obstacles, and pest pressure is particularly significant due to the evolution of resistance to synthetic pesticides. Many growers still rely on the use of conventional pesticides to protect their crops for financial reasons. However, due to their negative effects, the use of conventional pesticides has been strictly regulated. The use of alternatives such as biopesticides provides benefits as they are safer for the environment. Although the global market value is relatively small compared to that of synthetic pesticides, the growth rate in the biopesticides market value is encouraging. Growth in the agricultural sectors of affluent countries, in which the use of synthetic pesticides is controversial due to concerns related to human health, can only lead to increased demand for biopesticides.

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