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Review on the Bio-insecticidal Properties of Some Plant Secondary Metabolites: Types, Formulations, Modes of Action, Advantages and Limitations

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Authors' contributions

This work was carried out in collaboration between both authors who did various aspects of the literature searches. Both authors read and approved the final manuscript.

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Review Article

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ABSTRACT

Bio-pesticides are biological derived agents that are usually applied in a manner similar to synthetic pesticides but achieve pest management in an environmental friendly way. Bioinsecticides have the advantages of been reportedly eco-friendly both to man and the environment, are target specific, lack problem of residue, least persistent in environment, locally available, easily processed and inexpensive, though with the limitation of requiring repeated applications for the achievement of optimal control of insect pests while enhancing crop protection. The mode of action of bioinsecticides on insects includes repellent action, antifeedant activity, oviposition deterrent properties, growth and development inhibition, toxicity, attractants, sterility and death. Hence, bioinsecticides can be included in integrated pest management programs for crop protection and insect pest control. The review on biopesticidal properties of some plant secondary metabolites in the leaves, stems, bark, fruits, flowers, cloves, rhizomes, grains and seeds of plants and their interference with the growth, feeding, reproduction of insect pestsfor pest management has been elaborated.

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1. INTRODUCTION

The ancient man had deployed different methods of controlling insect population such as prayers, magic spells, cultivation systems, mechanical practices as well as application of organic and inorganic substances including pesticides, yet countries are faced with challenges in achieving the sound management of pests [1]. It has been estimated globally that about $38 billion is spent yearly on pesticicides [2]. United States Food and Drug Administration (FDA) reported that botanical pesticides (essential oils) are safer than synthetic pesticides which are reportedly known to increase the risk of ozone depletion, have neurotoxic, carcinogenic, teratogenic and mutagenic effects in non-targets species [3]. Other problems include the loss of estimated several billions of dollars worldwide by government in environmental and societal damages due pesticide impacts on public health; livestock and livestock product losses; crop and crop product losses; crop pollination problems and honeybee losses; fish and other wildlife losses and destruction of natural enemies [4]. In addition the development of insects resistance to synthetic pesticides (cross- and multi-resistance), have led to significant problems arising from failure of such chemicals to control pest [3,5-7]. The major economic and environmental losses due to the application of pesticides in the USA were: public health, $1.1 billion yearly; pesticide resistance in pests, $1.5 billion; crop losses caused by pesticides, $1.4 billion; bird losses due to pesticides, $2.2 billion; and groundwater contamination, $2.0 billion [4]. Furthermore, World Health Organization [8] estimated that between 50-100 million people in the developing countries do receive intensive pesticide exposure while another 500 million receive lower exposures which resulted into 3.5-5 million sufferers of subacute to acute pesticide poisonings yearly. According to Wilson, [9] an estimated sum of Rs11,471 per person are spent monthly on health challenge due exposure to pesticides in Srilanka. Devi, [10] calculated the costs of pesticide pollution in India to be $37 per person per year. Similarly, Atreya, [11] estimated a value of only $2 per individual per year for the similar effects in Nepal. Further, studies in Africa have also yielded a similar range of costs [12-13]. Hence, owing to the problems associated with the usage of the first to third generations of pesticides on human health, animals and the environment, researchers over the years delved towards the discovery of the fourth generation of pesticides which are plants and plant products based, termed biopesticides for the control of pests and bioinsecticides for the control of field, storage, domestic and structural insects of importance. For example Azadirachtin from neem plant has been reportedly used in the control of over 200 insect pests from different insect orders [14]. Therefore, the need for alternative, more effective and environment-friendly control agents or insecticides have become urgent [15]. However, the best pest control method is that which is non-toxic and environment friendly, hence the use of natural plant parts/products as bio-pesticides to overcome the problems of synthetic chemical hazards is considered the best control measure which has become popular. This gave rise to the recognition of plant secondary natural products which are natural chemicals extracted from plants for use as excellent alternative to synthetic pesticides [16-17].

Plant secondary constituents or metabolites further called active ingredients/phytochemicals are now been screened qualitatively, extracted quantitatively, identified, discovered and developed into formulations called green pesticides or bioinsecticides designed specifically for the control of insect pests. About 200 plants from the families Meliaceae, Rutaceae, Labiatae, Asteraceae and Canaliaceae have been studied extensively for their insecticidal properties [18-20]. Of repute is neem plant (*Azadirachta indica*) which has proven successful in the control of over 550 insect species in the orders Dictyoptera, Coleoptera, Isoptera, Homoptera, Heteroptera, Diptera, Orthoptera and others [14,21] Al-Quraishy et al., 2012b. Evidences abound that botanical pesticides are generally safe and effective [22]. This review is necessitated by the absence of a single material encompassing the types, formulations, applications, mode of action, advantages and limitations of bioinsecticides on insect pests.

2. BIO-INSECTICIDES?

Bioinsecticides are pesticides derived from natural materials like animals, plants, bacteria and some minerals. Bio-insecticide is a contraption of ‘biological insecticide’, which are biological derived agents that are usually applied in a manner similar to chemical pesticides but achieve pest management in environmental friendly way [23]. They are a group of naturally occurring, often slow-acting protecting agents that are usually safer to humans with minimal residual effects to the environment than conventional pesticides. They can be biochemical or microbial [24]. Biochemical insecticides include plant-derived botanicals that can interfere with the growth, feeding, reproduction of pests or insect pheromones applied for mating disruption, monitoring or attract-and-kill strategies [25]. Most of these plants example *Azadirachta indica, Dracaena arborea* and others are of great importance to the health of individuals and the environment. The insecticide properties of plants lie in their chemical substances also called active ingredients that produce definite physiological actions on the insect body [26]. According to Johnson et al., [27]; Nakanishi and Suzuki, [28], more than 30,000 secondary metabolites with insecticidal activities have been reported from plants.

Different plant parts such as bark, stems, leaves, fruits, flowers, cloves, rhizomes, grains and seeds possess phytochemical compounds being allelochemicals such as alkaloids, amines, non-protein amino acids, cyanogenic glycosides, glucosinolates, lectins and protease inhibitors. Others include terpenes, steroids, polypeptides, polyacetylenes, flavonoids, tannins, phenylpropanoids flavonoglycosides, arabinofucoglucanes, dihydrochalocones, fucogalactoglucoarabinanes and others with proven insecticidal properties such as feeding deterrent, growth regulator, repellent, oviposition (egg deposition) suppressant, sterilant or toxin, inhibiting growth or killing of insect pests [27-43].

According to Kaehler and Kennish, [44]; Dawes, [45], plant secondary metabolites are resident in plants at varying compositions while [46-47] related that the identification, composition and proportion of secondary constituents in plants, vary in the same plant based on its geologic distribution, time of collection and part of plant material used as well as the extraction procedure. This is supported closely by Angulo et al., [48]; Ramos et al., [49]; Gonzalez et al., [50] who reported that the concentration of secondary compounds in plants is dependent on genetic or environmental causes, development stage and storage time.

2.1 Types of Bio-insecticides

There are basically three classes of bioinsecticides based on their insecticidal properties that originated from natural living organisms. These include

I. Microbial pesticides: Are bioinsecticides produced by microorganisms such as bacteria (*Bacillus thuringensis, Bacillus subtilis, Bacillus papilliae,* Actinomycetes), fungi (*Trichoderma* species, *Coniothyrium minitans*, *Ampelomyces quisqualis, Beauveria bassiana*), viruses (Tospoviruses, Nucleo polyhedron virus, *Cydia pomonella granulovirus*), and entomopathogenic nematodes (Steinernematidae *e.g Steinernema feltiae* and Heterorhabditidae) for controlling different target insect pests [51-53]. Examples include the application of microbial insecticide *Chromobacterium subtsugae* for the suppression of pecan weevil (*Curculio caryae* Horn). Also, the combination of eucalyptus extract and microbial insecticide *Isaria fumosorosea* Wize for control of black pecan aphid *Melanocallis caryaefoliae* (Davis) were found promising as alternative insecticides [54]. Entomopathogenic nematode *Steinernema feltiae* was used as biocontrol agent against vine mealybug *Planococcus ficus* (Signoret) [55]. The fungus *Beauveria bassiana* has shown great potential for the management of the destructive invasive insect pest known as red turpentine beetle (RTB) *Dendroctonus valens* Le Conte, a specie of bark beetle [56].
II. Biochemical pesticides: These include plants and plant products hence called bioinsecticides, biorational or green pesticides [57]. They are naturally occurring substances that control pests by non-toxic mode of action. Included are sex pheromones that attract insect pests to traps thus disrupting mating, insect hormones example spinosad and insect growth regulators such as semiochemicals, pyrethrum, rotenone, neem oil and various essential oils [52,57-59]. Spinosad was reported effective in controlling Colorado potato beetle *Leptinotarsa decemlineata* [60]. Over 200 plants and their extracts have been documented with insecticidal properties against over 550 insect pests of various orders [14].
III. Plant Incorporated Protectants (PIPs): Are pesticide substances genetically engineered into plants (Genetically Modified crops) that destroy pests. This process involves the genetic incorporation of DNA into agricultural commodities against insect

pests. Example is *Bacillus thuringensis* cotton (Bt cotton) [52]. *Bacillus thuringensis* (Bt toxin) has been genetically engineered into plants and used to control insects of the order Coleoptera, Lepidoptera and Diptera [61]. Example is the successful combination of *Bacillus thuringiensis* Cry3Aa protoxin and protease inhibitor (potato carboxypeptidase inhibitor) which proved efficient against coleopteran insect pests of stored products and grains thus preventing them from damage [62].

2.2 Solvents of Extraction

Plant secondary constituents may be active or inactive therapeutically, thus phytochemical extraction is paramount in the discovery and isolation of the bioactive profile of the plant in order to maximize the amount of target compounds so as to obtain the highest biological activity of the plants and further understand the function, mode of action and level of toxicity [63-65]. The variety of bioactive compounds contained in plant materials and their solubility properties can be determined by extracting them in different solvents [66-67]. According to Turkmen et al., [68]; McDonald et al., [69]; Ngo et al., [70], the type of solvent used using extraction has tremendous effect on the extraction yield and the content of the bioactive compounds thus affected the biological activity of the extract significantly. The authors further stated that the efficiency of an extract is strongly dependent on the extraction method, temperature, extraction time, composition of the phytochemicals and the solvent used. McDonald et al., [69] stated that plant materials contained high level of polar compounds that are soluble in solvents with high polarity while [71] concluded that highly polar solvents such as water, methanol and ethanol favour extraction efficiency hence the use of polar solvents for phytochemical extraction process. Considering the above statements, solvents used for active component extraction of plant secondary constituents are as follows as stipulated by [72-76].

i. Water: Used for extracting anthocyanins, starches, tannins, saponins, terpenoids, polypeptides and lectins.
ii. Ethanol: Extraction of tannins, polyphenols, flavonols, terpenoids, polyacetylenes, sterols and alkaloids.
iii. Methanol: Extracts anthocyanins, terpenoids, saponins, tannins, xanthoxyllines, totarol, quassinoids, lactones, phenones, polyphenols and flavones.
iv. Chloroform: Extracts terpenoids and flavonoids.
v. Dichloromethanol: Extracts terpenoids.
vi. Ether: extracts alkaloids, terpenoids and fatty acids.

2.3 Methods for Extraction of Plant Metabolites

The active ingredients of plants can be extracted using the underlisted methods:

i. Plant Tissue Homogenization: Plant tissue homogenization in solvent has been widely used by researchers. Dried or wet, fresh plant parts are grinded in a blender to fine particles, put in a certain quantity of solvent and shaken vigorously for 5 - 10 minutes or left standing for 24 hours after which the extract is filtered. The filtrate then may be dried under reduced pressure and re-dissolved in the solvent to determine the concentration [77].
ii. Serial Exhaustive Extraction: It involves successive extraction with solvents of increasing polarity from a nonpolar (hexane) to a more polar solvent (methanol) to ensure that a wide polarity range of compounds could be extracted. Some researchers employ soxhlet extraction of dried plant material using organic solvent [77].
iii. Soxhlet Extraction: Is only required where the desired compound has a limited solubility in a solvent and the impurity is insoluble in that solvent. Simple filtration can be used to separate the compound from the insoluble substance if the desired compound has a high solubility in a solvent [78].
iv. Maceration: In maceration (for fluid extract), whole or coarsely powdered plant is kept in contact with the solvent in a stoppered container for a defined period with frequent agitation until soluble matter is dissolved [79].
v. Decoction: This method is used for the extraction of the water soluble and heat stable constituents from crude extract by boiling it in water for 15 minutes, cooling, straining and passing sufficient cold water through the residue to produce the required volume [80].
vi. Infusion: It is a dilute solution of the readily soluble components of the crude extract.

Fresh infusions are prepared by macerating the solids for a short period of time with either cold or boiling water [80].

vii. Digestion: This is a kind of maceration in which gentle heat is applied during the maceration extraction process. It is used when moderately elevated temperature is not objectionable and the solvent efficiency of the menstrum is increased thereby [80].

viii. Percolation: This is the procedure used most frequently to extract active ingredients in the preparation of tinctures and fluid extracts. A percolator (a narrow, cone-shaped vessel open at both ends) is generally used. The solid ingredients are moistened with an appropriate amount of the specified menstrum and allowed to stand for approximately 4 hours in a well closed container, after which the mass is packed and the top of the percolator is closed. Additional menstrum is added to form a shallow layer above the mass and the mixture is allowed to macerate in the closed percolator for 24 hours. The outlet of the percolator then is opened and the liquid contained therein is allowed to drip slowly. Additional menstrum is added as required, until the percolate measures about threequarters of the required volume of the finished product. The marc is then pressed and the expressed liquid is added to the percolate. Sufficient menstrum is added to produce the required volume, and the mixed liquid is clarified by filtration or by standing followed by decanting (Handa *et al*., 2008). ix. Sonication: The procedure involves the use of ultrasound with frequencies ranging from 20 kHz to 2000 kHz; which increases the permeability of cell walls and produces cavitation [81].

Qualitative and quantitative analysis of phytochemicals can be done using standard gravimetric and spectrophotometric procedures such as Gas chromatography mass spectroscopy, High performance liquid chromatography, High performance thin layer chromatography and Optimum performance laminar chromatography [80,82-85].

i. Gas Chromatography Mass Spectroscopy (GCMS) which can be applied to solid, liquid and gaseous samples. Here the samples are converted into gaseous state then analysis is carried out on the basis of mass to charge ratio. Thus it is most widely used for quantitative analysis. Example is the quantification of the phytochemicals in the leaves of *Annona muricata* (sour sop) and *Articarpus heterophyllus* (jackpot) [86].
ii. High Performance Liquid Chromatography (HPLC): This is applicable to compounds that are soluble in solvents. HPLC is useful for compounds that cannot be vapourised or that decompose under high temperatures. HPLC provides both quantitative and qualitative analysis in a single operation. Example is the quantitative analysis of alkaloids in the crude extracts of *Ephedra intermedia* [87].
iii. High Performance Thin Layer chromatography (HPTLC): Is applicable for the separation, detection, qualitative and quantitative analysis of phytochemicals. HPTLC is suitable for qualitative, quantitative and micro-preparative chromatography. Example is the phytochemical quantitative analysis of *Adansonia digitata* and *Acacia raddiana* [88].
iv. Optimum Performance Laminar Chromatography (OPLC): Combines both advantages of HPTLC and HPLC. Example is the quantitative phytochemical analysis by planar chromatography of the plant extracts of *Ruta graveolens*, *Citrus aurantium*, *Tilia cordata*, *Ginkgo bilobita* and *Hibiscus sabdariffa* [89].

2.4 Bio-insecticide Formulations and Application

Bio-insecticide formulations can be divided into two types depending on their physical state: liquid and dry formulations [90].

i. Liquid formulations can be water-based, oil-based, polymer-based or combinations. Water-based formulations demand the addition of inert ingredients like stabilizers, stickers, surfactants, coloring agents, antifreeze compounds and other nutrients. Water formulations include suspension concentrate, suspo-emulsions, capsule suspension.
ii. Dry formulations can be produced using different technologies such as spray drying, freeze drying or air drying either with or without the use of fluidized bed. They are produced by adding binder, dispersant and wetting agents [91-93]. Dry formulations include dust, powders, granules [94-95].

Bioinsecticides are usually formulated as: dry formulations for direct application – dusts (DP), seed dressing formulations – powders for seed dressing (DS), granules (GR), micro granules (MG), dry formulations for dilution in water – water dispersible granules (WG), and wettable powders (WP); liquid formulations for dilution in water – emulsions, suspension concentrates (SC), oil dispersions (OD), suspo-emulsions (SE), capsule suspensions (CS); ultra low volume formulations [94-95]. Bioinsecticides can be applied as stomach poison (added into the food and ingested by the insect), contact/surface poison (applied topically at the dorsal region of the insect head, fumigant by spreading around its abode), and finally as nervous poison (injectables).

2.5 Plant Extracts and their Insecticidal Properties

The plant parts utilized depend on the active ingredient of interest and their abundance in certain plant parts, which are dried, ground into fine powder and then extracted with organic solvents [96]. These are then utilized as essential oils, plant extracts or both [97].

2.5.1 Essential oils

Essential oils extracted from aromatic plants have increased considerably as insecticides owing to their popularity with organic growers and environmentally conscious consumers. They are produced by steam distillation of plant material and contain many volatile, low molecular weight terpenes and phenolics. They have been extracted from the plant families Myrtaceae, Lauraceae, Lamiaceae and Asteraceae. They have repellent properties [3,6,98], insecticidal activities [98-100], antifeedant properties [17,101-102], oviposition inhibiting [103-104], ovicidal [102], growth inhibiting [7,105] and interestingly larvicidal effects [106-107] on a variety of insects such as biting flies, phytophagous and garden insects. *Mentha piperita* oil repels ants, flies, lice, moths and is effective against *Callosobruchus maculatus* and *Tribolium castaneum* [108]. *Trachyspermum* species oil is larvicidal against *Aedes aegypti* and southern house mosquito, *Culex quinquefasciatus* [109]. Nepetalactone, the active constituent in catnip (*Nepeta cateria*) essential oil is highly effective for repelling mosquitoes, bees and other flying insects. It is particularly effective against *A. aegypti* mosquito, a vector for yellow fever virus. Oils of *Zingiber officinale* rhizomes and *Piper cubebaberries* exhibited insecticidal and antifeedant activities against *Tribolium castaneum* and *Sitophilus oryzae* [110-111]. Tagetes species oil possessed anti-insecticidal activity on *Ceratitis capitata* and *Triatoma infestans* [112]. Also, essential oil of *Tagetes minuta* has toxicity against *Cochliomyia macellaria* and has acaricidal and repellent properties [113]. *Melaleuca alternifolia* essential oil displayed fumigant toxicity against *Sitophilus zeamais* [114]. Rosemary, oregano, yarrow, eucalyptus and mint oils are all reportedly used as safe compounds for surface treatment or fumigation in cockroach control. Oregano oil is used as potential repellents against *Supella longipalpa* [115]. Also, *Laurus nobilis* essential oil exhibited toxic activities against *Rhyzopertha dominica* and T*ribolium castaneum*. *Lavandula hybrida*, *Rosmarinus officinalis* and *Eucalyptus globulus* oils were insecticidal against *Acanthoscelides obtectus* adults [116]. Eugenol, the principal compound of the essential oils from clove basil had strong repellent effect on mosquitoes while linalool also in basil oil had toxic effect against the *Bruchid Zabrotes sub fasciatus* and other storage pests [117-118]. Essential oil of *Zingiber zerumbet* showed repellence against *Lasioderma serricorne* [119]. *Juniperus procera* essential oil exhibited significant repellence against the malarial vector *Anopheles arabiensis* [120]. Verbenone and camphorin eucalyptus oil were active against *Anopheles obtectus* adults [121], antifeedant against biting insects, acted as insecticidal agents and prevented mosquito bite [122-125]. Lucia et al., [126] reported that essential oil from *Eucalyptus globules* proved toxic to *Anopheles aegypti* larvae. The United States of America, Center for Disease Control and Prevention [127], recommended the use of lemon eucalyptus oil as active ingredient for protection against West Nile virus that causes neurological disease or even death, spread by mosquitoes.

Toloza et al., [128] reported the fumigant toxicity/repellent activity of essential oil from *Eucalyptus cinerea*, *Eucalyptus viminalis* and *Eucalyptus saligna* against human head lice. Eucalyptus oils rich in cineole were affective against parasite of honey bee Varroa mite, *Varroa jacobsoni, Tetranychus urticae, Phytoseiulus persimilis* and *Dermatophagoides pteronyssinus* [129-131]. Eucalyptus essential oil significantly reduced the number of tick bites in humans and therefore useful in the control of tick-borne infections [132-133]. Pujiarti and Fentiyanti, [134] reported that *Eucalyptus* *deglupta* essential oils have repellent activity against *Culex quinquefasciatus* mosquito. Extracts from the plants clove basil and *Rosmarinus officinalis* possessed antifeedant property against adults of red palm weevil *Rhynchophorus ferrugineus* [135-137]. Insects exposed to garlic essential oil displayed altered locomotion activity, muscle contractions and paralysis resulting from toxic effect on the insect's nervous system. The toxicity of essential oils in insects indicated neurotoxic action with hyperactivity, hyperextension of the legs and abdomen and rapid knock-down effect or immobilization [138-139].

2.5.2 Phytochemicals

Plant extracts basically known as phytochemicals, active ingredients or secondary metabolites are proven to exhibit various pharmacological and biochemical actions when ingested by insect herbivores. Plant bioactivity depends on chemical compounds which may inhibit insect feeding. Toxic effects to insect pests are produced by the compounds terpenoids, steroids, phenols, flavonoids, tannins, alkaloids and cyanogenic glycosides [140]. Primarily, phytochemicals affect the midgut epithelium and secondarily affect the gastric caeca and malpighian tubules of insects initiating anti feedant properties and eventual death of insects making their presence in plants potential for use as insecticides [141]

2.5.2.1 Tannins

Tannins are the most abundant secondary plant metabolite ranging from 5-10% dry weight of tree leaves. It is found predominantly in plant tissues such as bark, wood, fruit, leaf, seed, stem and sap [142]. Plant tannins have important effect on the biochemical activity of insects. Tannins oxidize with high P^H guts, binding to certain semiquinone radicals and quinones and other reactive oxygen species production at high levels forming complexes which ultimately cause mortality in insects over a period of time [143]. Tannins crosslink proteins thus acted as inhibitors to protein digestion and function. Tannins hinder development of phytophagous insects as it precipitates and inactivates adhesion enzymes and cell development proteins with resultant effect of antifeedant properties and eventual death thus functioning as bioinsecticides and growth regulators [144]. According to the WHO [145], tannins possess astringent properties and thus drag the insect tissue together, restricting the flow of blood with resultant death of insects. Tannins also turn insect skin into leather by binding proteins to form water insoluble substances resistant to proteolytic enzymes.

Plant tannins affect insects by deterrence and or toxicity because they are polymers of phenolic compounds acting as feeding deterrents which reduce the digestibility of food in insect guts. As feeding deterrents in insects, tannins also cause stomach poisoning, showing systemic effects in insects [143].Tannins are phenolic compounds containing hydroxyl and carboxyl groups which form strong complexes with proteins and other macromolecules thus hindering the growth and afterwards development into adults by the immature stages of insects owing to the presence of ovicidal and larvicidal properties of the plants as confirmed by [146-149]. Wongo, [150] reported the biological activity of sorghum tannin extracts against the stored grain pests of *Sitophilus oryzae (L), Sitotroga cerealella (Olivier)* and *Tribolium castaneum*. The phytoconstituents found in the leaf extract of *Khaya senegalensis* such as tannins, saponins, flavonoids, steroids and alkaloids were responsible for the mortality of *Dinoderus porcellus* [151]. Ellagitannins reduced infestation of *Schizaphia graminum* and *Myzus persicae* while condensed tannins controlled *Gossypium hirsutum* of cotton. Ellagrit acid inhibited the growth of tobacco budworm *Heliothis virescens* [152]. Tannins extracted from aqueous spice applied on green beans (*Phaseolus vulgaris*) demonstrated mortality of 61-75% on whitefly, 67-75% on thrips and 72-78% on Coleoptera [153]. The spice extract also proved insecticidal against *Bemina tabaci, Calothrips impurus*, *Calothrips occipitalis* and *Nisotra* species of green beans [153]. Furthermore, tannins extracted from Mimosa (*Acacia mollisima*), Quebracho (*Schinopsis lorentzii*) and redpine bark (*Pinus brutia*) proved larvicidal against the wood damaging termite *Spondylis buprestoides* [154].

2.5.2.2 Alkaloids

Alkaloids are the most important group of natural substances playing important role as bio insecticides [155-156]. Alkaloids occur naturally in plant families such as Papaveraceae (Opium poppy), Renunalaceae (butter cups, jimson weed), Solanaceae (potato and tomato), Amaryllidaceae (Amaryllis). Alkaloids are known sources of potent insecticides, acting in synergy with saponins and tannins as repellents and antifeedant, thus deter insect pests with resultant adverse effects [25,157]. Alkaloids function as neurotoxins and attack the acetylcholinestarase receptor site of the insects, altering the permeability of the neuromuscular juncture, generating new nerve impulses that lead to spasmodic contractions, delay larval development, convulsions and finally death of the nymphs and adults as confirmed by [157-158]. Lee, [159]; Emam et al., [160]; Acheuk and Doumandji-Mitiche, [161]; Wachira et al., [162]; Velu et al., [163] reported that alkaloids exhibited adulticidal, larvicidal and antifeedant activities against insects. Velu et al., [163] stated that alkaloids from Arachis hypogaea extract had larvicidal activity against Anopheles mosquito. Acheuk and Doumandji-Mitiche, [161] reported that alkaloids extract of Pergularia tomentosa exhibited antifeedant and larvicidal effects while [159] concluded that pipernonaline and piperidine alkaloids had larvicidal activity on mosquito. Furocoumarin and quinolone alkaloids extracted from Ruta chalepensis leaves showed larvicidal and antifeedant activities against the larvae Spodoptera littoralis [160,164]. Wachira et al., [162] observed that pyridine alkaloids extracted from Ricinus communis proved insecticidal against the mosquito Anopheles gambiae.

2.5.2.3 Terpenoids

Terpenoids are natural plant products (organic chemicals) derived from five carbon isoprene units used extensively for their aromatic qualities. They play major roles in traditional herbal remedies and are responsible for the scent and flavor of eucalyptus, clove, cinnamon and ginger. Examples are menthol, citral, camphor and salvinorin. Steroids and Sterols in animals are biologically produced from terpenoid precursors [[165-166]. Terpenoids are classified into monoterpenoids, diterpenoids, triterpenoids, sesquiterpenoids and polyterpenoids. Terpenoids play major role in the regulation of moulting and other functions in insects. It blocks the pathway leading to the synthesis and formation of the juvenile hormone (hydroxyecdysone) in insects and arthropods thus regulating larval moults, onset of pupa formation and metamorphosis [167-169]. Terpenoids act as hormones, pheromones or insect deterrents [170]. Jose and Sujatha, [171] revealed that terpenoids, coumarin and phenols, present in the methanol extracts of *Gliricidium sepium* exhibited significant antifeedant activity. It also controls reproduction and other physiological processes such as embryonic development [172-174]. Terpenoids instil feeding deterrence and toxicity in insects [175-176]. Terpenoids are compound of tetranortriterpenoid that act as insect repellents and feeding inhibitor and as hormone ecdysone, thus controlling the process of metamorphosis by inhibiting the development of immature insects from nymphs to adult cockroaches as confirmed by [175-177]. Linaloola and monoterpenes extracted from flowers of *Philax paniculata* repelled the ant *Nasius niger* [178]. Sesquiterpene extracted from *Solanum habrochaites* repelled the silverleaf whitefly *Bemisia tabaci*, a vector for begomoviruses [179-181].

2.5.2.4 Flavonoids

Flavonoids are useful in pest-management strategy and exhibit insecticidal properties [182]. Flavonoids can be found in cocoa, citrus example tangerine, parsley, blueberry, grapefruit, onions, barley, maize, sorghum, amaranthus, turnip [183-184]. Flavonoids play significant role in the protection of plants against plant feeding insects and herbivores [161,185]. Flavonoid classes such as isoflavonoids and proanthocyanidins protect plants against insect pests by influencing their behaviour, growth, feeding, inhibit development and increase the mortality of insects [106,186-188]. According to Velu et al., [163]; Morimoto and Komai, [189]; Goławska et al., [190]; Goławska and Łukasik, [191]; Goławska et al., [192], flavonoids acted as feeding deterrent and extracts of flavonoids had larvicidal activity on the developmental stages of insects.

Flavonoids extracted from the shrub *Lonicera maacki* reported repellency against adult *Spodoptera exigua*, feeding deterrent and severe damage to the larval caterpillar stage ([193]. The extracts also induced weight reduction of larvae at 50% and mortality by 43% while establishing pivoted development in the larvae that survived with eventual reduction in pupa development and growth rate of the insect [193].

2.5.2.5 Cyanogenic glycosides

Cyanogenic glycosides present in plant species are considered to possess important role in plant defense against herbivores [194]. Glycosides are plant steroids and are poisonous derivative from plants. They are stored in inactive form conjugated with sugars. These poisons are activated by enzyme hydrolysis causing the sugar part to be broken off making the chemical available for use as the insects feed on the plant [195]. Velu et al., [163]; Kubo and Kim, [185]; Al-Rajhy and Kheir, [196], concluded that cardiac glycoside, possessed both larvicidal action and insect growth inhibitory activities. Glycosides also exhibited antifeedancy [197]. Al-Rajhy et al., [196] recorded that the cardiac glycoside extract digitoxin, from Digitalis purpurea, extract from Calotropis procera, azadirachtin and neem oil from Azadirachta indica were insecticidal against larvae and adult stages of the camel tick, Hyalomma dromedarii. Also, Kubo and Kim [185] found that flavan glycosides viscutin exhibited insect growth inhibitory activity against the cotton insect pest Pectinophora gossypiella. Furthermore, cyanogenic glycosides found in cassava, bamboo, flax and other plants were insecticidal as fumigants against stored-product insects [198]. Velu et al., [163] reported that glycosides extract from groundnut Arachis hypogaea was larvicidal against mosquitoes. Juvenogens a type of plant glycoside reportedly have potential application in insect pest control [199]. Adeyemi, [25] reported that insect antifeedants are mainly triterpenoids, which is on a 30-carbon skeleton, occurring as glycosides and highly oxygenated.

2.5.2.6 Saponins

Saponins are heterosides (substances containing one or more sugar molecules in their structures). They are glycosides with soapy characteristics and are reported to possess bioactive agents due to their bitter and acrid taste resulting in feeding deterrents in insects [200]. These molecules have pesticide potential and are toxic to insects. Insecticidal activities include toxicity to harmful insects (antifeedants, disturbance of moulting, growth regulation and mortality) due to their interaction with cholesterol, causing a disturbance of the synthesis of ecdysteroids, which serves also as protease inhibitors or cytotoxic to insects as moulting and ecdysis are disturbed [201-202]. Saponins interfere with insects behavior, regulate growth and induced high toxicity on a vast array of arthropod pests and vectors such as *Tetranychus urticae* Koch, *Spodoptera littoralis* (Boisduval), *Culex pipiens* Linnaeus [203], caused growth inhibition, larvicidal capacity and mortality in caterpillars and aphids [42]. Steroidal saponins acted as agonists or antagonists with the receptor site for ecdysone (insect moulting hormone) causing ecdysial problems [176]. Saponins are toxic because of their ability to increase permeability abilities of plasma membranes, causing lysis of erythrocytes in vitro [204]. Thus, a high dose of saponin in the gut of an insect leads to disruption of the cell membrane and cell lysis of the intestinal mucosal cells [202]. Saponins which are glycocides with soapy characteristics are reported to possess bioactive agents due to their bitter and acrid taste resulting in feeding deterrents in the insects [200]. Saponins cause haemolysis of blood and poisoning in insects hence interfering with the replication of Deoxyribonuclei acid (DNA) with eventual death of the insects [205]. Avicins triterpenoid saponins extracted from *Acacia victoriae* exhibited cytotoxicity, inhibited protease activities, thereby induced apoptoxic cell death by mitochondrial perturbation in animals including humans [206].

Saponins extracted from *Ilex apocea* initiated antifeeding property in *Limantria dispar* [207], mite species (*Oligonichus illicis*) and for two caterpillar species (*Hyphantria cunea* and *Malacosoma americanum*) ([208-209]. Also, Diacoraceae plants showed antifeedant activity to *Acromynes octospinosus* ant [210-211]. Saponin from alfalfa varieties applied on flour worm larvae *Tenebrio molitor* caused a decrease of dry food quantity metabolized by this insect [212], and also brought about reduction in larvae weight of *Ostrinia nubilalis* [213]. Saponins of leguminous plants (chickpeas, garden peas, broad beans, haricot beans, lentils, peanuts) in the artificial diet of *Callosobruchus chinensis* resulted in feeding deterrent of the insect [214]. A spirostanic saponin isolated from Solanaceae (*Solanum laxum*) showed antifeedant activity against *Schizaphis graminum* aphid on artificial diet [215]. While saponins extracted from *Blanites roxburghii, Agave cantala* and *Phaseolus vulgaris* exhibited antifeedancy on *Spilosoma obliqued* larvae. Glycoalcaloids extracted from solanum species instilled reduction in the weight of *Tribolium castaneum* and *Manduca sexta*. Saponins from *Cestrum parqui* showed repulsive activity against the caterpillar of *Pieris brassicae* as well as antifeedancy against larvae *Spodoptera littoralis* and *Helicoverpa armigera* [216].

The crude saponins extracted from *Cestrum parqui* injected to the fifth larval instar stage of *Schistocerca gregaria* larva increased insect mortality [217]. Spraying aqueous solution of alfalfa saponins reduced the number of *Tetranychus urticae* mite and *Pharodon* specie (aphids) by 85 and 90%, respectively found on tomato plant. Saponins of alfalfa also caused mortalities of eggs of *Tagetes urticae* [209]. The introduction of alfalfa saponins into the food of *Ostrinia nubilalis* caused 100% mortality of its second larval instar stage [213]. Prosper *et al*., [218] reported larvicidal activity of steroidal saponins from *Dracaena arborea* on *Aedes albopictu*. Also saponins extracted from *Quillaja saponaria* exhibited 100% larvicidal activity against the mosquito larvae of *Aedes aegypti* and *Culex pipiens* [219]. Saponin of alfalfa leaves, showed cumulative mortality of 90% at the larval and the nymphal stages of S*podoptera littoralis* [203]. The saponins extracted from the leaves and the roots of the alfalfa were toxic for *Leptinotarsa decemlineata* larvae [220]. Crude saponins of *Cestrum parqui* showed toxicity on tested insects such as *Schistocera gregaria, S. littoralis* and *Tribolium confusum* and the larvae of the mosquito *Culex pipiens* [216]. Saponins of alfalfa leaves resulted in reduction in the fertility and oviposition of *Spodoptera littoralis* [203]

Other effects of saponins on insects include repellent or deterrent activity, which alters the peripheral nervous system, leading to the insects neither eating nor sucking and causes them to move away from food source [203,220-221], reduced uptake of food through the insect gut leading to possible death through starvation [192,203,222], block the uptake of steroids assimilation [168,201], antagonistic or competitive activity on the ecdysteroid reporter complex [201] and apoptoxis inducing activities [176,204].

2.5.2.7 Phenolics

Phenolics are synonymous with toxicity as the compound plays important roles in plant herbivore and pathogen interaction. Phenols exhibited antioxidant properties which are pesticidal in nature [140]. Phenolics exert toxicity upon being ingested by the herbivore insect [181]. Isman and Duffey, [223] reported the toxicity of tomato phenolic compounds against the fruitworm, *Heliothis zea*. Johnson et al., [224] reported the repellent activity of extracted phenolic compounds of African shrub *Aloe vryheedensis* against honey bees found on sunbird pollinated plant. Also, the phenolic compounds rutin, vanillic- and synaptic acid in pepper (*Capsicum annum*), affected larval development and the response of the adult moth (Oriental leafworm *Spodoptera litura)*, [225].

2.5.2.8 Esters and fatty acids

Esters and fatty acids cause rapid toxic effects in larvae of insects at low concentrations and therefore have potentials for use in pest control [226-227]. Various authors in their studies revealed that esters and fatty acids from plants have insecticidal and larvicidal activities [228-229], repellent or antifeedant properties [230], reduction in larval body weight of insects [231]. Fatty acids extracted from the oil of coconut (*Elaeis guineensis*) are processed into soaps commercially sold as 'green soaps' which are sprayed as contact insecticide for the control of soft-bodied insects and arthropods such as plant lice, spider, mites, adelgids, scale insects, aphids, mealybugs, whiteflies, thrips and the larvae of sawfly [232-234]. Clements *et al*., [235] stated that the Colorado Potato Beetle *Leptinotarsa decemlineata* of solanaceous plants such as potato and tomato were controlled using conjugated linoleic acid from foliar potato. Also larval growth, embryogenesis and feeding preference in Colorado potato beetle were adversely affected. Insecticidal properties such as increased larval mortality, slowed larval development, antifeedancy and decreased egg viability after maternal ingestion were reported. Fatty acids methyl esters isolated from *Solanum lycocarpum* proved larvicidal against the vector of malaria *Culex quinquefasciatus* [229]. Mullens et al., [230] showed that saturated fatty acids of caprylic and capric acids mixture exhibited repellency and antifeedancy against houseflies, horn flies and stable flies.

2.6 Modes of Action of Bioinsecticides on Insects

Botanical insecticides also called green pesticides or bioinsecticides affect various insects in different ways depending on the physiological characteristics of the insect species as well as the type of the insecticidal plant. The efficacy of plant chemicals lie in their ability to cause destruction of cells by Reactive Oxygen Intermediates (ROIs), alkylation and oxidation of proteins, lipids and membranes, inactivation of channel proteins and disruption of membrane potential by interacting with electron transport chain in the mitochondrial membrane [76].

David et al., [141]; Rey et al., [236]; Achio et al., [237]; Kesetyaningsih, [238] disclosed that plant extracts primarily disrupt the cellular structure of insect midgut epithelium and secondarily the gastric caeca, columnar cells, peritrophic membrane, striated border and longitudinal muscles leading to mortality of insects.

Bioinsecticides also cause loss of nerve cell membrane action leading to loss of nerve function, paralysis and death. Biochemical groups from plants exert their toxic effects by disrupting the sodium and potassium ion exchange processes in insect nerve fibers and interrupting the normal transmission of nerve impulses leading to knockdown paralysis. These metabolites increase spontaneous activity of sensory nerves which send spurious information to motor nerves resulting in twitching, lack of co-ordination and convulsion affecting the central nervous system with eventual stimulation of motor nerves and resultant knockdown paralysis [239-240]. They exert their toxic effects primarily on nerve and muscle cells, causing rapid cessation of feeding, resulting in death several hours or few days after exposure to treatment [166,205]. Plant extracts inhibit the activity of the enzyme acetylcholinestarase (AChE) on the nervous system of insects with resultant deaths [241]. Essential oils from plants interfere with basic metabolic, biochemical, physiological, and behavioral functions of insects [242]. Chaubey, [110-111], demonstrated the interference of monoterpenes with acetylcholinestarase activity in insects. Rattan, [156] and Mikhaiel, [243] reviewed the mechanism of action of essential oils on the body of insects and documented several physiological disruptions such as inhibition of acetylcholinestarase (a key enzyme responsible for terminating the nerve impulse transmission through synaptic pathway thus affecting insects nervous system) and disruption of the molecular events of morphogenesis and alteration in the behavior and memory of cholinergic system.

Green pesticides also inhibited cellular respiration (process that converts nutrient compounds into energy at the cellular level), acted as extremely fast nerve toxin thus caused uncontrollable nerve firing, disrupted normal nerve impulse activity which resulted in rapid failure of insect body system [244]. Plant essential oils block the spiracles of insects, resulting in blockage of respiratory siphons (asphyxiation) and death [245-246]. The mode of action of oils was partially attributed to interference in normal respiration, resulting in suffocation. Most insects breathe through the trachea which leads to the opening of the spiracle that might have been blocked hence leading to suffocation [247-248]. Essential oils are lipophilic in nature and can be inhaled or ingested. The rapid action against insect pests is indicative of a neurotoxic mode of action and interference with the neuromodulator octopamine [249] or GABA-gated chloride channels [250].

The effects of various botanical insecticides can be classified into the following groups namely; repellents, feeding deterrents/antifeedants, toxicants, Entomotoxicants, growth retardants, chemosterilants and attractants [251].

2.6.1 Repellency

Botanical pesticides have repellent property that keep away insect pests thus protecting the plants in return with minimal impact on the ecosystem, as they drove away the insect pests from the treated materials by stimulating olfactory or other receptors [252-253]. According to Kimutai *et al*., [254], the effectiveness of the repellents is dependent on multiple factors including the type of repellents (active ingredients), formulation, mode of application, environmental factors (temperature, humidity, and wind), the attractiveness of individual plant to insects, loss due to removal by respiration and abrasion, the sensitivity of the insects to repellents and the biting density.

Repellency property of essential oils of plant and other plant extracts on insects have been fully documented by numerous authors including [255] who observed the efficacy of applying *Myrtus piperita*, *Rosmarinus officinalis,* and *Coriandrum sativum* oils for organic food protection due to the repellency activity of these essential oils on *Tribolium confusum*. Also Zhang *et al*., [256] reported the significant repellence activities of six essential oils of *Zanthoxylum* species against the adults of two storage pests (*Tribolium castaneum* and *Lasioderrma serricorne*).Various natural and saturated fatty acids have been proven with insecticidal properties, some involving action on acetylcholinesterase and octopaminergic receptors [107]. Repellent activity has been linked to the presence of essential oils that cause death of insects by inhibiting Acetylcholinestarase (AChE) activity on the nervous system of insects [241]. Saturated fatty acid mixture composed of caprylic acid and capric acid collectively called “C8910 acids”, repelled horn flies and caused feeding deterrent by > 85% [257], had high activity of behavioral deterrence responses of larvae and adults to different odour sources to the number of insects repelled, indicating their potential in the control of stored products insect pests [258-259]. Jayakumar and Tennyson, [260] reported the repellency activity of camphor, citronella, eucalyptus, lemon and wintergreen essential oils against rice weevil *Sitophilus oryzae.* Various extracts from the *Allium* genus (garlic, leek and chives) exhibited repellent activity against insect herbivores such as aphids, beetles, spider mites, whiteflies and caterpillars [261-264]. Boeke *et al*., [265] reported the repellent effect of *D. arborea* against *Callosobruschus maculatus.*

2.6.2 Feeding deterrents/antifeedants

Botanical pesticides inhibit feeding or disrupt insect feeding by rendering the treated materials unattractive or unpalatable causing the insects to remain on the treated material indefinitely and eventually starved to death [251-252]. Oils of plants and their chemical constituents have been demonstrated to possess obvious antifeedant activity, repellent activity and toxic effect against insects. Ghavami and Mohammadi, [266] demonstrated that essential oils from *Ziziphora tenuiore*, *Myrtus communis*, *Achillea wilhelmsii* and *Myrtus piperita* have repellent activities against human fleas. The phytoconstituents found in the leaf extract of plants such as tannins, saponins, flavonoids, steroids and alkaloids are responsible for the mortality of insects upon application [267]. Chaudhary *et al*., [268]; Ghoneim and Hamadah, [269] pointed out that azadirachtin which is a prominent constituent of neem is established as a pivotal insecticidal ingredient with antifeedant, repellent, and repugnant agent that induces sterility in insects by preventing oviposition and interrupting sperm production in male insects. Jose and Sujatha, [171] revealed that active compounds like terpenoids, coumarin and phenols, present in the methanol extracts of *Gliricidium sepium* exhibited significant antifeedant activity on the larva feeding behavior, while others disrupted hormonal balance thus making the food unpalatable. These active substances directly acted on the chemosensilla of the larvae resulting in feeding deterrence. Isman, [270] reported that the presence of phytoconstituents instilled natural defense on the plants against herbivory. Isman, [270], Bekele, et al., [271], disclosed that these secondary metabolites consisted of mixtures of closely related compounds rather than a single toxicant working synergistically to bring about the resultants effect on the insect.

2.6.3 Entomotoxicants

Phytochemicals and other compounds possessing insecticidal properties have been extracted and isolated from different parts of *Azadirachta indica, Dracaena arborea, Annona squamosa, Ocimum gratissimum* and other plants [14], Ukoroije et al., [272]. These botanical pesticides contained toxic compounds that caused the death of insect pests [273]. Essential oils of cinnamon, clove, rosemary, bergamot, Lavandula specie and Japanese mint have been proven to exhibit acute contact and fumigant toxicity, repellent activity, antifeedant activity, larvicidal property and mortality of larvae, adults and eggs. Also high insecticidal toxicity against nymphs and adults as well as development and growth inhibitory activity against different insects [258,274-281]. Essential oils are more useful as insect fumigants [118,282], have strong toxicity against insects due to high volatility and lipophilic properties and can penetrate insects rapidly thus, interfering in their physiological functions [283-284]. Park et al., [281] demonstrated that *Rosmarinus graveolens* oil had high insecticidal toxicity against *Pochazia shantungensis* nymphs and adults. Rotenone is a mitochondrial poison that blocks the electron transport chain and prevents energy production when ingested as stomach poison [285-286]. It is a combination of six insecticidal isoflavonoids, glycosides and tannins which caused death of insects [270]. Qari et al., [287] showed Deoxyribonucleic acid (DNA) damage due to alterations in enzymatic system (acetylcholinesterase, acid phosphatase, alkaline phosphatase, lactate dehydrogenase and phenol oxidase), total protein and DNA concentration after treatment with essential oils of *Citrus aurantium*, *Eruca sativa*, *Zingiber officinale* and *Origanum majorana* against *Rhizopertha dominica*. Park et al., [281] demonstrated that differences in the insecticidal toxicities of plant-derived oils could be the based on species-specific responses to plant species, type of phytochemical and the weight and size of the insect nymphs and adults. According to Regnault-Roger and Hamraoui, [282], Chu et al., [288], the insecticidal activity of volatile fumigant varies with plant-derived material, insect species, exposure time, variability of phytochemical patterns and the point of entry of the toxin(whether inhaled, ingested or absorbed) into the skin of the insect.

Volatile compounds have strong odour that block the tracheal respiration of insects leading to their death [98,289]. They further explained that the amount of fumigant absorbed is dependent on the insect's initial contact with the fumigant with correspondent stimulation of the tracheal opening. Moreover, the ability of the insect to exclude vapor from its cuticle and prevent dehydration of body fluid played vital role in susceptibility or tolerance to fumigants by various life stages of insects particularly beetles and weevils [290]. The insecticidal property of essential oils tested on insect differs but in all are equally toxic to both nymphs and adult stages [291-292].

According to David et al., [141]; Rey et al., [236]; Achio et al., [237]; Kesetyaningsih, [238], leaf extracts *of Annona squamosa* disrupted the cellular structure of cockroach midgut epithelium, gastric caeca, columnar cells, peritrophic membrane, striated border and longitudinal muscles leading to insects mortality. Khaleqquzaman and Sultana, [293] confirmed the mortality effect of *Annona squamosa* against the larvae and adults of the red flour beetle *Tribolium castaneum* while [238], disclosed the mortality activity of extracts of custard apple *Squamosa annona* against the adult *Perplaneta americana.* Adel et al., [203] observed the mortality of adult aphids (*Pharodon* species) and both the larval stages and adults of *Spodoptera littoralis* due extracts of Alfalfa. Kokila *et al*., [294], reported that extracts of *Tagetes patula, Clerodentron phillomedis* and *Catharanthus roseus* demonstrated mortality activities both individually and synergistically against the adult mosquito dengue vector *Stegomyia agyptii*. The authors further stated that the above extracts proved larvicidal and pupicidal against the larvae and pupae of the *Stegomyia agyptii* mosquito species even at very low concentrations. Also *Cestrum parqui* extract increased mortality of *Schitocerca gregaria* larvae [217]. Chaieb et al., [216] also reported the insecticidal activity of *Cestrum parqui* against the Lepidopteran insect pests *Pieris brassicae* and *Schitocerca littoralis*. Nnamani et al., [295], disclosed the larvicidal activity of leaf extracts of *Dracaena arborea* and *Vitex doniata* individually and synergistically on the larvae of Anopheles mosquito. Sosan *et al*., [296]; Edeoga et al, [297] reported the larvicidal activity at 100% mortality of *O. gratissimum* oil on larvae of *Aedes aegypti* at 300 mg/L concentration after twenty four hours of exposure. Several essential oil components reportedly acted on the octopaminergic system of insects (which is a neurotransmitter, neurohormone and neuromodulator), thus its disruption resulted in total breakdown of the insect's nervous system [298]. Therefore, the octopaminergic system of insects represents a target for insect control. Low molecular weight terpenoids are too lipophilic to be soluble in the hemolymph after crossing the cuticle and the proposed route of entry is tracheae [299] and may also bind to target sites on receptors that modulate nervous activity and interrupt normal neurotransmission leading to paralysis and death of insects [298]. Neem extracts and its formulation are reported to influence mortality, repellency and feeding of insect at contact and systemic toxicity. According to Ojebode *et al*., [300], *Cymbopogon citratus* (lemon grass), *Citrus sinensis* (orange peel) and *Azadirachta indica* (neem) extracts proved toxic to adults and prevented egg hatching of the storage insect pest of cowpea *Callosobruchus maculatus*. 100% mortality of adults was recorded within 1-3 hours of application. Ukoroije and Bobmanuel [301], reported the mortality action of neem, dragon tree and clove basil extracts on nymphs of the cockroach *Periplaneta americana*. Udo *et al*., [302] in their studies, reported the use of root, bark and leaf extracts of *Dracaena arborea* in controlling the storage pests of beans *Callosobruschus maculatus* (*Motsch*.) and maize *Sitophilus zeamais* (*Fab*.) while offering protection to the grains. Also Udo [303], reported stated that cut leaves of *D*racaena *steudneri* placed in a box with caterpillars of Charaxes (Nymphalidae) led to their death. Finally, Ukoroije and Bawo, [304], Ukoroije *et al*., [272,305] confirmed the biocidal effects of adult cockroaches due extracts of *Dracaena arborea, Azadirachta indica* and *Ocimum gratissimum* respectively.

2.6.4 Growth retardants and development inhibitors

Botanical pesticides showed deleterious effects on the growth and development of insects, reducing the weight of larva, pupa and adult stages and lengthening the developmental stages [252]. Plant derivatives also reduce the survival rates of larva and pupa as well as adult emergence [306]. Rajasekaran and Kumaraswami [307] reported that grains coated with neem seed kernel extracts completely inhibited the development of the insect pest of rice *Sitophilus oryzae.* It has been reported that both azadirachtin and neem seed oil increased aphid nymphal mortality significantly at 77% and 80%, respectively, and at the same time prolonged the development time of the survivors to adulthood ([308]. Many botanical pesticides have been reported to have pronounced effect on the developmental period, growth, and adult emergence of insects [309]. According to Mordue and Nisbet, [310], phytochemicals produce various effects in insects which suggested the diversity of physiological interference caused by them with resultant disruption of growth and inhibitory effects on reproduction.

2.6.5 Oviposition suppressant

Extracts of plants have been reported to significantly reduce the fecundity of the insect by induced sterility of the tested parental generation thus instilled oviposition delay in the process with subsequent reduction and control of oviposition [104,271,311,312]. According to Mordue and Nisbet, [310], plant extracts or phytochemicals produce various effects in insects which suggest the diversity of physiological interference caused by their presence leading to resultant alterations of biochemical contents in the reproductive system with subsequent reduction of mating, deformities in oocytes, delay or inhibition of oviposition and fecundity inhibitory effects. Tanzubil, [313] reported the reduction of oviposition or egg production of insect species treated with extracts from plants due to the presence of ovicidal protential in the plant secondary metabolites in form of pennogenin triglycosides. This was further supported by Wongo, [150] who stated the reason being that various secondary metabolites present in plants, functioned as toxicants hence affecting the eggs and developmental stages of insects. According to the observation by Musabyimana et al., [314], leaf powder and aqueous leaf extract of neem distrupted the settling response, egg laying and larval feeding of insects. This wss because Azadirachtin extracted from neem tree interfered with insect and acarids reproductive and hormonal systems, disrupted the growth and egg laying processes of cockroaches, bed bugs, scabies mites, dust mites, ants, fleas, ticks, fruit fly, whiteflies and Japanese beetles [146]. Musabyimana et al., [314], reported that the wetting of banana corm or pseudo-stem with neem cake extract, aqueous neem seed powder, neem kernel powder or with emulsified neem oil distrupted the settling response, egg laying and larval feeding of the insect *Cosmopolites sordidus* (Banana corm borer). According to Adel et al., [203], extracts of alfalfa instilled oviposition and fecundity reduction in the insect *Spodoptera littoralis.* Hexane extracts of *Andrographis lineat*, *Andrographis paniculata,* and T*agetes erecta* showed 100% ovicidal activity against *Anopheles subpictus* [315].

Dhar et al., [316] reported that oviposition declined at higher concentration of plant extracts due to the interruption of vitellogenesis and damage to the egg chamber which was possibly regulated by the volatile compounds absorbed through the cuticle leading to poor egg formation. Also, reduction in egg laying may be attributed to smaller size or lesser number of spermatophores leading to lower number of eggs getting fertilized. Srikanth, [317] in his study reported that neem bark extracts affected the growth and development of young insects while inhibiting egg laying in adults.

2.6.6 Sterility inducers/ reproduction inhibitors

Some botanical insecticides are used as chemosterilants. Sterility can be induced by sterile insect technique (SIT) or a chemosterilant (a chemical compound that interferes with the reproductive potential of sexually reproducing organism) [318]. Chemosterilants are used to control economically destructive or disease-causing insect pests by causing temporary or permanent sterility of one or both of the sexes or preventing maturation of the young to a sexually functional adult stage [319-320]. It has been reported that plant parts, oil, extracts and powder of *Ocimum gratissimum* mixed with grain, reduced insect oviposition, egg hatchability, postembryonic, and progeny development in maize wevil and mosquito [309,321]. At the physiological level, azadirachtin blocks the synthesis and release of molting hormones from the prothoracic gland, leading to incomplete ecdysis in immature and adult insects thus employing sterility [286].

2.6.7 Attractants

Botanical chemicals that cause insects to make oriented movements toward their source are called insect attractants. They influence both gustatory (taste) and olfactory (smell) receptor or sensilla. Iso-thiocyantes from seeds, sugar and molasses and terpenes from bark of *Crucifera* with pheromones are natural attractants for various insects of Cruciferaceae and bark beetles. In onion, propylmercapton from *Umbelliferae* and phenylacetaldehyde from flowers of *Araujia serisofera* are attractants of carrot fly (*Psila rosae*) and Lepidoptera respectively. Also, alkaloid gelsemine extracted from the nectar of *Carolina jerramine* attracted bumble bees (*Bulbus impatiens* and *Bulbus binaculatus* while extracts of *Gelsemium sempervirens* attracted most pollinators [42,322]. Insect attractants can be used in three ways in sampling or monitoring of insect populations to assess the extent of infestation thus deciding the measure of control to be adapted, in luring insect to insecticide-coated traps or poison baits and in distracting insects from normal mating, aggregation feeding or ovipostion. They do not kill the insects, therefore, do not disturb the ecosystem. Attractants are used to misguide the insects to wrong oviposition sites aimed at reducing their numbers by starvation or by producing unfertilized eggs [323]. Tansy, dill (*Anethum graveolens* L.) and coriander (*Coriandrum sativum* L.) are used to attract natural enemies of insect pests [324].

2.6.8 Protectants

Plant active ingredients in addition to protecting the plants against insect herbivory also act as protectants to the plants at the field and the plant products during storage (Rajashekar *et al*., 2012). Significant quantities of crops are lost as a result of application of non-selective crop protection agents like chemical pesticides that end up destroying the crops and natural enemies that eventually feed on the crops. Therefore, the agrochemical industry is faced with increasing demand for the development of new crop protection agents that are safe both to the environment and consumers. [251,325] noted that the most promising natural grain protectants were generally observed in the leaf, bark, seed and oils of the plant families: Annonaceae, Asteraceae, Canellaceae, Labiatae, Meliaceae and Rutaceae. Udo et al., [302] stated in his work that ethyl acetate and aqueous fractions of leaf extract of *Dracaena arborea* demonstrated insecticidal activity against *Sitophilus zeamais* (*Motsch*.) and *Callosobruchus maculatus* (*Fab*.) and offered protection to the stored grains. Bekele et al., [326] also reported that extracts of Ocimum suave (Willo.) offered protection to the grains *zea mays* against *Sitophilus zeamais*. Dawit & Bekele, [327] demonstrated that Orange peel *Citrus sinensis* (L) offered a source of repellent, toxicant and protectant against the Coleopteran insect pest *Zabrotes subfasciatus.* Reports indicated that when mixed with stored grains, extracts of these plants reduce oviposition rate, suppress adult emergence of stored product insects and also reduced seed damage rates [109,124,252,328-332]. Neem oil and kernel powder gave effective grain protection against stored grain insect pests *Sitophilus oryzae, Tribolium cataneum, Rhyzopertha dominica* and *Callosobruchus chinensis* at the rate of 1 to 2% kernel powder and seed kernel oil [333]. Tiwari, [334] reported that the powders of *Rauvolfia serpentina, Acorus calamus* and *Mesua ferrea* offered grain protectant quality against *Rhyzopertha dominica*. Coconut oil when applied to *Vigna radiate* (green gram) at 1% proved effective against *Callosobruchus chinensis* for a storage period of six months [335]. Essential oils of the plants *Xylopia aethiopica, Vepris heterophylla* and *Luppia rugosa* proved as protectants of stored grains from attack of stored grain insect pests [336]. Leaves of the *Ocimum suave, Ocimum canum* and the cloves of *Eugenia aromatic* are reportedly used as stored grain protectants against *Callosobruchus maculatus, Tribolium castaneum* and *Sitophilus granaries* in East Africa [118,337].

2.7 Factors Affecting the Effectiveness of Bioinsecticides

The effectiveness or optimal performance of plant derived insecticide is dependent on multiple factors. According to Kimutai et al., [254]; Mathur and Ram, [338]; Agarwal and Gupta, [339]; Ho et al., [340]; Kim et al., [341], the optimal performance of plant derived insecticide is dependent on diverse factors such as type of insecticide (active ingredients), formulation, mode of application, environmental factors (temperature, humidity and wind), the attractiveness of individual plant to insects, respiration inhibition/ abrasion effect on insect cuticle, sensitivity of the insects and the biting density. Shaalan et al., [309], stated that the insecticidal effects of plant extracts vary according to plant species, animal species, geographical variation, plant parts used, the age of the plant part, methodology and the polarity of the solvents used during extraction. Furthermore, Jood et al., [30]; Cassida and Quistad, [342]; Osafo, [343] affirmed that the bioactivity of bioinsecticides against insect pest is dependent on chemical composition, species susceptibility and variation in insect behavior. While Liu and Ho, [289] however concluded that insecticidal activity of plant pesticides vary with regard to plant derived material(s), insect pest specie(s) and exposure time.

2.8 Advantages of Bioinsecticides

Botanical pesticides are considered safe in pest control because they have low or none pesticide residue making them safe to humans, environment and ecosystem [252]. According to Mondal and Mondal, [14], Rembold, [344];

Montasser et al., [345]; the use of these plant derived products are advantageous because they are bio degradable, target specific, eco-friendly, inexpensive, locally available, have multiple uses (such as medicinal, spices, ornamentals and even food and or as feed for man and animals) [346] and generally safe, thus offering potential for quality and effective control of insect pests. Senthil and Kalaivani, [347] reported that plant active ingredients are easily degradability, least persistence and least toxic to non- target organisms, economical and easy availability. Green pesticides are good alternatives to the synthetic ones as they cause little or no environmental pollution, have low toxicity level to humans in addition to several other advantages [348-351]. Biopesticides are capable of repelling, inhibiting growth or killing pests [42]. Castillo-Sanchez et al., [352-353] stated that they are inexpensive and are easily integrated into other pest management option. Other advantages include least toxicity to beneficial organism since they are target specific with none or little allelopathic effect [354]. Dubey et al., [355-356] viewed other complimentary attributes of botanical insecticides such as low residual effect in treated crop products and environment, reliable and acceptable in sustainable agriculture. Essential oil based insecticides exhibit low toxicity, not environmental persistence, are eco-friendly, have no worker re-entry and harvest restrictions and are compatible with biological control programs and indigenous natural enemies of pests [357]. When incorporated in Integrated Pest Management programs, biopesticides reduce the use of conventional synthetic pesticides [52].

2.9 Limitations of Bioinsecticdes

The use of bioinsecticides in Nigeria as in other parts of Africa is still hampered by some challenges such as most data gathered are obtained from laboratory trials; field data are rare. There is still hardly any developed appropriate technology for the application of botanicals, especially the oil and dust formulations [358]. Also, when compared with synthetic insecticides, the effects of natural insecticides are short-lived thus frequent applications are required to obtain reasonable degree of insect pest control ([359]. Furthermore, bioinsecticide formulations are yet to be available to farmers in usable forms and commercial quantities so as to serve as alternatives to synthetic pesticide. Although, biological control has an important role to play in modern vector control programs, it lacks the provision of a complete solution by itself, irrespective of the less harm and eco-friendly methods suggested and used in the control programs. Kole *et al*., [359] stated some of the shortfalls to include ability to degenerate or break down very quickly in sunlight and that both highly alkaline and acid conditions accelerate their degradation thus they require repeated applications for optimal effectiveness.

3. CONCLUSION

Over 550 insect pests populations in the orders Dictyoptera, Coleoptera, Isoptera, Heteroptera, Diptera, Homoptera and Orthoptera and others have been successfully controlled using active ingredients extracted from well over 200 agricultural plants ranging from the families Meliaceae, Lamiaceae, Annonaceae, Solanaceae, Agavaceae, Rutaceae, Lauraceae and several others. These green pesticides have been proven as ecofriendly to animals, man and the environment at large with great advantages against a few shortfalls. Therefore, plant and plant products with insecticidal potentials should be discovered, developed, processed, branded and commercially utilized in the control of field, storage and structural pests. The awareness and education of farmers should be advocated on the availability, usage and prospects of adopting this approach of insect control. Finally, there should be a call out for bioinsecticides to be incorporated and adopted in Integrated Pest Management strategies for insect control.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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