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Phytochemical activity and role of botanical pesticides in pest management for sustainable agricultural crop production

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ABSTRACT

Increased demand for food to feed the ever-growing population led to development and adoption of synthetic chemicals as a quick and effective strategy of managing crop pests and diseases. However, overreliance on synthetic pesticides is discouraged due to their detrimental effects on human health, the environment, and development of resistant pest and pathogen strains. This, coupled with increasing demand for organically produced foods, stimulated search for alternative approaches and botanical pesticides are particularly gaining importance. Botanical pesticides are efficacious in managing different crop pests, inexpensive, easily biodegraded, have varied modes of action, their sources are easily available and have low toxicity to non-target organisms. Their varied modes of action are attributed to the phytochemical composition in different plants. Therefore, they can be incorporated into integrated pest management systems and contribute to sustainable agricultural production. Nevertheless, botanical pesticides have not been fully adopted due to challenges in formulation and commercialization which are attributed to lack of chemical data and positive controls. Many publications have featured botanical pesticides with skewed interest towards management of insect pests. This review brings together information regarding botanical pesticides, their phytochemical composition and mechanisms of action against pests of importance in agricultural production. The paper also presents chemistry data of selected botanical pesticides, their biodegradation, role in integrated pest management and the challenges facing their adoption and utilization for sustainable crop pest management.

Glossary

Pest- any species, strain or biotype of plant, animal or pathogenic agent injurious to plants or plant products [55]

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Pesticide - any substance or mixture of substances of chemical or biological ingredients intended for repelling, destroying or controlling any pest or regulating plant growth (FAO, [39])

Background

Agricultural crops are constantly exposed and or threatened by pests which affect their growth and later quality. To protect the crops from pest attack, farmers usually rely on quick pest management options, mainly synthetic chemicals [103]. Despite the efficacious attribute of synthetic pesticides, continuous usage has its challenges such as development of pesticide resistant pests [135]. Overuse and misuse of synthetic pesticides can result in harmful effects on humans and the environment and toxicity to non-target organisms, thus impacting negatively on biodiversity [130]. Constituent compounds of synthetic pesticides have been attributed to chronic human ailments either due to consumption or exposure [31,77]. Most of the synthetic pesticides are not easily biodegradable thus accumulate in the environment and cause pollution to soil and ground water in addition to depletion of the ozone layer [130,157]. The disadvantages associated with the misuse and overuses of synthetic pesticides have stirred the need for alternative pest management options [84].

Plants with bioactive compounds have been used to manage different crop pests and human infections with notable success [69,151]. Pyrethrum (*Tanacetum cinerariifolium*) flowers and sweet wormwood (*Artemisia annua*) are examples of plants that have successfully been exploited as sources of safe insecticides for management of insect pests and malaria vectors respectively [134]. Management of pests using plant-based products was practised over time until technology took over and synthetic pesticides were developed [84]. The synthetic pesticides were immediately embraced due to their effectiveness and efficacy in managing serious crop diseases such as rusts and blights [121]. Consequently, the use of natural products of plant origin slowly faded until recently when use of synthetic pesticides started threatening human health and environmental safety [102]. The current global trend is towards consumption of food produced using safe and preferably natural plant protection products. Detection of hazardous chemical pesticide residues in foods and increased consumer awareness on food safety has resulted to ban of certain pesticides in agricultural production and plant-based pesticides are gaining popularity in organic agriculture [66,88].

Continuous use of synthetic pesticides has resulted in negative effects such as pollution, health hazards and loss of biodiversity, while adoption of botanical pesticides results into healthy environment and sustainable agriculture [135]. Use of synthetic pesticides has negatively affected farmers involved in export trade especially of horticultural produce [98]. Detection of banned pesticides or having traces above the regulatory residue limits has led to loss of market and income to both the growers and the exporters in developing countries. For example, Alphadime® (alpha-cypermethrin +dimethoate) and Demeton® were banned from use on export fresh produce [19,20].

The importance of botanical pesticides is attributed to their efficacy, biodegradability, varied modes of action, low toxicity as well as availability of source materials [100]. They also have short pre-harvest and re-entry intervals. Commonly used botanical pesticides are popular in organic farming where organically produced food fetches premium prices [144]. Therefore, botanical pesticides are gaining popularity because they are safe to use on crops produced for human consumption and recently there is a lucrative market among consumers willing to pay more for organically produced food [89]. There are many studies involving the known and yet to be exploited plant species with pesticidal properties [41,60]. Examples of plants that are sources of commercially available botanical pesticides include pyrethrum (*Tanacetum cinerariifolium*), neem (*Azadirachta indica*), sabadilla (*Schoenocaulon officinale*), tobacco (*Nicotiana tabacum*) and ryania (*Ryania speciosa*) [14]. Traditionally, farmers have used crop protection products of plant origin in post-harvest pest management especially in preservation of grains during storage.

Botanical pesticides are derivatives of plants that repel, inhibit growth or kill pests [52]. Most botanical pesticides are used to manage insect pests and many studies have focused majorly on insect pest management [7,57,58,91,141,146]. Plants with pesticidal properties also possess compounds that have effects on plant pathogens such as bacteria, fungi, viruses as well as nematodes [33,42,57,155,162]. This review discusses the place of botanical pesticides in sustainable management of crop pests by bringing together information regarding their phytochemical composition, mechanisms of action against pests, chemistry data, the challenges facing their adoption and utilization.

Sources of botanical pesticides

Botanical pesticides are derived from plants belonging to different families and are either utilized as plant extracts, essential oils or both [90]. Plant parts used to make botanical pesticides include barks, leaves, roots, flowers, fruits, seeds, cloves, rhizomes and stems. The plant part used is dependent on the targeted bioactive compounds and their abundance within that particular part. Plant families that have been reported to have plants containing bioactive compounds with activity against important crop pests include Myrtaceae, Lauraceae, Rutaceae, Lamiaceae, Asteraceae, Apiaceae, Cupressaceae, Poaceae, Zingiberaceae, Piperaceae, Liliaceae, Apocynaceae, Solanaceae, Caesalpinaceae, Sapotaceae [3,44,62,154]. The plant parts are dried and ground into fine powder and extracted with organic solvents that will maximize extraction of the targeted compounds [24]. The extracts are then concentrated, formulated and evaluated for efficacy under laboratory, controlled or field conditions [164]. Some of the botanical compounds with pesticidal activity that have successfully been isolated and

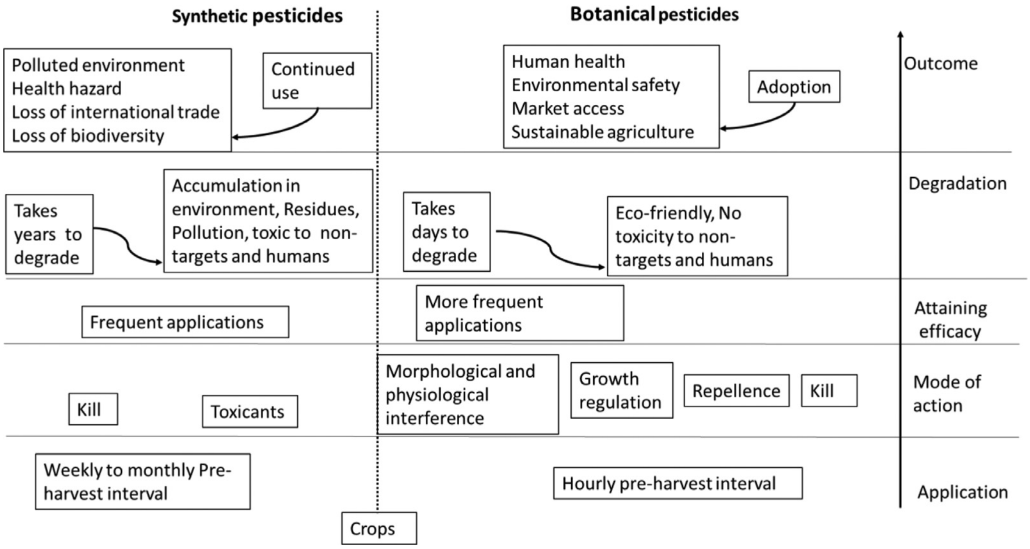

Fig. 1. A model illustrating differences between synthetic pesticides and botanical pesticides with respect to use, mode of action, persistence and effect on ecosystem.

commercialized include azadiractin from neem (*Azadirachta indica*) and pyrethrin from pyrethrum (*Tanacetum cinerariifolium*) [22,64,136]. Other plants with pesticidal properties include garlic (*Allium sativum*), turmeric (*Curcuma longa*) rosemary (*Rosmarinus officinalis*), ginger (*Zingiber officinale*) and thyme (*Thymus vulgaris*) (Table 1).

Botanical pesticides in agricultural production

Plants that are sources of botanical pesticides are easily available in the environment and most of them have multiple uses such as medicines, spices, ornamentals, food and or as feed [144]. Their availability makes them inexpensive and hence they are easily incorporated into agricultural production systems [22]. Commercialized pesticides from plants such as pyrethrum, neem and sabadilla are some of the least toxic especially to non-targets organisms such as pollinators and fish [34]. This attribute makes botanical pesticides effective, reliable and acceptable in sustainable crop protection. In addition, they do not leave residues on crop produce and the environment thus contributing to environmental conservation and ensuring safety to consumers [35]. The interaction between botanical pesticides and the pests is naturally biochemical therefore pests are unlikely to develop resistance [64,43]. The plant-based chemical compounds in extracts and essential oils are target specific which ensures safety on non-target organisms especially the beneficial organisms including pollinator bees and predators [51,99]. Depending on the source plant and the concentrations used, the botanical pesticides have zero or little allelopathic effect on crops [12,131]. Their efficacy is dependent on the species of the source plant, whether dry or fresh, solvents used for extraction and the extraction methods [49]. Botanical pesticides exhibit varied modes of action on the target pests such as repellence, toxicity, growth regulation and structural modification making them suitable alternatives in crop pest management [78,124]. They interfere with insect behaviour, physiological activities, biochemical processes, morphology and metabolic pathways. The activity of the metabolites is specific in their effect on the pest, for example terpenes block glucose on chemosensory receptor cells in the mouth of lepidopteran larvae [124] while some plant essential oils have chemosterilant activity ([34]; Fig. 1). Examples of plants with pesticidal activity, their chemical composition and target organisms are as shown in Table 1.

Acceptance, adoption and utilization of botanical pesticides has been reviewed by various authors [24,68]. Sufficient evidence and information regarding chemistry and efficacy of botanical pesticides is needed to satisfy the pesticides registration regulations [58]. This is in addition to information on their formulation, degradation, longevity and toxicity [132].

Integration of botanicals in agricultural production systems ensures major benefits to the farmers including food safety, reduced pest levels, improved quality of produce which fetches higher prices and guaranteed market access [101]. The consumers in lucrative markets are willing to pay higher prices for organically produced foods, thereby creating market opportunities for botanical pesticides [89]. Possible adoption pathways guiding synthetic and botanical pesticides have been described in Fig. 1. Synthetic pesticides have a key role in crop pest management as they contribute to reduction in damage to crops and the resultant losses in produce and revenue [30,83]. However, they need to be used judiciously and applied by trained personnel. This is especially important in the case of small holder farmers where a lot of care and sensitization is required to ensure human and environmental safety [83]. Therefore, incorporating botanical pesticides into integrated pest management programs would reduce unnecessary usage of the synthetic pesticides [25,30].

Table 1
Examples of plants with antimicrobial activity, target pathogen and their active ingredients.

Name of plant	Target pathogen	Major active chemical ingredient	Reference
Origanum spp	*Bacillus* spp *Staphylococcus saprophyticus Micrococcus luteus, Serratia marcescens*	Terpinen-4-ol, gamma-Terpinen, o-Cymene, cis-beta-Terpineol, alpha-Terpinen, beta-Phellandrene, alpha-Terpieol, Carvacrol, p-Cymene, thymol	Jnaid et al. [62]; Saaed and Tariq [127]; Soković et al. [142]; Sharoba et al. [117], [137]
Aloe vera	*Pseudomonas aeruginosa Staphylococcus aureus Bacillus cereus Streptococcus pyogenes*	Anthraquinones, p – coumaric acid, ascorbic acid, pyrocatechol, cinnamic acid	Karpagam and Devaraj [69]; Rubina et al. [126]
Jatropha spp	*Alternaria alternata, Aspergillus* spp *Fusarium oxysporum, Rhizoctonia solani, Trichoderma viride*	Gallic acid, pyrogallol, rutin, myricetin, daidzein, 2-(hydroxymethyl)-2 nitro-1,3-propanediol, β-sitosterol, 2-furancarboxaldehyde	Gaikwad et al. [43]; Oskoueian et al. [110]
Cinnamon spp	*Staphylococcus aereus, Escherichia coli*	Eugenol, eugenyl acetate	Cui et al. [27]
Lantana camara	*Klebsiella pneumoniae Escherichia coli*	Hexadecanoic acid phytol,caryophyllene oxide, 9,12,15-octadecatrienoic acid, methyl ester, (Z,Z,Z) caryophyllene, α-caryophyllene, germacrene D, isocaryophillene, γ-muurolene, γ-elemene	Swamy et al. [149]; Pawar et al. [114]
Satureja hortensis spp	*Bacillus cereus, Candida kruzei*	Rosmarinic acid, Carvacrol, γ-Terpinene,	Stanojkovićc et al. [145]; Karami-Osboo [67]
Thymus vulgaris	*Erwinia amylovora Eschrichia coli Staphylococcus aureus Bacillus cereus*	Thymol, _β-Cymene, Caffeic acid, Rosmarinic acid, Luteolin-7-O-glucoside	Karami-Osboo [67]; Koz£owska et al. [75] Sharoba et al. [137]
Allium cepa	*Escherichia coli*	2,2-diphenyl-1-picrylhydrazyl	Abdel-Salam et al. [1]
Citrus spp	*Escherichia coli, Salmonella enterica, Pseudomonas putida, Staphylococcus aureus*	neohesperidin, hesperetin, neoeriocitrin, eriodictyol, naringin, naringenin, limonene, tetrazin, coumarin	Mandalari et al. [86]; [117]; Soković et al. [142]; Dhanavade et al. [32]
Cymbopogon spp	*Escherichia coli, Staphylococcus aureus*	Geraniol	[117]; Sharoba et al. [137]
Artemisia spp	*Bacillus* spp *Staphylococcus aureus Pseudomonas aerogenosa Candida albicans, Rhizopus japonicum*	borneol, camphene, camphor, 1,8-cineole, p-cymene, β-eudesmol, α-gurjunene, α-pinene, terpene-4-ol, sabinene, myrcene, chamazulene, α-thujone, β-thujone, 1,2-dehydro acenaphthylene	Juvatkar et al. [65]; Erel et al. [40]
Centella aciatica	*Listeria monocytogenes*	germacrene A, germecrene B, germacrene D	[116]
Tanacetum cinerariaefolium,		CinerinI,Cinerin II, Jasmolin I, Jasmolin II, Pyrethrin I Pyrethrin II, Chrysanolide, β-Cyclopyrethrosin, Chrysanin, Dihydro-β-cyclopyrethrosin, Taraxasterol, Pyrethrosin, 11, 13-Dihydrotatridin-A, 11,13-Dihydrotatridin-B,	[136]
Mentha piperita	*Enterococcus faecium, Salmonella choleraesuis, Staphylococcus aureus, Bacillus subtilis*	menthol, menthone, isomenthone, neomenthol, acetylmenthol, pulegone, methyl acetate	Pramila et al. [10], Soković et al. [142]
Salvia officinalis	*L. monocytogenes, P. aeruginosa and P. mirabilis.*	Camphor, α-thujone	Soković et al. [142]
Lavandula angustifolia	*Micrococcus flavus*	Linalool, linalyl acetate	Soković et al. [142]
Rosmarinus officinalis	*Listeria monocytogenes, Staphylococcus aureus Escherichia coli*	Caffeic acid, rosmarinic acid, cineole, camphor, α-pinene, β-pinene,camphene, isocarnosol	Genena et al. [46]; Sienkiewicz et al. [138]; Koz£Owska et al. [75]
Euphorbia Tirucalli	*Staphylococcus* spp	hydroxycinnamic acid.	Araújo et al. [13]
Ocimum basilicum	*Escherichia coli*	Estragole, 1,8-cineole, trans-α-bergamotene	Sienkiewicz et al. [138]
Piper nigrum	*Escherichia coli, Salmonella typhi, Proteus* sp *Staphylococcus aureus, Fusarium oxysporum*	Piperine, chavicine	Rani et al. [123]; Ganesh et al. [45]
Azadirachta indica	*Aspergillus niger, Microsporum. gypseum, Aspergillus flavus*	Azadirachtin, nimonol, epoxyazadiradione	Mahmoud et al. [85]

Table 2
Mode of action of selected botanical pesticides on selected crop pests.

Source Plant	Mode of action	Target pests	References
Neem (*Azadirachta indica*)	Binding to acetylcholine receptors thereby disrupting the nervous system Repellence Feeding deterrence Inhibition of oviposition, egg hatching and moulting	Insects	Grdisa and Grsic [47]
Garlic (*Allium sativum*)	Delay and inhibit spore germination Inhibits protein and DNA synthesis Inhibits production of mycotoxins Disrupts cellular components and their activities Hyphal and mycelial modifications	Fungi	Perelló et al. [115]
Aloe vera	Inhibits cellular activities Impairs permeability of plasma membrane Denatures proteins Inhibits ATP production and glucose uptake	Bacteria	[69]
Tagetes erecta	Inhibits egg hatching Larval toxicity Structural modification Mortality	Nematodes	[42]
Nepeta nuda subsp *nuda*	Host plant manipulation Inhibits virus replication and multiplication Prevents virus adsorption Inhibits nucleic acids liberation	Viruses	[152]

Phytochemical composition of botanical pesticides

The increasing interest in natural plant products in medicine, agriculture and food industry has spurred research in the composition of compounds in various plant families [62,118]. The common bioactive compounds in botanical pesticides are majorly secondary metabolites such as steroids, alkaloids, tannins, terpenes, phenols, flavonoids and resins that possess antifungal, antibacterial, antioxidant or insecticidal properties [3]. For instance, seed kernels of *Jatropha carcus* contain high amounts of phenolics, esters and flavonoids [110] while leaves of *Mentha piperita* contain tannins and flavonoids as the major bioactive compounds [120]. The specific compounds found in given species of plants make them effective against a given category of pests (Table 1). The bioactive compounds found in plants also dictate their mode of action on the target pests.

Mechanisms of action of botanical pesticides

The bioactive compounds in botanical pesticides have varied modes of action against different pests including insects, fungi, bacteria, nematodes and plant host cells infected by viral pathogens (Table 2). The modes of action include repellence, inhibition, denaturation of proteins and other effects depending on type of botanical compound and pest. For instance, pesticides from pyrethrum target the nerve cells of insects leading to paralysis and later death while neem-based pesticides have anti-feedant and repellence properties, induce moulting abnormalities, hinder oviposition and disrupt the endocrine system [47]. The synthetic pesticides are more specific on their targets and are mostly neurotoxicants with similar end results as the botanical pesticides [146]. Understanding the mode of action including the physical, biological and chemical interactions between the pest and pesticide is vital in pest management as it dictates the management strategy to be adopted [80,158]. The sections hereunder contain descriptions of modes of action of botanical pesticides against specific groups of agricultural pests.

Mode of action against insect pests

Most plant extracts act on insects by repelling, deterring feeding and oviposition, toxicity, lethal activity and interfering with physiological activities [79]. The multi-active role of botanical insecticides on insect pests makes them more popular in the market [56]. For example, commercialised products from plants such as pyrethrum have been reported to possess among others the neurotoxicant effects on insect pests causing paralysis and knock down and consequently mortality [47]. Botanical pesticides also interfere with production of important enzymes such as those responsible for moulting thus inhibiting growth and development [104].

Garlic (*Allium sativum*) and turmeric (*Curcuma longa*) extracts cause mortality, repellence, toxicity and inhibition of progeny emergence on the red flour beetle (*Tribolium castaneum*) [7]. Extracts from these plants have been reported to interfere with oviposition, egg hatching and general development of the insect pests. Some botanical pesticides have been associated with paralysis and blockage of electron transportation in respiratory processes of insects, immobilization and toxicity [93,141]. Botanical insecticides constitute the largest share of botanical pesticides present in the market all over the world [56]

Mode of action against fungal pathogens

The terpenes, phenols, alcohols, alkaloids, tannins and other secondary metabolites found in botanical pesticides induce toxicity to fungal cell walls, cell membranes and cell organelles [162]. These metabolites also inhibit spore germination, mycelial development, germ tube elongation, delayed sporulation and also inhibit production of important enzymes, DNA and protein synthesis [87]. The plant compounds also induce structural modifications of the hypha and mycelia thus inhibiting production of substances such as aflatoxin and fumonisin from some fungi such as *Aspergillus* spp and *Fusarium* spp. respectively. This results in reduced pathogenicity of mycotoxin producing fungal pathogens [87].

Exposure of *Fusarium verticillioides* to different plant extracts has been shown to cause disruption of cell walls, loss of cellular components and inhibiting production of essential compounds like fumonisin and ergosterol [18]. For instance, ginger (*Zingiber officiale*) extracts reduce cytoplasmic content of *Fusarium* in addition to inducing change in the morphology of microconidia [159]. According to Perelló et al. [115] allicin, the most active constituent of garlic (*Allium sativum*), causes morphological abnormalities such as collapsing, thinning and damaging of hyphal strands, inhibited germination of spores and hyphal growth. It also inhibits production of cysteine proteinases, alcohol dehydrogenases and thioredoxin reductases in amoeba that causes dysentery in humans [11]. Allicin, like other secondary metabolites found in the plants, is target specific and always work in synergy with other compounds to inhibit sporangium formation and spore germination [50,158]. There are a number of botanical fungicides majorly containing essential oils as the active constituents [163].

Mode of action on bacterial pathogens

The chemical composition of botanical pesticides has varied antibacterial properties including growth inhibition [8]. Gram-negative bacteria are more susceptible than gram-positive bacteria due to absence of a peptidoglycan cell wall [33]. Some of the effects of the botanical pesticides on bacteria include inhibition of cellular processes such as protein synthesis, increasing permeability of plasma membrane leading to leakage of cell contents and finally death [73]. For instance, methanolic extracts of *Aloe vera* were shown to inhibit growth of *Escherichia coli* and *Bacillus subtilis* while acetone extracts inhibited *Pseudomonas aeruginosa*. The antimicrobial activity of *A. vera* is attributed to presence of phytochemicals which denature microbe proteins hence disrupting their functionality. *Aloe vera* contains cinnamic acid which inhibits glucose uptake and production of ATP [33]. Ascorbic and coumaric acids, also present in *A. vera*, inhibit enzymatic activities which in turn affects the functionality of the microorganisms [69]. Essential oils of *Thymus vulgaris* possess antimicrobial activity against *Bacillus cereus, Klebsiella pneumonia, Staphylococcus aureus, Salmonella typhimurim* and *Ecshrichia coli* [137]. Their activity is attributed to presence of thymol which makes the bacterial membranes permeable and depolarizes them resulting to interference of cell mechanisms [117].

Mode of action on nematode pests

Botanical pesticides have nematicidal properties including inhibition of egg hatching and suppression of nematode population. Some of the constituent compounds in botanical pesticides affect the populations of other microorganisms in the soils which further affects survival of nematode eggs and juveniles [72]. Some compounds specifically kill the second stage juveniles, egg masses, cause general larval toxicity, reduce galling and eventually affect the populations of nematodes in an ecosystem [71]. For example, plant extracts derived from *Brassica napus, Lantana camara, Tagetes erecta* and *Azadirachta indica* inhibited eggs hatching of root knot nematodes (*Meloidogyne incognita*), leading to immobilization and later death of second stage juveniles. Under greenhouse conditions, application of *Lantana camara* and *Trichoderma harzianum* decreased the incidence and reproduction of root knot nematodes, their populations, egg masses and the number of galls in tomato [42]. The inhibition of egg hatching, motility and mortality of second stage juveniles of root knot nematodes is attributed to presence of phytochemicals such as alkaloids, tannins and glycosides in plants [4,15]. The active compounds in the plant extracts also affect root knot nematodes through paralysis, reducing infectivity potential and death of the infective juveniles [106]. Plant extracts and essential oils have also been reported to cause mortality for second stage juveniles of root knot nematode (*Heterodera cajani*) [141]. Some of the phytochemicals found in botanical extracts are lipophilic enabling them to easily dissolve the cytoplasmic membrane of nematodes thereby interfering with protein structures responsible for growth, development and survival [113].

Mode of action on virus pathogens

Botanical pesticides inhibit viral pathogen development mainly through manipulation of the host by production of antiviral proteins which induce inhibition of any activity between plants and the virus [92]. Some compounds found in plants with antiviral properties induce systemic resistance of the host plants, inhibit transmission of viruses and have insecticidal properties against insect vectors [155]. General modes of action include inhibiting virus penetration into the host cell, inhibiting virus replication, enzymatic activity as well as hamoagglutination, which is vital for virus attachment [122]. Inhibiting virus attachment to the host cell as well as multiplication at the early stages is key in achieving antiviral action [16]. Prevention of adsorption of the virus to the host is also a major mechanism of plant extracts in managing viral infections [74]. Acetone extracts of cotton seed oil sludge highly inhibited *Tobacco Mosaic Virus* isolated from infected tobacco (*Nicotiana tabacum*) plants under laboratory conditions. The extracts also reduced the disease levels caused by *Rice Stripe Virus* and *Southern Rice Black Streaked Dwarf Virus* in rice (*Oryza sativa*) under field conditions. The antiviral activity was attributed to presence of gossypol and β-sitestrol, compounds present in the cotton seed oil sludge. A derivative of gossypol was also reported to block formation of cell fusion activated cores while β-sitestrol was reported to cause apoptosis [165]. *Thuja orientalis* inhibited multiplication of *Watermelon Mosaic Virus* isolated from water melon (*Citrus lanatus*). There was a reduction in symptoms of virus infection on the hypocotyls of explants after treatment with the extracts. The reduction in disease symptoms was attributed to blockage of liberation of nucleic acids, thus inhibiting multiplication of the virus [38]. Table 2 summarizes examples of modes of action of botanical pesticides against various categories of crop pests.

Natural biodegradation of botanical pesticides

The biological nature of botanical pesticides makes their degradation swift and therefore, do not accumulate in the environment such as in water and soils therefore eliminating chances of pollution [142]. Their exposure to air, sunlight, moisture and high temperatures is enough to break down their constituents [48]. For instance, thymol, a compound found in *Thymus vulgaris, Satureja hortensis, Zataria multiflora* and *Piper nigrum* takes about 28 hours to degrade under sunlight and about 8 days in soils [82] while the half-life of azadirachtin, isolated from neem (*Azadirachta indica*), is between one and two days in crops and soil respectively [160,161]. Storage of plant extracts such as neem under sunlight degrades their effectiveness as pesticides, indicating that they degrade just as fast after application [37]. Pyrethrum-based insecticides last for only few hours after application under field conditions [47]. According to Gunasekara [48], natural pyrethrins undergo photodegradation in presence of sunlight and oxygen from 100% to about 1% in five hours. Microorganisms in the ecosystems also hasten the biodegradation process through oxidative metabolism due to abundance of detoxification enzymes [95]. A common biodegradation pathway is hydrolysis of ester bonds mediated by carboxylesterases enzymes produced by microorganisms such as *Bacillus cereus* and *Aspergillus niger* (Cycon and Piotrowska-Seget, [28]). Successful biodegradation is subject to the complexity of the pesticide and enzymatic potential of the microbial population in the soils. Pesticides are either biodegraded completely into water, gases and salts and the by-products are either absorbed by soil or further broken down contributing to biomagnification [109].

The soil microorganisms produce enzymes that first modify the botanical pesticides into breakable groups which are less toxic than the parent product, and then render those metabolites biologically unavailable and non-toxic [109,153]. Bacteria species reported to degrade pyrethroids, carbamates, organophosphates and organochlorine pesticides include *Bacillus, Serratia, Pseudomonas, Spingobium, Aerobacter, Escherichia, Ochrobactrum, Arthrobacter, Flavobacterium, Brevibacillus, Sphingobacterium* and *Streptomyces*[28,81,119]. *Trichoderma* spp has been reported to degrade DDT, an organochloride pesticide [119]. Synthetic pyrethroids have ester linkages that undergo hydrolysis in presence of microorganisms and produces organic acids which are further broken down to carbon (iv) oxide gas under aerobic conditions [63]. Effectiveness of such biotransformation is dependent on factors that influence growth and survival of microbial populations such as salinity, pH, water and oxygen supply. Population dynamics of involved microorganisms influence the availability and concentration of biotransformation enzymes [139]. Effective microbial degradation of pesticides is subject to state and nature of microorganisms, their interaction with the pesticides as well as environmental conditions [28,109]. The swift degradation of botanical pesticides is a good attribute in relation to environmental conservation.

Role of botanical pesticides in integrated pest management

Integrated pest management (IPM) is an approach that combines a number of strategies to achieve sustainable pest management [90]. The objective is to sustainably reduce pests, attain high and profitable yield while keeping the environment safe [5]. Botanical pesticides are natural products that are effective against bacteria, fungi, nematodes, viruses and insect pests [42,47,69,115,152]. They are highly biodegradable, have varied modes of action, are less toxic to humans, are non-pollutant and they are readily available in the environment [100]. Therefore, they are a key component of IPM together with other crop protection strategies that include host resistance or tolerance, good agricultural practices, use of natural enemies such as predators and parasitoids, microbial pesticides and limited use of safe synthetic pesticides [96,108,143,156]. This approach coupled with early pest monitoring and detection using smart technology such as internet of things (IoT) and geographic information systems would achieve timely, effective and sustainable crop pest management [23,150,160].

Pesticidal compounds found in plants have been reported to be effective against insects [54], fungi [129], bacteria [53], nematodes [100] and viruses [38]. Sales et al. [128] evaluated antifungal activity of several plant extracts using mother tinctures against *Fusarium guttiforme* and *Chalara paradoxa* causing pineapple fusariosis. The plant extracts inhibited growth of *Fusarium guttiforme* by up to 46% and *Charala paradoxa* by up to 29%. Extracts from *Aloe vera, Allium sativum* and *Glycyrrhiza glabra* were as effective as the synthetic fungicide Tebuconazol®. In another study, extracts from *Azadirachta indica* and

Oscimum sanctum inhibited mycelia growth of tomato wilt pathogen, *Fusarium oxysporum*, by up to 100% [24]. *Azadirachta indica*, *Cerbera odollam* and *Capsicum frutescens* inhibited mycelium growth of *Penicillium digitatum*, causal agent of grey mould disease in oranges by up to 90% [9]. In the same study, *Zingiber officinale* and *Cymbopogon nardus* reduced mycelia growth of *Penicillium digitatum* by up to 70% *in vitro*. Orange fruits treated with *A. indica*, *Cerbera odollam* and *Capsicum frutescens* showed no symptoms of the grey mould infection leading to a significant reduction in fruit damage and loss in quality. Jantasorn et al. [59] reported that *Hydnocarpus anthelmithicus* fruit extracts were active against *Pyricularia oryzae*, *Phytophthora palmivora* and *Rhizoctonia solani*, and inhibited growth of *Pyricularia oryzae* by 100%. This makes *H. anthelmithicus* very promising in management of fungal diseases of rice leading to reduction in the use of synthetic fungicides. Extracts of *Tagetes patula*, *Sambucus nigra*, *Glycyrrhiza glabra* and *Equisetum arvense* at 10% concentration were effective against *Rhizoctonia solani*, a fungal pathogen that causes root rot in tomatoes, Rodino et.al. [125].

Botanical pesticides even in their crude form have been demonstrated to possess insecticidal properties [7]. *Piper nigrum*, *Cinnamomum zeylanicum* and *Cinnamomum cassia* are strong repellents to thrips (*Megalurothrips sjostedti*) while formulations of extracts from *Piper retrofractum*, *Annona squamosa* and *Aglaia odorata* decreased population of *Crocidolomia paronana* and *Plutella xylostella* in cabbage [2]. Application of these extracts had no toxicity to the natural enemies of the insect pests [29]. According to Ogah [105], *Azadirachta indica* and *Allium sativum* extracts effectively decreased populations of *Maruca vitrata* and *Megalurothrips sjostedti* on cowpea leading to improved grain yield. *Nicotiana tabacum*, *Sinapsis arvensis* and *Cardaria draba* were tested for effectiveness against *Trogoderma granarium* and proved efficacious in decreasing populations of the pests in stored wheat grains. *Cardaria draba* was very effective against larval stages of the pest [133]. Insecticidal activity against *Tribolium castaneum* was exhibited by extracts of *Pegaum harmala*, *Ajuga iva*, *Aristolochia baetica* and *Raphanus raphanistrum*. The extracts acted by disrupting the insect developmental cycles and inhibiting production of F1 progenies [61].

Microbial antagonists (*Trichoderma*, *Paecilomyces*) and crude extracts from *Allium sativum*, *Zingiber officinale*, *Curcuma longa* and *Citrus limon* significantly reduced population of whiteflies and thrips as well as severity of rust (*Uromyces appendiculatus*), angular leaf spot (*Phaeoisariopsis griseola*) and anthracnose (*Colletotrichum lindemuthianum*) on snap beans (*Phaseolus vulgaris*) [96]. Extracts from *Allium cepa*, *Allium sativum*, *Phyllanthus emblica*, *Curcuma zedoaria*, *Calotropis procera*, *Azadirachta indica* and *Ocimum canum* coupled with cow dung and minerals salts in cow urine were reported to be effective against tomato pests, including *Helicoverpa armigera*, reduced tomato fruit damage and increased yield [148]. Ouma et al. [111] reported significant reduction of thrips and increase in yield of snap beans after spraying a combination of commercial botanical pesticide *Azadirachta indica* and *Metarrhiziam anisopliae*. The study reported that it was more cost effective to use biological pesticides in combination with synthetic pesticide formulations. The combination of biological and synthetic pesticides increased yield by up to 50% and reduced thrips population by over 60%. Larvae of *Spodoptera littoralis*, a polyphagous pest of cotton, were effectively intoxicated by extracts of *Allium sativum* and *Citrus limon* and the activity was attributed to reduced proteins and lipids in the midgut of the larvae [6]. *Tephrosia vogelli* is effective against spotted cucumber beetle (*Diabrotica undecimpunctata*) and melonfly (*Bactrocera curcubitae*) [166]. *Tephrosia toxicaria* is also effective against second stage juveniles of *Meloidogyne enterolobii* and *M. javanica* [94].

Botanical pesticides have also been found to be effective in management of post-harvest pests. Immersion of banana in essential oils of *Allium sativum*, *Copaifera langsdorfii*, *Cinnamomum zeylanicum* and *Eugenia caryophyllata* reduced anthracnose (*Colletotrichum musae*) by up to 90% [26]. In addition, alcoholic extracts of suicide tree (*Cerbera odollam*), clove (*Syzygium aromaticum*) mahogany (*Swietenia macrophyllai*) at a concentration of 3000 ppm inhibited growth of post-harvest fungi, *Aspergillus niger*, *Penicllium digitatum* and *Fusarium* sp. by 40-90% on citrus [140]. Application of increased concentrations of extracts from *Curcuma longa* and *Allium sativum* increased mortality rate of *Tribolium castaneum* adults, reduced weight of the insects and had anti-moulting properties on the larvae, pupa and adults [7]. Extracts of *Eucalyptus terreticonis*, *Tagetes minuta* and *Lantana camara* caused mortality of adults of maize weevil (*Sitophilus zeamais*) at an application rate of 20g per 200 g of maize grains [112].

The above examples demonstrate that botanical pesticides can make a significant contribution to sustainable management of crop pests in IPM programmes. Their activity against varied range of pests, their varied mode of action, activity in varied agro-climatic zones, seasons and crops, botanical pesticides can play a major role in maximizing crop yields while safeguarding the environment, biodiversity and human health.

Challenges in adoption of botanical pesticides

Despite availability of proof of efficacy of botanical pesticides against a wide range of crop pests, they are still not well represented in the pesticide market [70]. Commercialization of botanical pesticides is dependent on availability of the source plants in large quantities and the plants should be readily cultivated. The source plants are either grown for other uses such as food, medicinal, shade, ornamental or growing naturally in forests and other uncultivated land. Cultivation of plants needed for production of botanical pesticides would require large areas, thus posing potential competition with food production in highly arable agricultural lands. In addition, some of the plants that are sources of botanical pesticides are used as food and farmers would therefore, opt to invest in the more profitable enterprises, thus endangering food security [144]. Consequently, availability of arable land for production of required volumes of botanical pesticides would be a major limiting factor. Also, storage and processing facilities of the bulky amounts of plant material needed for producing botanical pesticides would require large scale investments in ware houses, preservation technology and machinery.

Botanical pesticides also face a lot of competition from the synthetic pesticides that are easy to manufacture, easy to formulate, have long shelf life, ease of application and have established production facilities [49]. Formulation of botanical pesticides is quite challenging because one plant could have several active compounds that differ in chemical properties [76]. This attribute could however be explored by combining several plants with related compounds whose synergy is effective against pests [146]. In spite of the little or no toxicity exhibited by botanicals, their regulatory procedures into agricultural use are no different from the synthetic products especially in developing countries [17]. The registration process is expensive and has a number of barriers thus making botanical pesticides somewhat unavailable in the market.

There is little awareness among the small holder farmers about the usefulness of botanical pesticides in managing crop pests [107,145]. Application of botanical pesticides is also dictated by weather conditions since they are easily degraded especially if applied in their crude form [128]. The biodegradability of botanical pesticides also shortens their shelf life [21]. Despite the safety associated with botanical pesticides, some plants with antimicrobial activity are also associated with toxicity towards a group of non-targets. For example, rotenone, extracted from *Derris* and *Lonchocarpus* is toxic to mammals, fish and insects [14]. While *Tephrosia* spp is an effective potential insecticide against several pests, it is also acutely toxic to farmed clariid (*Clarias gariepinus*) [36,147]. The quality and stability of botanical pesticide is dependent on the nature of the plants used for preparation of plant extracts, solvent system, temperature range and storage medium [21,98]. In addition, extraction of botanical pesticides requires use of organic solvents whose disposal poses problems of polluting the environment [97]. This calls for better methods of extraction and waste disposal. Due to the above challenges, most agrochemical companies are unwilling to invest in production of botanical pesticides.

Conclusion and research needs

Natural environment is a rich source of a wide range of plants, some of which have been used to cure human, animal and plant diseases. Following concerns of human health, environmental safety and strict regulations on pesticide residues in agricultural produce, the use of synthetic pesticides needs to be done judiciously and only when absolutely necessary. Nevertheless, even with cautious use of synthetic pesticides, continued reliance on those chemicals still poses a hazard to the environment, non-target organisms and human health because of their residual effects. Therefore, efficacy and role of botanical pesticides in managing crop pests needs to be reconsidered due to their renewable nature and contribution to human and environmental safety.

Considering the huge volumes of material needed to produce botanical pesticides, large scale cultivation of source plants could be done in marginal lands that are not suitable for arable agriculture to avoid competition with food crops. Commercialization of producing such plants would generate income that would help sustain the livelihoods of communities in semi-arid areas. Low height plants such as rhizomes and herbs could be grown in forested areas without interfering with the forest trees. Compounds identified to have pesticidal properties in plants may also be synthesized following collaborations between chemical engineers and scientists.

Processing and extraction of the botanical pesticides using inexpensive solvents should be explored to reduce the cost of production and minimize the problems associated with waste disposal. This would make it possible for the small holder farmers to afford and adopt the safe pest control products.

The swift biodegradable nature of botanical pesticides is good but also delicate due to their short shelf life. There is hence need for more research to develop formulations with longevity while retaining the desired efficacy. It is recommendable that research aiming at stability of botanical pesticides especially under field conditions be explored. Remarkable contribution towards stability has been done using nanotechnology as a formulation technique and has been reported to be effective in dispersion of the active compounds under field conditions. This will in turn improve the efficacy of botanical pesticides at the farm level.

More research is required to improve exploitation of plants with bioactive compounds of relevance to crop protection. This may involve domestication and improvement of identified wild plants through breeding to improve content of the active molecules, in addition to developing appropriate husbandry practices, including plant nutrition and agronomic practices. The improvement of the source plants may involve identifying the genes regulating the formation and accumulation of the active compounds which would further guide the breeding approaches that would lead to high yield of the target pesticidal compounds. Those compounds should then be formulated into products that are accessible especially by small holder farmers.

Concerned stakeholders should, in support of researchers and policy makers, create more awareness on the need to embrace botanical pesticides and other natural products as safe pest management tools. Researchers and scientists working on such products have a role to provide field efficacy data that is consistent and reproducible. The increased use of organic pest control products in integrated pest management strategies will lead to improved acceptability of agricultural produce in niche markets, thus contributing to improved international trade, food safety as well as conservation of biodiversity, protection of environmental and human health.

Declaration of Competing Interest

Authors have no competing interest.

CRediT authorship contribution statement

Geraldin M.W. Lengai: Writing - original draft. **James W. Muthomi:** Data curation. **Ernest R. Mbega:** Data curation.

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References

[1] A.F. Abdel-Salam, M.E. Shaheda, B.A. Jehan, Antimicrobial and antioxidant activities of red onion, garlic and leek in sausage, Afr. J. Microbiol. Res. 27 (2014) 2574–2582.
[2] A. Abtew, S. Sevgan, X. Cheseto, K. Serge, T.G. Giovanna, M. Thibaud, Repellency of plant extracts against the legume flower thrips *Megalurothrips sjostedti* (Thysanoptera: Thripidae), Insects 6 (2015) 608–625.
[3] W. Ahmad, S. Shilpa, K. Sanjay, Phytochemical Screening and antimicrobial study of *Euphorbia hirta* extracts, J. Med. Plant Stud. 2 (2017) 183–186.
[4] F. Akyazi, Effect of some plant methanol extracts on egg hatching and juvenile mortality of root-knot nematode *Meloidogyne incognita*, Am. J. Exp. Agric. 11 (2014) 1471–1479.
[5] M.Z. Alam, M. Haque, M. Islam, E. Hossain, S.B. Hasan, S.B. Hasan, M. Hossain, Comparative study of integrated pest management and farmers practices on sustainable environment in the rice ecosystem, Int. J. Zool. 2016 (2016) 1–11.
[6] A.M. Ali, D.S. Mohamed, E.S.H. Shaurub, A.M. Elsayed, Antifeedant activity and some biochemical effects of garlic and lemon essential oils on *Spodoptera littoralis* (Boisduval) (Lepidoptera: Noctuidae), J. Entomol. Zool. Stud. 3 (2017) 1476–1482.
[7] S. Ali, S.M.H. Muhammad, A. Muneer, H. Faisal, F. Muhammad, H. Dilbar, S. Muhammad, G. Abdul, Insecticidal activity of turmeric (*Curcuma longa*) and garlic (*Allium sativum*) extracts against red flour beetle, *Tribolium castaneum*: a safe alternative to insecticides in stored commodities, J. Entomol. Zool. Stud. 3 (2014) 201–205.
[8] M.N. Aljamali, Study effect of medical plant extracts in comparison with antibiotic against bacteria, J. Sci. Innov. Res. 5 (2013) 843–845.
[9] G.F. Al-Samarrai, S. Harbant, S. Mohamed, Extracts some plants on controlling green mold of orange and on postharvest quality parameters, World Appl. Sci. J. 4 (2013) 564–570.
[10] H.I. Al-Taweil, Antimicrobial effect of mint essential oils on some pathogenic bacteria, Int. J. Life Sci. Res. 4 (2014) 90–93.
[11] S. Ankri, D. Mirelman, Antimicrobial properties of allicin from garlic, Microbes Infect. 2 (1999) 125–129.
[12] Y. Arafat, K. Shahida, L. Wenxiong, F. Changxun, S. Sehrish, A. Niaz, A. Saadia, Allelopathic evaluation of selected plants extract against broad and narrow leaves weeds and their associated crops, Acad. J. Agric. Res. 10 (2015) 226–234.
[13] M.K. Araújo, L. Alessandro, N.S. Jurandy, L.R. Larissa, P.V. Quelemes, C.S. Raimunda, A.J. Rocha, O.A. Éryka, S.A.J.R. Leite, J. Mancini-Filho, A.T. Reginaldo, Identification of phenolic compounds and evaluation of antioxidant and antimicrobial properties of *Euphorbia Tirucalli* L., Antioxidants 3 (2014) 159–175.
[14] J.T. Arnason, S.R. Sims, I.M. Scott, Natural products from plants as insecticides, Encyclopedia of Life Support Systems (EOLSS) (2012) 1–8.
[15] M. Asif, M. Tariq, A. Khan, M.A. Siddiqui, Biocidal and antinemic properties of aqueous extracts of *Ageratum* and *Coccinia* against root-knot nematode, *Meloidogyne incognita in vitro*, J. Agric. Sci. 2 (2017) 108–122.
[16] V. Bhanuprakash, M. Hosamani, V. Balamurugan, P. Gandhale, R. Naresh, D. Swarup, R.K. Singh, *In vitro* antiviral activity of plant extracts on goatpox virus replication, Indian J. Exp. Biol. 46 (2008) 120–127.
[17] R. Blackfor AATF [African Agricultural Technology Foundation], A Guide to the Development of Regulatory Frameworks for Microbial Biopesticides in Sub-Saharan Africa, African Agricultural Technology Foundation, Nairobi, 2013 Available at https://www.aatf-africa.org/Regulatory-Frameworks-for-Microbial-Biopesticides-in-Sub-Saharan-Africa (Accessed date: 20 January 2018).
[18] S.N. Bomfim, P.N. Lydiana, J.F.O. Pinheiro, Y.K. Cassia, S.A.M. Galerani, G. Renata, B.N. Samuel, A.M. Carlos, A.A.F. Benicio, M.J. Miguel, Antifungal activity and inhibition of fumonisin production by *Rosmarinus officinalis* L. essential oil in *Fusarium verticillioides* (Sacc.) Nirenberg, Food Chem. 166 (2014) 330–336.
[19] Business Daily. (2013). Chemical ban hits vegetable exports to the EU Market. 14 February 2013.
[20] Business Daily. (2014). Regulator suspends use of pesticides on vegetables. 13 October 2014.
[21] P. Can˜izares, I. Gracia, L.A. Gońez, A. Garcıá, C.M. Argila, D. Boixeda, L. Rafael, Thermal degradation of allicin in garlic extracts and its implication on the inhibition of the *in-vitro* growth of *Helicobacter pylori*, Biotechnol. Prog. 20 (2004) 32–37.
[22] L.E. Castillo-Sánchez, J.J. Jiménez-Osornio, M.A. Delgado-Herrera, B. Candelaria-Martínez, J.J. Sandoval-Gío, Effects of the hexanic extract of neem *Azadirachta indica* against adult whitefly *Bemisia tabaci*, J. Entomol. Zool. Stud. 5 (2015) 95–99.
[23] A. Chougule, V.K. Jha, D. Mukhopadhyay, Using IoT for integrated pest management, in: Proceedings of the International Conference on Internet of Things and Applications (IOTA), IEEE, 2016, pp. 17–22.
[24] P.M. Chougule, Y.S. Andoji, Antifungal activity of some common medicinal plant extracts against soil borne phytopathogenic fungi *Fusarium oxysporum* causing wilt of tomato, Int. J. Dev. Res. 6 (3) (2016) 7030–7033.
[25] J. Cooper, H. Dobson, The benefits of pesticides to mankind and the environment, Crop Prot. 26 (9) (2007) 1337–1348.
[26] M.E.S. Cruz, K.R.F. Schwan-Estrada, E. Clemente, A.T. Itako, J.R. Stangarlin, M.J.S. Cruz, Plant extracts for controlling the post-harvest anthracnose of banana fruit, Revis. Bras. Plantas Med. 4 (2013) 727–733.
[27] H.Y. Cui, H. Zhou, L. Lin, C.T. Zhao, X.J. Zhang, Z.H. Xiao, C.Z. Li, Antibacterial activity and mechanism of cinnamon essential oil and its application in milk, J. Animal Plant Sci. 2 (2016) 532–541.
[28] M. Cycoń, Z. Piotrowska-Seget, Pyrethroid-degrading microorganisms and their potential for the bioremediation of contaminated soils: a review, Front. Microbiol. 7 (2016) 1463.
[29] E.D.F. Dadang, P. Djoko, Effectiveness of two botanical insecticide formulations to two major cabbage insect pests on field application, Int. Soc. Southeast Asian Agric. Sci. 1 (2009) 42–51.
[30] C.A. Damalas, Safe food production with minimum and judicious use of pesticides, in: Food Safety, Springer, Cham, 2016, pp. 43–55.
[31] C.A. Damalas, S.D. Koutroubas, Farmers' exposure to pesticides: toxicity types and ways of prevention, Toxics 1 (2015) 1–10.
[32] M.J. Dhanavade, B.J. Chidamber, S.G. Jai, D.S. Kailash, Study antimicrobial activity of lemon (C*itrus limon* l.) peel extract, Br. J. Pharmacol. Toxicol. 3 (2011) 119–122.
[33] D.E. Djeussi, J.A.K. Noumedem, J.A. Seukep, A.G. Fankam, I.K. Voukeng, S.B. Tankeo, A.H.L. Nkuete, V. Kuete, Antibacterial activities of selected edible plants extracts against multidrug-resistant Gram-negative bacteria, BMC Complement. Altern. Med. 164 (2013) 1–8.
[34] N.K. Dubey, R. Shukla, A. Kumar, P. Singh, B. Prakash, Prospects of botanical pesticides in sustainable agriculture, Curr. Sci. 98 (4) (2010) 479–480.
[35] N.K. Dubey, B. Srivastava, A. Kumar, Current status of plant products as botanical pesticides in storage pest management, J. Biopestic. 1 (2) (2008) 182–186.
[36] P.B. Ekpo, U.U. Uno, E.C. Effiong, S.E. Etta, Acute toxicity of *Tephrosia vogelli* on the early life stages of farmed clariid (*Clarias gariepinus*), Asian J. Adv. Agric. Res. 3 (2) (2017) 1–5.

[37] H.A.M. El Shafie, A.A.M. Almahy, Effect of storage conditions and duration on the potency of neem (*Azadirachta indica* A. Juss) seeds as a home-made insecticide, Agric. Biol. J. N. Am. 10 (2012) 385–390.

[38] E.K.F. Elbeshehy, E.M.R. Metwali, O.A. Almaghrabi, Antiviral activity of *Thuja orientalis* extracts against Watermelon Mosaic Virus (WMV) on *Citrullus lanatus*, Saudi J. Biol. Sci. 22 (2015) 211–219.

[39] Food and Agricultural Organization. (2018) Environmental and Social Management Guidelines, environmental and social standard 5. Available at http://fao.org/environmental-social-standard/en/ accessed on 7th August 2019.

[40] B.S. Erel, R. Gottfried, Ş.S. Gökhan, Ü.K.Y. Nefi, S. Konyalioğlu, U.Z. Ahmet, Antimicrobial and antioxidant properties of *Artemisia* L. species from western Anatolia, Turkey J. Biol. 36 (2012) 75–84.

[41] T.F. Erenso, D.H. Berhe, Effect of neem leaf and seed powders against adult maize weevil (*Sitophilus zeamais* Motschulsky) mortality, Agric. Res. 2 (2016) 90–94.

[42] B. Feyisa, A. Lencho, T. Selvaraj, G. Getaneh, Evaluation of some botanicals and *Trichoderma harzianum* for the management of tomato root-knot nematode (*Meloidogyne incognita* (Kofoid and White) Chit Wood), Adv. Crop Sci. Technol. 1 (2015) 1–10.

[43] R.S. Gaikwad, R.B. Kakde, A.U. Kulkarni, D.R. Gaikwad, V.H. Pancha, *In vitro* antimicrobial activity of crude extracts of *Jatropha* species, Curr. Bot. 3 (2012) 09–15.

[44] M.M. Gakuubi, W. Wanzala, J.M. Wagacha, S.F. Dossaji, Bioactive properties of *Tagetes minuta* L. (Asteraceae) essential oils: a review, Am. J. Essent. Oil Nat. Prod. 2 (2016) 27–36.

[45] P. Ganesh, K.R. Suresh, P. Saranraj, Phytochemical analysis and antibacterial activity of pepper (*Piper nigrum* L.) against some human pathogens, Central Eur. J. Exp. Biol. 2 (2014) 36–41.

[46] A.K. Genena, H. Haiko, S.J. Artur, M. Simone, Rosemary (*Rosmarinus officinalis*) – a study of the composition, antioxidant and antimicrobial activities of extracts obtained with supercritical carbon dioxide, Ciência e Tecnologia de Alimentos 2 (2008) 463–469.

[47] M. Grdiša, K. Gršić, Botanical insecticides in plant protection, Agric. Conspect. Sci. 2 (2013) 85–93.

[48] A.S. Gunasekara, Environmental fate of pyrethrins, Environmental Monitoring Branch, California Dept. Pesticide Regulation, 2005.

[49] M.S. Gurjar, A. Shahid, M. Akhtar, S.S. Kangabam, Efficacy of plant extracts in plant disease management, Agric. Sci. 3 (2012) 425–433.

[50] M. Hadi, B. Kashefi, A. Sobhanipur, M. Rezaarabsorkhi, Study on effect of some medicinal plant extracts on growth and spore germination of *Fusarium oxysporum* schlecht. *in vitro*, Am. Eurasian J. Agric. Environ. Sci. 4 (2013) 581–588.

[51] D. Hernandez-Moreno, I. Casa-Resino, A. Lopez-Beceiro, L.E. Fidalgo, F. Soler, M. Perez-Lopez, Secondary poisoning of non-target animals in an Ornithological Zoo in Galicia (NW Spain) with anticoagulant rodenticides: a case report, Vet. Med. (Praha) 10 (2013) 553–559.

[52] W.M. Hikal, R.S. Baeshen, H.A. Said-Al Ahl, Botanical insecticide as simple extractives for pest control, Cogent Biol. 3 (1) (2017) 1404274.

[53] E. Ichim, L. Marutescu, M. Popa, S. Cristea, Antimicrobial efficacy of some plant extracts on bacterial ring rot pathogen, *Clavibacter michiganensis* ssp. *sepedonicus*, EuroBiotech. J. 1 (2017) 93–96.

[54] K.P. Ingle, A.G. Deshmukh, D.A. Padole, M.S. Dudhare, M.P. Moharil, V.C. Khelurkar, Bioefficacy of crude extracts from *Jatropha curcas* against *Spodoptera litura*, J. Entomol. Zool. Stud. 1 (2017) 36–38.

[55] F. IPPC, ISPM No 5: glossary of phytosanitary terms, Int. Stand. Phytosanit. Meas. (1) (2006) 57–79.

[56] M.B. Isman, Botanical insecticides: a global perspective, in: Proceedings of the Biopesticides: State of the art and future opportunities, ACS Symposium Series, 2, 2014, pp. 21–30.

[57] M.B. Isman, Bridging the gap: moving botanical insecticides from the laboratory to the farm, Ind. Crops Prod. 110 (2017) 10–14.

[58] M.B. Isman, M.L. Grieneisen, Botanical insecticide research: many publications, limited useful data, Trends Plant Sci. 19 (3) (2014) 140–145.

[59] A. Jantasorn, M. Boontida, D. Tida, *In vitro* antifungal activity evaluation of five plant extracts against five plant pathogenic fungi causing rice and economic crop diseases, J. Biopestic. 1 (2016) 1–7.

[60] N. Jawalkar, S. Zambare, S. Zanke, Insecticidal property of *Datura stramonium* L. seed extracts against *Sitophilus oryzae* L. (Coleoptera: Curculionidae) in stored wheat grains, J. Entomol. Zool. Stud. 4 (2016) 92–96.

[61] R. Jbilou, E. Abdeslam, S. Fouad, Insecticidal activity of four medicinal plant extracts against *Tribolium castaneum* (Herbst) (Coleoptera:Tenebrionidae), Afr. J. Biotechnol. 10 (2006) 936–940.

[62] Y. Jnaid, R. Yacoub, F. Al-Biski, Antioxidant and antimicrobial activities of *Origanum vulgare* essential oil, Int. Food Res. J. 4 (2016) 1706–1710.

[63] D. Jones, Environmental fate of cypermethrin, Environmental Monitoring and Pest Management, Department of Pesticide Regulation, 1995.

[64] B. Joseph, S. Sujatha, Insight of botanical based biopesticides against economically important pest, Int. J. Pharm. Life Sci. 11 (2012) 2138–2148.

[65] Juvatkar P.V., Kale, M. K., Jalalpure, S. S., Waghulde, S., Naik, P., Jain, V. (2012). Antimicrobial activity of leaves of Artemisia vulgaris L. (Doctoral dissertation, Phd Thesis, Department of Pharmacognosy and Phytochemistry Konkan Gyanpeeth Rahul Dharkar College of Pharmacy, Karjat, Dist-Raigadh).

[66] G. Karaca, M. Bilginturan, P. Olgunsoy, Effects of some plant essential oils against fungi on wheat seeds, Indian J. Pharm. Educ. Res. 3 (2017) S385–S388.

[67] R. Karami-Osboo, M. Khodaverdi, F. Ali-Akbari, Antibacterial effect of effective compounds of *Satureja hortensis* and *Thymus vulgaris* essential oils against *Erwinia amylovora*, J. Agric. Sci. Technol. 12 (2010) 35–45.

[68] P. Kareru, Z.K. Rotich, E.W. Maina, Use of Botanicals and Safer Insecticides Designed in Controlling Insects: The African Case, In Tech, 2013 available from: https://www.intechopen.com/books/insecticides-development-of-safer-and-more-effective-technologies/use-of-botanicals-and-safer-insecticides-designed-in-controlling-insects-the-african-case accessed on 29th January 2018.

[69] T. Karpagam, A. Devaraj, Studies on the efficacy of *Aloe vera* on antimicrobial activity, Int. J. Res. Ayurveda and Pharm. 4 (2011) 1286–1289.

[70] P.T.R. Kekuda, S. Akarsh, S.A.N. Nawaz, M.C. Ranjitha, S.M. Darshini, P. Vidya, *In vitro* antifungal activity of some plants against *Bipolaris sarokiniana* (Sacc.) Shoem, Int. J. Curr. Microbiol. Appl. Sci. 6 (2016) 331–337.

[71] İ. Kepenekçi, D. Erdoğuş, P. Erdoğan, Effects of some plant extracts on root-knot nematodes in vitro and in vivo conditions, Turk. J. Entomol. 40 (1) (2016) 3–14.

[72] A. Khan, M. Sayed, S.S. Shaukat, Z.A. Handoo, Efficacy of four plant extracts on nematodes associated with papaya in Sindh, Pakistan, Nematol. Mediterr. 36 (2008) 93–98.

[73] R. Khan, B. Islam, M. Akram, S. Shakil, A. Ahmad, S.M. Ali, M. Siddiqui, A.U. Khan, Antimicrobial activity of five herbal extracts against multi drug resistant (mdr) strains of bacteria and fungus of clinical origin, Molecules 14 (2009) 586–597.

[74] L.K. Kohn, M.A. Foglio, R.A. Rodrigues, I.M. Sousa, O. de, M.C. Martini, M.A. Padilla, L.D.F. Neto, C.W. Arns, *In-vitro* antiviral activities of extracts of plants of the Brazilian Cerrado against the avian Metapneumovirus (aMPV), Braz. J. Poult. Sci. 3 (2015) 275–280.

[75] M. Koz£owska, E.L. Agnieszka, P. Jaros£aw, Z. Ma£gorzata, M. Ewa, Chemical composition and antibacterial activity of some medicinal plants from Lamiaceae family, Acta Polon. Pharm. Drug Res. 4 (2015) 757–767.

[76] S. Kumar, A. Singh, Biopesticides: present status and the future prospects, J. Fertil. Pestic. 2 (2015) 1–2.

[77] K.A. Kumari, K.N.R. Kumar, C.N. Rao, Adverse effects of chemical fertilizers and pesticides on human health and environment, J. Chem. Pharm. Res. 3 (2014) 150–151.

[78] T. Kushram, Y.K Yadu, M.K. Sahu, A.K. Kulmitra, R. Kumar, Bio efficacy of botanical insecticides against defoliators pests on soybean, Int. J. Curr. Microbiol. Appl. Sci. 3 (2017) 2196–2204.

[79] C. Laxmishree, S. Nandita, Botanical pesticides – a major alternative to chemical pesticides: a review, Int. J. Life Sci. 4 (2017) 722–729.

[80] H. Lee, D.G. Lee, Mode of action of bioactive phytochemicals, plant secondary metabolites, possessing antimicrobial properties, Formatex (2015) 185–192.

[81] Q.S. Lin, S.H. Chen, M.Y. Hu, M.U. Haq, L. Yang, H. Li, Biodegradation of cypermethrin by a newly isolated actinomycetes HU-S-01 from wastewater sludge, Int. J. Environ. Sci. Technol. 1 (2011) 45–56.

[82] B. Liu, B. Chen, J. Zhang, P. Wang, G. Feng, The environmental fate of thymol, a novel botanical pesticide, in tropical agricultural soil and water, Toxicol. Environ. Chem. 99 (2) (2017) 223–232.

[83] B. Lomborg, The Skeptical Environmentalist, reprint ed., Cambridge University Press, 2001 (August 28, 2001). ISBN: 0521010683.

[84] I. Mahmood, S.R. Imadi, K. Shazadi, A. Gul, K.R. Hakeem, Effects of pesticides on environment, in: Plant, Soil and Microbes, Springer, Cham, 2016, pp. 253–269.

[85] D.A. Mahmoud, N.M. Hassanein, K.A. Youssef, Z.M.A. Abou, Antifungal activity of different neem leaf extracts and the nimonol against some important human pathogens, Braz. J. Microbiol. 42 (2011) 1007–1016.

[86] G. Mandalari, R.N. Bennett, G. Bisignano, D. Trombetta, A. Saija, C.B. Faulds, M.J. Gasson, A. Narbad, Antimicrobial activity of flavonoids extracted from bergamot (*Citrus bergamia* Risso) peel, a by-product of the essential oil industry, J. Appl. Microbiol. 103 (2007) 2056–2064.

[87] J.A. Martińez. Natural Fungicides Obtained from Plants, Fungicides for Plant and Animal Diseases, Dr. Dharumadurai Dhanasekaran (Ed.) ISBN: (2012) 978-953.

[88] R.K. Mishra, A. Bohra, N. Kamaal, K. Kumar, K. Gandhi, G.K. Sujayanand, M. Mishra, Utilization of biopesticides as sustainable solutions for management of pests in legume crops: achievements and prospects, Egypt. J. Biol. Pest Control 28 (1) (2018) 3.

[89] H.P. Misra, Role of botanicals, biopesticides and bioagents in integrated pest management, Odisha Rev. (2014) 62–67.

[90] E.S. Mizubuti, V.L. Júnior, G.A. Forbes, Management of late blight with alternative products, Pest Technol. 2 (2007) 106–116.

[91] P.A. Mkenda, P.C. Stevenson, P. Ndakidemi, D.I. Farman, S.R. Belmain, Contact and fumigant toxicity of five pesticidal plants against *Callosobruchus maculatus* (Coleoptera: Chrysomelidae) in stored cowpea (*Vigna unguiculata*), Int. J. Trop. Insect Sci. 35 (4) (2015) 172–184.

[92] J.A. Montanha, P. Moellerke, S.A.L. Bordignon, E.P. Schenkel, P.M. Roehe, Antiviral activity of Brazilian plant extracts, Acta Farm Bonaer. 2 (2004) 183–186.

[93] M.D. Moreira, M.C. Picanço, L.B. Cláudio de Almeida, R.N.C. Guedes, M. Ribeiro de Campos, G.A. Silva, J.C. Martins, Plant compounds insecticide activity against Coleoptera pests of stored products, Pesquisa Agropecuária Brasileira 7 (2007) 909–915.

[94] F.J.C. Moreira, B. de Abreu Araújo, F.G. do Nascimento Lopes, A. de Assis Lopes de Sousa, A. Evami Cavalcante Sousa, L.B. da Silva Andrade, A. Ferreira Uchoa, Assessment of the *'Tephrosia toxicaria'* essential oil on hatching and mortality of eggs and second-stage juvenile (J2) root-knot nematode (*'Meloidogyne enterolobii* and *M. javanica'*), Aust. J. Crop Sci. 12 (12) (2018) 1829.

[95] N. Mpumi, K. Mtei, R. Machunda, P.A. Ndakidemi, The toxicity, persistence and mode of actions of selected botanical pesticides in Africa against insect pests in common beans, P. vulgaris: a review, Am. J. Plant Sci. 7 (2016) 138–151.

[96] J. Muthomi, A.M. Fulano, J.M. Wagacha, A.W. Mwang'ombe, Management of snap bean insect pests and diseases by use of antagonistic fungi and plant extracts, Sustain. Agric. Res. 3 (2017) 52.

[97] M.A.S. Nashwa, Control of tomato early blight disease by certain aqueous plant extracts, Plant Pathol. J. 4 (2011) 187–191.

[98] S.M.A. Nashwa, A.M.K. Abo-Elyousr, Evaluation of various plant extracts against the early blight disease of tomato plants under green house and field conditions, Plant Prot. Sci. 2 (2012) 74–79.

[99] M. Nawaz, M. Juma, H. Hongxia, Current status and advancement of biopesticides: microbial and botanical pesticides, J. Entomol. Zool. Stud. 2 (2016) 241–246.

[100] G.S. Neeraj, A. Kumar, S. Ram, V. Kumar, Evaluation of nematicidal activity of ethanolic extracts of medicinal plants to *Meloidogyne incognita* (kofoid and white) chitwood under lab conditions, Int. J. Pure Appl. Biosci. 1 (2017) 827–831.

[101] A. Nefzi, B.A.R. Abdallah, H. Jabnoun-Khiareddine, S. Saidiana-Medimagh, R. Haouala, M. Danmi-Remadi, Antifungal activity of aqueous and organic extracts from *Withania somnifera* L. against *Fusarium oxysporum* f.sp. *radicis-lycopersici*, J. Microbial Biochem. Technol. 3 (2016) 144–150.

[102] M. Nikkhah, M. Hashemi, B. Mohammad, N. Habibi, R. Farhoosh, Synergistic effects of some essential oils against fungal spoilage on pear fruit, Int. J. Food Microbiol. 257 (2017) 285–294.

[103] E.F. Nkechi, O.G. Ejike, N.J. Ihuoma, O.C. Maria-goretti, U. Francis, N. Godwin, R. Njokuocha, Effects of aqueous and oil leaf extracts of *Pterocarpus santalinoides* on the maize weevil, *Sitophilus zeamais*, pest of stored maize grains, Afr. J. Agric. Res. 13 (2018) 617–626.

[104] Ntalli, N. G., Menkissoglu-Spiroudi, U. (2011). Pesticides of botanical origin: a promising tool in plant protection. Pesticides-formulations, effects, fate, 1-23.

[105] O.E. Ogah, Field evaluation of plant extracts in the management of *Megalurothrips sjostedti* and *Maruca vitrata* of cowpea in South Eastern Nigeria, World Essays Journal 1 (2013) 11–17.

[106] Y. Oka, B. Ben-Daniel, Y. Cohen, Nematicidal activity of the leaf powder and extracts of *Myrtus communis* against the root-knot nematode *Meloidogyne javanica*, Plant Pathol. 61 (2012) 1012–1020.

[107] A.I. Okunlola, O. Akinrinnola, Effectiveness of botanical formulations in vegetable production and bio-diversity preservation in Ondo State, Nigeria, J. Hortic. For. 1 (2014) 6–13.

[108] J. Onditi, N. Kiarie, S. Solomon, Improving potato tuber yields using genotypes with multiple virus resistance in Kenya, Agric. Biol. J. N. Am. 4 (2013) 406–412.

[109] M.L. Ortiz-Hernández, E. Sánchez-Salinas, E. Dantán-González, M.L. Castrejón-Godínez, Pesticide biodegradation: mechanisms, genetics and strategies to enhance the process, Biodegrad. Life Sci. (2013) 251–287, doi:10.5772/56098.

[110] E. Oskoueian, N. Abdullah, S. Ahmad, W.Z. Saad, A.R. Omar, W.Y. Ho, Bioactive compounds and biological activities of *Jatropha curcas* L. kernel meal extract, Int. J. Mol. Sci. 12 (2011) 5955–5970.

[111] B. Ouma, J. Muthomi, J. Nderitu, F. Toroitich, Management of thrips in French beans by integrating biological and synthetic pesticides in conventional spray regimes, J. Renew. Agric. 2 (2014) 27–37.

[112] Parwada C., Chikuvire T. J., Kamota A., Mandumbu R., Mutsengi K. (2018). Use of botanical pesticides in controlling *Sitophilus zeamais* (maize weevil) on stored *Zea mays* (maize) grain. Modern Concepts and Developments in Agronomy, 4.

[113] M. Pavaraj, G. Bakavathiappan, S. Baskaran, Evaluation of some plant extracts for their nematicidal properties against root-knot nematode, *Meloidogyne incognita*, J. Biopestic. 5 (2012) 106–110.

[114] K. Pawar, S. Khetmalas, B. Motkar, R. Bande, H. Wable, Antimicrobial activity of *Lantana camara* (L) Var. Aculeata (L) Mold. (Verbanaceae), Indo Am. J. Pharm. Res. 3 (4) (2013) 3284–3294.

[115] A. Perelló, U. Noll, A.J. Slusarenko, *In vitro* efficacy of garlic extract to control fungal pathogens of wheat, J. Med. Plants Res. 24 (2013) 1809–1817.

[116] N. Pitinidhipat, P. Yasurin, Antibacterial activity of *Chrysanthemum indicum*, *Centella asiatica* and *Andrographis paniculata* against *Bacillus cereus* and *Listeria monocytogenes* under osmotic stress, AU J. Technol. 4 (2012) 239–245.

[117] J. Plant, B. Stephens, Evaluation of the antibacterial activity of a sizable set of essential oils, Med. Aromat. Plants 2 (2015) 1–5.

[118] A. Plata-Rueda, L.C. Martínez, M.H. Santos, F.L. Fernandes, C.F. Wilcken, M.A. Soares, J.E. Serrão, J.C. Zanuncio, Insecticidal activity of garlic essential oil and their constituents against the mealworm beetle, *Tenebrio molitor* Linnaeus (Coleoptera: Tenebrionidae), Sci. Rep. 7 (2017) 46406.

[119] A.L.M. Porto, G.Z. Melgar, M.C. Kasemodel, M. Nitschke, Biodegradation of pesticides, in: Stoytcheva M. (Ed.), Pesticides in the Modern World–Pesticides Use and Management, 1, Tech, 2011, pp. 407–438.

[120] D.M. Pramila, R.. Xavier, K. Marimuthu, S. Kathiresan, M.L. Khoo, M. Senthilkumar, K. Sathya, S. Sreeramanan, Phytochemical analysis and antimicrobial potential of methanolic leaf extract of peppermint (*Mentha piperita*: Lamiaceae), J. Med. Plants Res. 2 (2012) 331–335.

[121] N. Raja, Botanicals: Sources for eco-friendly biopesticides, J. Biofertil. Biopestic. 5 (2014) e122.

[122] D. Rajasekaran, E.A. Palombo, T.C. Yeo, D.L.S. Ley, C.L. Tu, F. Malherbe, L. Grollo, Identification of traditional medicinal plant extracts with novel anti-influenza activity, PLoS One 8 (11) (2013) 1–15.

[123] S.S.K. Rani, S. Neeti, Udaysree, Antimicrobial activity of black pepper (*Piper nigrum* L.), Global J. Pharmacol. 1 (2013) 87–90.

[124] R.S. Rattan, Mechanism of action of insecticidal secondary metabolites of plant origin, Crop Prot. 29 (9) (2010) 913–920.

[125] S. Rodino, B. Alina, B. Marian, P.C. Calina, *In vitro* efficacy of some plant extracts against damping off disease of tomatoes, J. Int. Sci. Publ. Agric. Food (2012) http://www.scientific-publications.net.
[126] L. Rubina, T. Priyanka, J. Ebenezer, Isolation, purification and evaluation of antibacterial agents from *Aloe vera*, Braz. J. Microbiol. 40 (2009) 906–915.
[127] S. Saeed, P. Tariq, Antibacterial activity of oregano (*Origanum Vulgare* Linn.) against gram positive bacteria, Pak. J. Pharm. Sci. 4 (2009) 421–424.
[128] M.D.C. Sales, H.B. Costa, M.B.F. Patrícia, A.V. José, D.M. Debora, Antifungal activity of plant extracts with potential to control plant pathogens in pineapple, Asian Pac. J. Trop. Biomed. 1 (2016) 26–31.
[129] N. Salhi, S.A.M. Saghir, V. Terzi, N. Brahmi Ghedairi, S. Bissati , Antifungal activity of aqueous extracts of some dominant Algerian medicinal plants, Biomed. Res. Int. 2017 (2017) 7526291, doi:10.1155/2017/7526291.
[130] D. Sande, J. Mullen, M. Wetzstein, J. Houston, Environmental impacts from pesticide use: a case study of soil fumigation in Florida tomato production, Int. J. Environ. Res. Public Health 12 (2011) 4649–4661.
[131] E. Sarkar, N.C. Samarendra, P. Chakraborty, Allelopathic effect of *Cassia tora* on seed germination and growth of mustard, Turk. J. Bot. 36 (2012) 488–494.
[132] M. Sarkar, R. Kshirsagar, Botanical pesticides: current challenges and reverse pharmacological approach for future discoveries, J. Biofertil. Biopestic. 5 (2014) e125.
[133] A.G. Sarmamy, H. Hashim, A. Sulayman, Insecticidal effects of some aqueous plant extracts on the control of Khapra Trogoderma granarium Evert, in: Proceedings of the International Conference on Chemicals, Biological, and Environmental Sciences (ICCEBS-December, 2011), 2011, pp. 55–70.
[134] M. Sarwar, Microbial insecticides- an eco-friendly effective line of attack for insect pests management, Int. J. Eng. Adv. Res. Technol. 2 (2015) 4–9.
[135] Y.M. Shabana, M.E. Abdalla, A.A. Shahin, M.M. El-Sawy, I.S. Draz, A.W. Youssif, Efficacy of plant extracts in controlling wheat leaf rust disease caused by *Puccinia triticina*, Egypt. J. Basic Appl. Sci. 1 (2017) 67–73.
[136] S. Sharafzadeh, Pyrethrum, coltsfoot and dandelion: important medicinal plants from Asteraceae family, Aust. J. Basic Appl. Sci. 12 (2011) 1787–1791.
[137] A.M. Sharoba, H.A. El Mansy, H.H. El Tanahy, K.H. El Waseif, M.A. Ibrahim, Chemical composition, antioxidant and antimicrobial properties of the essential oils and extracts of some aromatic plants, Middle East J. Appl. Sci. 2 (2015) 344–352.
[138] M. Sienkiewicz, Monika Ł., P. Marta, B. Wojciech, E. Kowalczyk, The potential of use basil and rosemary essential oils as effective antibacterial agents, Molecules 18 (2013) 9334–9351.
[139] D.K. Singh, Biodegradation and bioremediation of pesticide in soil: concept, method and recent developments, Indian J. Microbiol. 48 (2008) 35–40.
[140] H. Singh, G. Alsamarai, M. Syarhabil, Performance of botanical pesticides to control post-harvest fungi in citrus, Int. J. Sci. Eng. Res. 4 (2012) 1–4.
[141] U.P. Singh, B. Prithiviraj, B.K. Sarma, M. Singh, A.B. Ray, Role of garlic (*Allium sativum* L.) in human and plant diseases, Indian J. Exp. Biol. 39 (2001) 310–322.
[142] M. Soković, J. Glamočlija, P.D. Marin, D. Brkić, J.L.D.G. Leo, Antibacterial effects of the essential oils of commonly consumed medicinal herbs using an *in vitro* model, Molecules 15 (2010) 7532–7546.
[143] M.G. Solomon, J.V. Cross, J.D. Fitzgerald, C.A.M. Campbell, R.L. Jolly, R.W. Olszak, H. Vogt, Biocontrol of pests of apples and pears in northern and central Europe-3, Predat. Biocontrol Sci. Technol. 2 (2000) 91–128.
[144] D. Srijita, Biopesticides: an eco-friendly approach for pest control, World J. Pharm. Pharm. Sci. 6 (2015) 250–265.
[145] T. Stanojković, B. Kolundžija, B. Ćirić, M. Soković, D. Nikolić, T. Kundaković, Cytotoxicity and antimicrobial activity of *Satureja kitaibelii* (Wierzb. ex Heuff) (Lamiaceae), Digest J. Nanomater. Biostruct. 2 (2013) 845–854.
[146] P.C. Stevenson, M.B. Isman, S.R. Belmain, Pesticidal plants in Africa: a global vision of new biological control products from local uses, Ind. Crops Prod. 110 (2017) 2–9.
[147] P.C. Stevenson, S.R. Belmain, in: *Tephrosia Vogelii*: a Pesticide of the Future for African Farming, Boletín SEEA, 2017, pp. 19–22.
[148] A. Sumitra, A.K. Kanojia, A. Kumar, N. Mogha, V. Sahu, Biopesticide formulation to control tomato lepidopteran pest menace, Curr. Sci. 7 (2014) 1051–1057.
[149] M.K. Swamy, R.S. Uma, S.A. Mohd , *In vitro* pharmacological activities and GC-MS analysis of different solvent extracts of *Lantana camara* leaves collected from tropical region of Malaysia, Complement. Altern. Med. (2015) 506413 2015, doi:10.1155/2015/506413.
[150] Taylor P. (2015). Plantwise diagnostic field guide: a tool to diagnose crop problems and make recommendations for their management.
[151] S. Thiruppathi, V. Ramasubramanian, T. Sivakumar, A.V. Thirumalai, Antimicrobial activity of *Aloe vera* (L.) Burm. f. against pathogenic microorganisms, J. Biosci. Res. 4 (2010) 251–258.
[152] D. Todorov, K. Shishkova, D. Dragolova, A. Hinkov, V. Kapchina-Toteva, S. Shishkov, Antiviral activity of medicinal plant *Nepeta nuda*, Biotechnol. Biotechnol. Equip. 1 (2015) 39–43.
[153] J.B. Velázquez-Fernández, A.B. Martínez-Rizo, M. Ramírez-Sandoval, D. Domínguez-Ojeda, Biodegradation and bioremediation of organic pesticides, Pesticides-Recent Trends in Pesticide Residue Assay, InTechOpen, 2012.
[154] G.M. Vidyasagar, N. Tabassum, Antifungal investigations on plant essential oils; a review, Int. J. Pharm. Pharm. Sci. 2 (2013) 19–28.
[155] H.M.A. Waziri, Plants as antiviral agents, J. Plant Pathol. Microbiol. 2 (2015) 1–5.
[156] S.N. Wegulo, P.S. Baenziger, J.H. Nopsa, W.W. Bockus, H. Hallen-Adams, Management of Fusarium head blight of wheat and barley, Crop Prot. 73 (2015) 100–107.
[157] S.A. Wimalawansa, S.J. Wimalawansa, Agrochemical-related environmental pollution: effects on human health, Glob. J. Biol. Agric. Health Sci. 3 (2014) 72–83.
[158] M. Wink, Modes of action of herbal medicines and plant secondary metabolites, Medicines 2 (2015) 251–286.
[159] M.M.G. Yamamoto-Ribeiro, G. Renata, Y.K. Cássia, D.F. Flavio, A.G.M. Simone, L.S. Expedito, A.A.F. Benicio, J.M.G. Mikcha, J.M. Machinski, Effect of *Zingiber officinale* essential oil on *Fusarium verticillioides* and fumonisin production, Food Chem. 141 (2013) 3147–3152.
[160] Y. Yan, C.C. Feng, K.T.T. Chang, Towards enhancing integrated pest management based on volunteered geographic information, ISPRS Int. J. Geo Inf. 7 (2017) 224.
[161] X. Yang, Q. Huang, T. Jiang, H. Xu, Degradation dynamics of Azadirachtin in cabbage and soil, J. South China Agric. Univ. 38 (4) (2017) 37–40.
[162] M. Yoon, B. Cha, J. Kim, Recent trends in studies on botanical fungicides in agriculture, Plant Pathol. J. 1 (2013) 1–9.
[163] M. Zaker, Natural plant products as eco-friendly fungicides for plant diseases control-a review, Agriculturists 14 (1) (2016) 134–141.
[164] L. Zarubova, K. Lenka, N. Pavel, Z. Miloslav, D. Ondrej, J. Skuhrovec, in: Botanical Pesticides and Their Human Health Safety on the Example of *Citrus Sinensis* Essential oil and *Oulema Melanopus* Under Laboratory Conditions, Mendel Net, 2014, pp. 330–336.
[165] L. Zhao, C. Feng, C. Hou, L. Hu, Q. Wang, Y. Wu, First discovery of acetone extract from cottonseed oil sludge as a novel antiviral agent against plant viruses, PLoS One 2 (2015) 1–13.
[166] F.O. Alao, Adebayo T. A., Comparative efficacy of *Tephrosia vogelii* and *Moringa oleifera* against insect pests of watermelon (*Citrullus lanatus* Thumb), International Letters of Natural Sciences 35 (2015) 71–78, doi:10.18052/www.scipress.com/ILNS.35.71.