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Plants Derived Products: As an Eco-friendly Alternative of Synthetic Pesticide for Agri-pest Management: A Review

Bhanu Prakash[1*], N. K. Dubey[2] and Kiran S.

[1&2] Department of Botany, Banaras Hindu University, Varanasi, INDIA
[*] Correspondance: E-mail: bhanubhu08@gmail.com

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ABSTRACT: Since the beginning of agriculture, farmers have had to compete with pest to secure food, feed and various economically important raw materials. Nearly one-third of agri-crop products is destroyed by pest every year during production, processing and storage. Therefore, pest management is a key concern to secure food products and other economically important raw materials in the near future. Indeed, synthetic pesticides have contributed significant role in pest control from late 1930's, but most of these chemicals exhibit side effects on human health and environment. Hence, there is a strict need to develop some biorational alternative to synthetic pesticides. In this perspective, plants-derived products possess strong pesticidal potential could play a significant role in the development of biorational pesticides. Some of the phytochemicals and their active formulation are kept in generally Recognized As Safe (GRAS) category by the USFDA and Environmental Protection Agency (EPA). The article presents an overview on the potential practical use of plants-derived products as an eco-friendly alternative of synthetic pesticides. In addition, the areas where important research must be carried out are emphasized in the future outlook.

Keywords: Essential oil; Pest management; plants-derived products and Sustainable crop protection.

INTRODUCTION: The global population is expected to reach 9.1 billion by 2050. To meet the demands of such an enormous population, the world agri-crop production will have to increase by 60-70 percent of present day production.[1] According to FAO estimates, one-third of agri-crop products are destroyed by pest every year during production, processing and storage.[2] In developing countries, approximately 40–50% of agricultural food products are loss by pest attack compared with 25-30% in Europe and United States.[3] Apart from food commodities pest infestation cause significant losses to the economically important crop used as sources of non-food industrial products such as, pharmaceuticals, essential oils, colorants, dyes, and cosmetics. Hence, pest management is a key concern to manage food commodities and other economically important raw materials in the near future. Indeed, conventional pesticides (synthetic) have contributed a significant role in pest management from late 1930's with their quick action on target pests and stability for longer periods. Having a lead role in achieving green revolution conventional pesticides were widely accepted among the farmers and agri-industries. However, *in view* of the adverse effects of synthetic pesticides such as toxic residues, pest resistance, secondary pests, and pest resurgence; there is an increasing demand for eco-friendly alternatives to synthetic ones. In this context, plants-derived products often have low mammalian toxicity, less or no impacts on non-target organism can be used as an eco-friendly alternative of synthetic pesticide. The ancient literature revealed use of plant-derived pesticides as the foremost part of traditional agriculture system in India, China, Egypt, and Greece.[4] Before 1930-40, natural products *viz.* nicotine (*Nicotiana tabacum*), strychnine (*Strychnos spp*), rotenone (*Lonchocarpus nicou*), ryanodine (*Ryania speciosa*), neem based products (*Azadirachta indica*) and sulphur compounds were extensively used for pest control. Indeed, currently plant-derived products played a minor role comparison to synthetic ones in pest control the demand for botanicals is increasing day by day due to an increasing shift in organic industries as well as consumer demand for safe food.[5]

The article presents an overview on the potential use of plants-derived products in pest management. In addition, some perspectives and remarks on the development of the new biorational pesticide based on recently discovered pesticidal plant products are succinctly discussed.

Plants-derived products: Biorational alternatives to synthetic pesticides: Application of plant products for pest management and crop protection is not a new concept such products already been used in common practices by our ancestor since time. In nature, plant guards themselves against pests by evolved defence chemicals which alter the behaviour of selected pest. Such behaviour altering chemicals are defined as semiochemicals well known for their static mode of action, less persistence, and biodegradable nature. Plant harbour several secondary metabolite products with a high structural diversity. The numerous major and minor compounds of plant secondary metabolites act as natural cocktail and exerts their effect on different target sites of pest thereby reduce the chances of resistance development as observed in the case of synthetic ones. These metabolites are broadly categorised in three group viz., terpenes and terpenoids (~25000 types), alkaloids (~12000 types) and phenolics (~8000 types).[6] Among the plant products, azadirachtin, pyrethrum, sabadilla, etc. are known to have a successful history in pest control.

Potential of plant-derived products against storage pest of agri-food commodities: The magnitude and pattern of post-harvest losses of agri-food commodities vary greatly among commodities and across the countries based on their stage of economic development. Currently, post-harvest losses are the major threats to global food security adversely affect the economy of poor farmers and small scale industries. Therefore, reducing postharvest food losses by the eco-friendly tools is worldwide demands to secure food availability without increasing the burden of toxic pesticides residues on the environment. A perusal of the literature unveils that plant bioactive compounds *viz*., Alkaloids, glycosides, phenols, tannins and terpenes exhibit strong pesticidal properties. In this context, plants-derived products having a strong pesticidal potential can be exploited as eco-chemical and biorational alternative of synthetic pesticide for crop protection.[7] Therefore, a number of studies have been performed in past few decades for extraction of bioactive compounds from plants.

Cantrell et al.[8] reported that approximately 63% approved new active ingredient as pesticides by Environmental Protection Agency (EPA) between 1997-2010 are natural product-based pesticides, where plant products is largest one at 35.7%, followed by 27.4% biological ones. Furthermore, out of the five insecticidal group (carbamates, neonicotinoids, pyrethroids, organophosphates, and natural products) available in the world market, three (neonicotinoids, pyrethroids, and natural products) are either completely natural product based or their modified form.[9] Insect repellent compound p-menthane-3,8-diol (PMD) and L-carvone were isolated from oil of *Corymbia citriodora* and *Mentha spicata.*[7] The insecticidal compounds such as decalesides I, II, oleandrin, and calamusenone were extracted from the root, leaf and rhizome of *Decalepis hamiltonii*, *Dodonaea angustifolia* and *Acorus gramineus* respectively.[10,11 & 12] Rajashekar et al.[13] studied biofumigant potential of coumaran compound isolated from the leaves of *Lantana camara* and reported its potent toxicity against *Sitophilus oryzae, Callosobruchus chinensis,* and *Tribolium castaneum.* The fungicidal compounds viz., cinnamaldehyde, sampangine, and coruscanone A and B were extracted from *Cinnamomum* spp., *Cleistopholis patens,* and *Piper coruscans* respectively.[9]

Recently, aromatic plant products such as essential oils (EOs) and their bioactive compounds are extensively studied throughout the world as a fumigant pesticides.[14 & 15] Fumigation is one of the best methods to prevent the pest contamination with minimal or no residual effect.[16] Attia et al.[17] reported acaricidal properties of *Deverra scoparia* essential oil and its blends with some of the major constituents. Bachrouch et al. 2015 investigated the insecticidal activities of two Tunisian *Artemisia* spp. essential oils against the coleopteran pests.[18] Tripathi and Kumar1[9] have reported that the *Putranjiva roxburghii* seed EO significantly protect the peanut seeds without experiencing any adverse effect on seed germination and seedling growth. Kurdelas et al.[20] explored the potential of *Baccharis darwinii* EO against the *Ceratitis capitata* (Mediterranean Fruit Fly) and recommended its application as an alternative of synthetic chemicals for pest control. Campolo et al.[21] studied the effects of kaolin and diatomaceous earth alone and in combinations with *Citrus sinensis* EO against *Rhyzopertha dominica* and reported Kaolin admixed with *C. sinensis* EO as an effective plant-based pesticides in insect pest management. Yang et al.[22] reported insecticidal potential of *Litsea cubeba* fruits essential oil against the cigarette beetle *Lasioderma serricorne*, and the booklouse *Liposcelisbo strychophila*,. Kim et al.2[3] studied the biological activities of origanum oil and its components, thymol, camphene, α-pinene, p-cymene, and γ-terpinene and recommend them as an effective fumigant and repellent for managing *T. castaneum* adults. Eco-SMART is one of the leading EO-based industries in the world developed several effective formulations against a range of pests. Some of the EOs viz., cinnamon, clove, lemongrass, oregano, thyme, nutmeg, basil and EO compounds; carvone, cinnamaldehyde, citral, p-cymene, eugenol, limonene, menthol, linalool, etc. are generally recognised as safe (GRAS) in United States (U.S. Code of 253 Federal Regulations, 2013).[24] **Table 1** summarised the efficacy of plant-derived product against storage pest of agri-food commodities.

Potential of plant-derived products in protection of economically important crop products: Although in present day the use of botanical products appears to be limiting in field crop protection, they have greater potential to evolve themselves as the plant-based pesticides at field level. Therefore in past few decades, several botanical formulations have been studied in field condition and were found effective against a variety of agricultural crops pest. Water extracts of *Vitex negunda*, *Croton sparsiflorus*, *Aegle marmelos*, *Ocimum sanctum*; and seed oils of *Azadirachta indica*, *Calophyllium inophyllum*, *Madhuca longifolia*, *Annona squamosa* were exhibited potent efficacy against the green leafhopper of rice crop.[25] Neem kernel extracts (38.57%) and neem oil (5%) sprays effectively manage the Gram pod borer (*Helicoverpa armigera*) population, a major insect pest of chickpea, tomato, and pigeonpea.[26] Karanja, a bioactive flavonoid compound was isolated from *Pongamia glabra* showed strong toxic effect against the variety of field pest. Lee et al.[27] evaluated acute toxicities of 34 naturally occurring monoterpenoids against the larva of the western corn rootworm, and the adult of the two spotted spider mite and reported α-terpineol as a more effective compound among all tested monoterpenoid in the greenhouse pot test. Varma and Dubey[28] have demonstrated the *in vivo* practical effectiveness of EOs of *Caesulia axillaris* and *Mentha arvensis* as fumigant for protection of orange fruits by fungal deterioration. Dang et al.[29] determined pesticidal activity of methanolic extract of dried roots of *Euphorbia kansui*, against brown plant hopper (*Nilapar vatalugens*) and two-spotted spider mite (*Tetranychus urticae*) and reported 3-O-(2,3-dimethylbutanoyl)-13-O-dodecanoylingenol(1) and 3-O-(2′E,4′Z-decadienoyl)-ingenol as an alternative of synthetic pesticide. Mansour et al.[30] studied efficacy of some EOs against the 3rd nymphal instars of the desert locust, *Schistocerca gregaria* and reported fenitrothion, as the most toxic compounds against test pest. You et al. 2014 investigated the chemical composition, insecticidal and repellent activities of *Purple Perilla* EO and its components R-(+)-carvone, perilla aldehyde, 2-furyl methyl against *Lasioderma serricorne*. Gougoulias et al.[14] reported the potential of neem and oregano plant material as a soil biopesticide without any negative effects on the availability of mineral nutrients. Glucosinolates are sulphur containing organic compounds naturally occurring in brassica plants (*Brassicaceae*) are used to combat parasites, bacteria and fungi attacking crops in organic farming. Incorporation of glucosinolate-containing plant material in the soil, release their bioactive hydrolysis products (isothiocyanates, thiocyanates, indoles) which exert toxic effects on soil pests. Being the biodegradable in nature plant derived products could be used as an eco-friendly alternative of toxic synthetic fumigants used for soil fumigation.

Recently, in South Africa, based on the knowledge of chemical ecology of the plant and insect pheromone, a Push–Pull or stimulo-deterrent strategy has been introduced to protect maize, sorghum and other cereal crops from insect pests.[32] In past few years, there has been and increase interest on push-pull concept for pest control in agricultural crops. This strategy is based on trapping phenomenon, involves semiochemicals to repel insect pests from the crop ('push') and to attract them into trap crops ('pull'). Knowledge of such chemical ecology of plant may be successfully employed in the management of insect pest population in field crops by companion cropping, i.e. intercropping for the push and trap cropping for the pull. Semiochemicals (behavior-modifying volatile organic compounds) often produce by aromatic plants may act as signal molecules for the natural enemies to locate their prey organism. Based on this several semiochemical compounds synthetic, semi-synthetic and natural one are developed and widely accepted for controlling the pests of high-value horticultural crops. **Table 2** summarised the potential practical application of botanicals in the agri-field against the crop pest.

Table 1: Plants-derived products against stored product pest.

Plants	Plant parts	Major compound/ formulation	Target pest	Experimental setup	Results	Ref.
Rosmarinus officinalis L.	L	2-methoxy-3-(2-propenyl)-phenol, 1,8-cineole, andcamphor	*S.o.* and *O.s.*	Fumigant toxicity: Different conc. (0.025 to 0.2 µl/ml) of EO was prepared and used as fumigant for (3 to 72h) exposure.	At 0.15 µl/ml EO exhibited 100% toxicity and antifeedant activity against the test insect	46
Gaultheria procumbens L.	L	Methyl Salicylate	*S.o.* and *R. d.*	Fumigant toxicity: Different conc. (1 to 200 µl/l) of EO and methyl salicylate was prepared and used as fumigant for 24h exposure.	Both EO and methyl salicylate showed 100% mortality at 150 and 5.0 µl/l air against *S. oryzae*	47

					and *R. dominica* respectively on 24 h of exposure	
Chenopodium ambrosioides L.	A	EO, ascaridole, δ-4-carene, ρ-cymene, Isoascaridole, α-terpinene	*S. z.*	Fumigant toxicity: Different conc. (0.5–5.0 g/l of compounds and 1.4-5.0 g/l of EO) was prepared and 20 µl of these were put on filter paper and then placed on the underside of the screw cap of a glass chamber for 24h exposure. Contact toxicity: Different conc. (1.3–50 g/l) for both compounds and EO prepared and aliquots of 0.5 µl of the dilutions were applied topically to the dorsal thorax of the insects. Observation was taken after 24 h up to 7 day.	LC_{50}values (fumigation) were recorded at 0.84, 14.02, 23.28, 2.45, and 5.46 for compounds and 3.08 mg/l for EO respectively. LC_{50}values (contact) were recorded at 0.86, 3.55, >23.18, 2.16, 3.47 for compounds and 2.12µg/g for EO respectively.	48
Carum copticum C. B. Clarke and *Vitex pseudonegundo* Hand I. MZT	S and L	EOs	*C. m.*	Experiments were performed in glass jars exposed to test EOs as fumigant at varying conc. (0.714 to 25µl/l), > 24h, for ovicidal and larvicidal activity. For adults different conc. ranged between (0.43 -1.47µl/l) for *C. copticum* and (0.71-35.71µl/l)for *V. pseudonegundo* were exposed for 24h.	(LC_{50}) for egg, larvae and adult were found (1.01, 2.50 and 0.90 µl/l) for *C. copticum*, and 2.20, 8.42 and 9.39 µl/l) for *V. pseudonegundo*.	49
Zingiber officinale Roscoe	Rh	Zingiber oil Curcumene	*S. ob., R. s.*	Insect growth inhibition assay and anti-feedant activity were performed in Jar exposed for 24h at conc. ranged between (0.1-1.0%) and (1-10g/l) for EO and curcumene respectively. For antifungal: Poisoned food technique assay was carried out using PDA medium at varied conc. (1000-62.5 mg/l)	Insect growth inhibition: EC_{50} (mg/ml) Curcumene: 9.5; Oil: 9.6 Feeding inhibition: EC_{50}(mg/ml) Curcumene:9.6; Oil: >10 Antifungal : EC_{50} (mg/l) Curcumene: 97; Oil: 90	50
Datura alba Nees	L	Acetone extract	*T. g., S. o.*	Filter papers were soaked with different concentration (1.5, 2.0, and 2.5 %) exposure for 7 days.	At 2.5% of extract, 33.5 and 45 % mortality was observed for *T. granarium* and *S. oryzae* respectively. A high demographic decrease in the F_2 generations has been observed.	51
Clausena anisata	L	Powdered leaves	*S. z., P. tr.*	The leaves powders (0.25 to 4 g) of *C. anisata* and *P.*	LD_{50}values for the exposure	52

(Willd.) J.D. Hook ex. Benth. and *Plectranthu sglandulosus* Hook f.				*glandulosus* were separately admixed to 50 g of disinfestedmaize in 250 ml glass jars. Thereafter, 20 insects of mixed sexes of both insect sp. were added and adult mortalities were recorded after 1 - 4 weeks.	periods of 1, 2 and 4 weeks for *S. zeamais*(German strain) was observed as 2.75, 1.49 and 1.14 g/100 g grain, while for Cameroonian strain it was 1.86, 1.23 and 0.89 g/100 g grain. In case of *P. truncates* even with a higher powder content of 8 g/100 g grain, only up to 40% mortality observed.	
Azadirachta indica A. Juss.	S	Calneem oil	*T. c.*	Calneem was applied at six dosage (0.1, 0.2, 0.5, 1.0, 2.0 and 3.0% v/v) for both in filter paper assay and in contact with grain in Jar.	3% of Calneem oil killed approx. 90% of the beetles within 72 h on grain, and 88% on filter paper.	53
Illicium verum Hook. f.	Fr	Extract in methyl alcohol (MA), ethyl acetate (EA), and petroleum ether (PE)	*S. z.*	Filter papers were soaked with different doses of 1.25, 2.50, 5.00, 10.00, and 20.00 mg/l, respectively and hung in the centre of glass bottle.	The LD_{50} of the MA, EA, and PE extracts were recorded as 7.10, 3.93, and 4.55 mg/l, following 72 h treatment respectively.	54
Cymbopogon citrates (DC) Stapf. and *Eucalyptus citriodora* Hook	A, L	EOs, geranial, neral, geraniol and citronellal, isopulegol, citronellol	*T. c.*	Different conc. (0.001 to 1ml/l) was prepared using acetone as solvent. 0.5 ml of each conc. poured in half of filter paper and observation were taken after 2 and 4 h of exposure.	Both oils, *C. citrates* (> 80%) and *E. Citriodora* (>75%) exhibited potent repellency.	55
Neem Azal powder, neem seed powder neem seed oil and *Plectranthus glandulosus* Hook f. leaf powder	S, L	Powder, oil	*S. z.*	Different conc. for each test compound was prepared tested under lab condition and mortality was recorded 1, 3, 7 and 14 days, followed by the determination of F_1 progeny production. Experiment related to grain damage, population increase and grain germination were also assessed for treated grains stored for 4 months.	Neem Azal and neem seed oil exhibited sufficient efficacy to be a component of an integrated pest management.	56
Cinnamomum aromaticum (Nees)	B	*cis*-cinnamaldehyde	*C. m.*	Surface film bioassay was performed at varying concentration between 7.86 to 62.85 μg/cm^2.	The LD_{50} value was recorded at 27.56μg/cm^2 after 24 h of exposure.	57
Schizonpeta multifida (L.) Briq.	FA	EO Menthone, pulegone	*S. z.*, *T. c.*	Filter papers were impregnated with 20 μl of an appropriate conc. (25–1%	LC_{50} value for EO, pulegone and menthone against	58

				v/w) for *S. zeamias*and 30–1% (v/w) for *T. castaneum* five concentration for each was applied in glass vial. Observations were taken after 7 days.	*S. zeamais;* 8.33, 3.47 and 10.32 mg/cm^3, while for *T. castaneum*26.41, 11.56 and 31.25 mg/cm^3 respectively.	
Eucalyptus globules Labill., *E. Viminalis* Labill., *E. dunnii* Maiden., *E. saligna* Smith., *E. benthamii* Maid. & Camb.	L	EO	*S. z.*	The contact toxicity of five eucalyptus spp. against *S. zeamais*was evaluated on filter paper discs treated with different dosages of EO (0.07 to 2.60 µg/cm^2). Insect mortality was determined after 24 h.	LC_{50} value recorded at 0.08, 0.10, 0.16, 0.25, 0.79 µg/cm^2 respectively.	59
Artemisia species (*A. absinthium*, *A. santonicum* and *A. spicigera*)	A	EOs (Camphor, 1,8-cineole, chamazulene, nuciferol, propionate, nuciferol, butanoate, caryophyllene oxide, terpinen-4-ol, borneol and α-terpineol)	*S. g.*	Different doses of EOs (3, 6 and 9 µl/l air) were applied in desiccator for 48h and for compounds (0.5, 0.75 and 1 µl) in petri-dish for 12 h exposure.	The oils showed about 80–90% mortality of *S. granarius*at 9 µl/l air after 48 h of exposure. 1,8-cineole, and terpinen-4-ol showed 100% mortality at all doses after 12 h of exposure.	60
Lippia alba (Mill.) N.E. Brown and *Callistemon lanceolatus* (Sm.)	L	EOs, 1,8-cineole, Geranial	*C. ch.*	Repellency test were performed in Y-shaped olfactometer at varying doses (10 -150 µl) of each treatments. For fumigant toxicity filter paper discs treated with different doses of treatments were introduced into the plastic jars to achieve final concentrations ranged between (0.012, -0.100 µl/ml). Insect mortality was determined after 12 -24 h.	At 150 µl EO of *C. lanceolatus* exhibited 100% repellency, while 76, 74.7 and 63% repellency observed in case of *L. alba*, 1,8-cineoleand geranial. As a fumigant at 0.1 µl/ml following 24 h exposure except geranial (82.5%) all exhibited 100 % mortality.	61
Ricinus communis L.	L	Aqueous and methanolic extract, flavonoid (quercetin)	*C. ch*	Insecticidal experiment was performed in jar having 25 g green gram treated with various conc. of flavonoid (1-6 mg/ml) and extracts.	100 % mortality was observed in case of methanolic extract while for aquous extract it was > 73% after 9 h incubation period. Quercetin, exhibited 100% mortality at 3 mg/ml after 4 h	62

					treatment.	
Foeniculum vulgare Miller,	Fr	(E)-anethole and estragole, fenchone	*S. o.*, *C. ch.*, *L. s.*	Different conc. (0.168 to 0.063 %) (0.032 to 0.005 %), (0.105 to 0.013 %) mg/cm^2 of all three bioactive compounds were applied for direct contact toxicity against target pest. For fumigant toxicity 0.42mg/cm^2 concentrations were applied for all treatments.	At highest conc. mortality was observed between 60-100% for all test compounds following 4 day incubation. For fumigant toxicity 100% mortality was observed at 0.42mg/cm^2.	63
Tagetes terniflora Kunth, *Cymbopogon citratus* Stapf. and *Elyonurus muticus* (Spreng) Kuntz	L	EOs (*cis*-cimene *cis* + *trans*-Tagetone, *cis* + *trans*-Ocimene, Dihydrotagetone, Geranial, Neral)	*T. c.*, *S. o.*	Different concentration of EOs was applied for contact (impregnated paper) and fumigant toxicity. Insect mortality was determined after 72 h.	LC_{50} value of contact and fumigant toxicity against both *T. castaneum*, and *S. oryzae* were recorded at (217.26 and 146.58); (362.82 and 322.61) µgcm^{-2} respectively only for *T. terniflora*. While, *C. citratus* and *E. Muticus* exhibit contact toxicity against *S. oryzae* and LC_{50} 435.41 and 99.63 µg/cm^2.	64
Cinnamomum glaucescens (Nees) Hand. – Mazz	D.b	Crude EOs	*C. ch.*, *A.f.*,	For fumigant toxicity chickpea seeds var. Radha inoculated with *A. flavus* and *C. chinensis* separately in closed containers were fumigated with EO with varying conc. (0.025-0.150 µl/ml) for insect and (4.5 µl/ml) against *A. flavus* for 12 months.	EO as fumigant in food system providing 71.07% protection of chickpea samples from fungal infestation and 100% antifeedant activity against the insect.	15
Cuminum cyminum (L.)	S	EO (Cymene,laevo beta pinene, and γ-terpinene)	*C. ch.*, *S. o.*,	To determine the fumigant toxicity, appropriate concentration of test materials were applied separately on the filter papers (Whatman No. 1, 2 cm diameter), to achieve the final concentration 10, 20, 40, 60, 80 and 100 µl/L air without using any solvent and attached to the undersurface of lids of plastic jars with volumes 200 mL	The EO, exhibited100% and 96.89% feeding deterrent index at 100 µl/l air concentration against *C. chinensis* and *S. oryzae* damage respectively without affecting viability of chickpea and wheat.	65

EO, Essential oil; conc., Concentration; PDA, Potato Dextrose Agar; PDB; Potato Dextrose Agar; DMSO, Dimethyl sulfoxide; LC50 values: Lethal concentration; EC50 values; Effective concentration; MIC, Minimum inhibitory concentration.

Plant Part: A, Aerial part; S, Seed; L, Leaves; Rh, Rhizome; Fr., Fruit; B, Bark; FA, Fowering aerial parts;O.g,Oleoresin-gum; D.b., Dried berries; B, Bark

Target Pest: Insect spp.: S.z., Sitophilus zeamais; C. m.,Callosobruchus maculatus; S. ob., Spilosoma oblique, T. g., Trogoderma granarium; S.o., Sitophilus oryzae; P. tr., Prostephanus truncates; T.c., Tribolium castaneum;S.g.,Sitophilu sgranarius; C.ch., Callosobruchu schinensis; L.s.,Lasioderma serricorne,. O.s Oryzaephilus surinamensis

Table 2: Plants-derived products against the economically important crop pest.

Plants	Active ingredient	Group	Target pest	Ref.
Rosemarinus officianalis L.,	1,8-cineole, borneol, camphor	Insecticide	Aphids, beetles, spider mites, thrips, and caterpillar larvae etc.	33
Anethum graveolens L., *Cuminum cyminum* L., *Foeniculum vulgare* Mill.,and *Petroselinum crispum* (Mill.) Fuss	EOs	Insecticide	*Pseudaletia unipuncta*	66
Bauhinia scandens L.	Dichloromethane extracts	Insecticide	*Plutella xytostella*	67
Schinus polygama (Cav.) Cabrera, and *Baccharis spartioides* (Hook. &Arn. ex DC.)	EOs	lure-and-kill technology	*Ceratitis capitata*	68
Ocimum ciliatum Hornem	Methyl chavicol, methyl eugenol and 1,8-cineole	Bactericidal	*Ralstonia solanacearum, Pseudomonas syringae, P. syringae, P. tolaasii, Xanthomonas oryzae, Xanthomonas citri, Brenneriani grifluens, Panto eastewartii, Agrobacterium vitis,* and *Rhodococcus fascians*	69
Rosmarinus officinalis L., and *Salvia officinalis L.*	EOs	Insecticide	*Tetranychus urticae*	70
Azadirachta indica A. Juss.	Neem extract (NeemAzal)	Insecticide	Mirid bugs	71
Azadirachta indica A. Juss.	Neemarin (0.15% EC azadirachtin), Neemazal (1% EC azadirachtin), Neemix (0.25% EC azadirachtin) and Neem oil (1% EC azadirachtin)	Insecticide	*Helicoverpa armigera*	72
*Rhododendron molle*G. Don	Rhodojaponin-III (R-III)	Insecticide	*Pieris rapae*	73
Laurelia sempervirens (Ruiz &Pavon) Tul.and *Drimys winteri* JR Forster & G Forster.,	Safrole, limonene	Insecticide	*Acyrthosiphon pisum*	74
Acmella oleracea (L.) RK Jansen	hexane extract (spilanthol, (*E*)-*N*-isobutylundeca-2-en-8,10-diynamide, and (*R*, *E*)-*N* (2methylbutyl) undeca-2-en-8,10-diynamide)	Insecticide	*Tuta absoluta*	75

Chenopodium ambrosioides L.	UDA-245	Insecticide	Spider mites, aphids and small caterpillars	76
Pogostemon cablin Benth., *Thymus vulgaris* L., *Allium sativum* L.,and *Cymopogon nardus*L.	Patchouli alcohol, α-guaiene,δ-guaiene; thymol,ρ-cymene; diallyldisulfide,di-2-propenyl trisulfide; citral,trans-verbeno, camphene respective-ly.	Insecticide	*Choristoneura rosaceana, Trichoplusia sp.*	77
Cephalotaxus fortune Hook.	Drupacine	Nematicide	*Meloidogyne incognita* and *Bursaphelen chusxylophilus*	78
Macleaya cordata (Willd.) R.Br.	Sanguinarine, chelerythrine, protopine and allocryptopine	Fungicide	Powdery mildew, *Alternaria* leaf spot, and *Septoria* leaf spot	79
*Azadirachta indica*L., *Artemisia annua* L., *Eucalyptus globules* Labill., *Ocimum sanctum* L., *Rheum emodi* Wall.	Leaf water extract (20% w/v)	Fungicide	*Fusarium solani*	80
Jatropha gossypifolia L.,and *Melia azedarach* L.	Ethanolic senescent leaf extracts	Insecticide	*Spodoptera frugiperda*	81
*Cinnamomum zeylanicum*Blume.,	EO, Eugenol and isoeugenol	Weedicide	Lambsquarter, ragweed, Johnsongrass	82
Tanacetum aucheranum (Dc.) Schultz Bip and *Tanacetum chiliophyllum* (Fisch. &Mey.) Schultz Bip.,	EO, Camphor, 1,8-cineole, and borneol	Weedicide and Phytopatho-genic	30Phytopathogenic fungi; and Weeds*: Amaranthusretroflexus, Chenopodium al-bum* and *Rumexcrispus*	83
Achillea gypsicola Hub-Mor., *Achillea biebersteinii* Afan., and n-hexane extract	EOs components: Camphor, 1,8-cineole, piperitone, borneol and α-terpineol; n-hexane components: camphor,1,8-cineole, piperitone, *n*-eicosane, *n*-heneicosane*n*-tricosane, linoleic acid and borneol.	Weedicide and Phytopatho-genic	12 phytopathogenic fungi and Weeds; *Amaranthus retroflexus, Cirsium arvense, Lactuca serriola.*	84
Oryza sativa L.	Momilactone B	Weedicide	Inhibit the germination and growth of rice weeds.	85
*Azadirachta indica*A. Juss. and *Eucalyptus citriodora* Denn.	Neem and Eucalyptus leaf extract mixture formulation	Insecticide	*Marucavitrata, Clavigralla Tomento sicollis*	86
Melia azedarach L. *Azadirachta indica*A. Juss.	Neemix 4.5®	Insecticide	*Plutella xylostella,*	87
*Pongania pinnata*L., *Thymus vulgaris* L., *Foeniculum vulgare*Mill., *Azadirachta indica*A. Juss., oils	Formulation made by different combination of individual such as Pongam oil;Pongam oil + thyme oil; Pongam oil + fennel oil; NeemAzal T/S (NA)	Insecticide	*Plutellax ylostella*	88

*Pongamia pinnata*L.,	Tween 85: pongamia oil (1 : 9)	Insecticide	Green peach aphid (*Myzus persicae*)	89
*Pongamia pinnata*L., + thymol	Tween 85: oil : thymol(1 : 8 : 1)	Insecticide	do	do
Pongam + *Thymus vulgaris* L.extract	Tween 85: oil : extract(1 : 8 : 1)	Insecticide	do	do
Pongam + *Sapindus saponaria* L. Extract	Tween 85 : oil : extract (1 : 8 : 1)	Insecticide	do	do
NA – NeemAzal TS	Azadirachtin A 10 g/kg	Insecticide	do	do
Azadirachta indica A.Juss.,	Neem oil	Insecticide	*Diaprepes abbreviates, Schistocerca americana*	90
Azatrol EC†	Azadirachtin	Insecticide	do	do
Sabadilla Pest Control †	Sabadilla alkaloids	Insecticide	do	do
Rotenone 5 †	Rotenone	Insecticide	do	do
Ryan 50 †	Ryanodine	Insecticide	do	do
Hot Pepper Wax†	Capsaicin and other capsaicinoids	Insecticide	do	do
Neem Azal T/S	Azadirachtin	Insecticide	Brassica pod midge	91
Sorghum + Brassica	Water extract + Pendimethalin	Weedicide	*Trianthema portulacastrum*	92
Ageratum conyzoides L.	demethoxy-ageratochromene, β-caryophyllene, α-bisabolene, and E-β-farnesene,	Push-pull approach	citrus red mite	93
Melinismin utiflora, Desmodium uncinatum, D. Intortum and *Pennisetum purpureum, Sorghum vulgares udanense*	Intercrops with trap crops	Push-pull approach	Stem borer	32
Molasses grass (*Melinismin utiflora*) and silver leaf desmodium (*Desmodium uncinatum*)	Herbivore-induced plant volatiles (HIPVs) such as methyl salicylate and (Z)-Jasmine	Push-pull approach	Stem borer	do
Neem seed extracts with pigeon peaor maize	Intercrops with trap Crops	Push-pull approach	*Helicoverpa armigera* and *H. punctigera*	do
Maize, molasses grass	(E)-ocimene and (E)-4,8-dimethyl-1,3,7-nonatriene	Push-pull approach	*Stem borers*	94 & 95

Hyparrhenia tamba, Pennisetum purpureum, Sorghum bicolor, and *Zea mays*	hexanal, (E)-2-hexenal, (Z)-3-hexen-1-ol, and (Z)-3-hexen-1-ylacetate	Push-pull approach	Lepidopterous stem borers	96
Prunus persica (L.) Batsch	(Z)-3-hexen-1-acetate,(Z)-3-hexen-1-ol and benzaldehyde in a 4:1:1 ratio	Push-pull approach	*Cydia molesta*	97
Piper nigrum L.,	Oil	Repellent	Squirrels and small mammals	79
Cinnamaldehyde*	50% cinnamaldehyde + activated charcoal	Push-pull approaches	*Delia antique*	32
Karanjin*		Insecticide and fungicide	Caterpillars, aphids, jassids, beetles	79
Capsaicin*	-	Insect and mite repellent	Beetle and mites	do
9,10-anthraquinone*	-	Repellent	Bird repellent	do
cis-jasmone*	-	Push-pull approaches	herbivorous pest	98
Azadirachtin*	Azamax^R	Miticide	*Tetranychusurticae*	99
BOA/DIMBOA*, Pelargonic acid*, Sarmentine*, Citral*	-	Insecticide, fungicide, herbicide	Broad spectrum	4

*EO = Essential oil; * = Compounds; †=formulation based on compounds*

Plant-derived products as a role model for synthetic pesticide development: Indeed, no single pest control method can operate individually to manage pest population and crop protection; therefore integrated pest management (IPM) approaches were introduced in the late 19th centuries by R.F. Smith and R. van den Bosch. Synthetic pesticides have golden past as a pest control agent for protection of agricultural crop and stored food items. Although world agri-food industries are looking towards the alternative of synthetic ones their application cannot be avoided overall. Therefore, IPM strategies where synthetic one is a part of pest control combined with all the available pest control methods (biological, microbial, botanical, and cultural practices) are widely accepted by agri-industries. The European Union (EU), recently introduced a package of legislative measures in 2009 based around IPM, including the Framework Directive on the Sustainable Use of Pesticide; Directive 2009/128/EC (establishing a framework for sustainable use of pesticides), Regulation (EC) No 1185/2009 (concerning statistics on plant protection products), Regulation (EC) No 396/2005 (on maximum residue levels of pesticides in or on food and feed;) Directive 2004/35/CE (on environmental liability)(http://www.ecpa.eu/files/attachments/Registration_web.pdf).

Approximately 11% of global sales of agricultural pesticides formulation are developed based on the bioactive compounds owing to the discoveries of pesticidal natural products.[33] A pesticide having new mode of action, stable in nature and acceptable under IPM tactic is more appropriate for future pest control in the agriculture sector. In this context, plant-derived products and their mode of action may provide a framework for the development, and design of on newer synthetic pesticides. Indeed, many commercial available synthetic or semi-synthetic pesticides have been developed based on the plant bioactive compounds and their mode of action. Physostigmine, a model compound for the development of the carbamate insecticides was isolated from the *Physostigma venenosum*. Flubendiamide, a potent insecticide compound was developed based on the elucidation of the molecular target site of the ryanodine alkaloid obtained from *Ryania speciosa*.[34] Juvocimenes, juvabione, and farnesol are the plants derived products served as model compounds for the development of insect juvenile hormone analogs such as methoprene and kinoprene available for the control of flies, fleas, and some stored-products pests. Para-methane 3-8, diol (PMD), a commercially available repellent discovered in the 1960s was based on the systematic screening of plants for repellent activity.[35] Further, modification in the chemical structure of known plant bioactive compounds, by the application of modern advanced technologies and chemistry, leads to the development of their synthetic analogue with desired beneficial character. Such structural modification and their effective formulations may be enhanced; their biological activity, toxicological properties, effective release, stability and leads to the discovery of an active compound of commercial importance such as pyrethroids, neonicotinoids, pyrroles, quinolines, and spinosyns. A number of synthetic compounds have been developed and design based on the study of natural products, having worldwide availability and acceptability. Pyrethrins, a group of naturally occurring insecticidal compounds found in *Chrysanthemum cinerariifolium* flowers; are chemically unstable as it degrade quickly upon exposure to sunlight and air. However, its synthetic analogues pyrethroids have desirable character: quick knockdown of insect, low mammalian toxicity, stability in the outdoor environment.[8] Structurally modified ryanodine exhibited increased insecticidal activity against a wide range of targeted pest.[36] Neonicotinoids are natural product-derived pesticides registered as an insecticide in the world market. Acibenzolar-S-methyl, a structural analogue of salicylic acid, is useful in the control of downy mildew on leafy vegetables, and works by inducing host plant resistance.[8] In addition, allelopathic agents such as terpenoids, phenylpropanoids, quinones, coumarins, flavonoids, tannins, phenolics, and cyanogenic glycosides can play an important role to develop newer synthetic or semi-synthetic pesticides. The development of newer synthetic pesticides based on the action of newly discovered plant bioactive compounds using the knowledge of combinatorial chemistry and metabolomics approaches would reduce the need of raw materials and large-scale cultivation of pesticidal plant.

Current constraints of plant-derived products as pesticides: Plant-derived products often pose major drawback for their application as natural pesticides such as shorter life span, narrow target range, inconsistent efficacy, availability of raw material; lack of quality control, unknown mode of action, and phytochemical variation. Indeed, phytochemical variation in pesticidal plants is one of the serious hurdle to the plant-derived pesticides for their commercialization. Further, botanicals are not considered always to be safe for consumers, as some of active compounds were found toxic to mammalian system *viz.,* nicotine (LD_{50} = 50 mg/kg), rotenone (LD_{50} = 132 mg/kg), cevadine (LD_{50} = 13 mg/kg), pulegone (LD_{50} = 150 mg/kg), and α-thujone ((LD_{50} = 45 mg/kg) [5]. In food system, the plant-derived products such as essential oils/extracts may be impaired by interactions of biomolecules such as lipid, starch and proteins.[37] Strong aroma of botanicals especially essential oils and their compounds even at low concentrations, may adversely affect the organoleptic property of applicable items. In addition, high cost of most of the plant-derived products compare to available synthetic pesticides is one of the greatest challenges for their commercialization.

Present status and future prospect: The recent awareness toward the green consumerism and sustainable agriculture constrained the agri-industries to look towards the safer alternative of health hazardous pesticides. Currently, a number of the botanical formulations are available in organic farming or small scale industries. Requiem TM was the first botanical registered in the USA in 2008 for its use against a wide range of pests including aphids, whitefly, thrips, and mites.[38] Apilife VAR™ (based on thymol and cineole), Citrus oil have been used for control of pest management in organic farming in European Countries.[39] CinnamiteTM and ValeroTM, (cinnamon oil with cinnamaldehyde), Green Ban® (citronella, cajuput, lavender, safrole free sassafras, peppermint, and bergaptene free bergamot oil); Buzz Away® (citronella, cedarwood, eucalyptus, and lemongrass); Matran II™ (Clove oil, wintergreen oil, butyl lactate, lecithin), Eco-Exempt™(2-Phenethyl proprionate, clove oil), "DMC Base Natural" (50% EO rosemary, sage, citrus and 50% glycerol), GreenMatch EX™ (Lemongrass oil 50% and a mixture of water, corn oil, glycerol esters, potassium oleate and lecithin) are some of the commercially available formulation based on plant-derived compounds.[40, 4, 41 & 42] Stapfianine A (C19-diterpenoid alkaloid) and stapfianine B (benzamide derivative were isolated from the roots of *Aconitum stapfianum.*[43] *Ligularia*, an important genus of the Compositae family harbour hundreds of secondary metabolites with various skeletons has captured the interest of natural product chemists for years.[44]

As per the European Union procedure for plant protection 2008, natural products that were not found to have harmful effects on human health, animals, ground water, or any unacceptable effects on the environment are allowed for the inclusion as a pesticides ingredient.[45] Hence, it is hoped that plant-derived pesticides can play a cornerstone role in pest management and crop protection in the near future. Therefore, the following areas of research need attention for the exploitation of plant-derived products as an alternative of synthetic pesticides for sustainable pest management:

Bioprospection: an approach to explore and commercialize plants-derived products: In view of the global resurgence in the application of naturally occurring products, traditional knowledge is increasingly becoming a source of pesticide formulation. Countries like India, China, Sri Lanka, Brazil, Egypt and African entities, etc. have depth of traditional knowledge about the pesticidal plants. Such traditional knowledge of the pesticidal plant may be helpful for exploitation of newer bioactive compounds. Although an initial step has already been started by the biodiversity rich countries as a central component of research and development policy and practice. More scientific approaches are needed for exploitation of pesticidal plant, their active compounds and mode of action for their usefulness in pest management and crop protection.

Collaborative research work between R &D institutions and industries: In today's global world there is a strict need of collaborative research between research institutions and industry in order to maximize the use of the research output at ground level. The recent knowledge of combinatorial chemistry with advanced technologies are appropriate to design plant-derived chemicals and their active formulation as a component of pest management which are highly effective at low doses in both storage and field condition, selective in their activity, with less/or no adverse environmental effects. Neem based pesticide is one of the classical examples of collaborative partnership between P. J. Margo (India) and W.R. Grace (USA). Therefore, there is a strict need of collaborative research work between scientific organization, industries and regulatory body to make an effective sustainable path for commercialization of plant-derived pesticides and their formulation.

Use of modern techniques to design better carriers for plants-derived compounds: The recent development of nanotechnology in conjunction with biotechnology can play a significant role to design better carriers for plants-derived compoundswith improve bioavailability, stability, and functionality. Although, nanoencapsulation technique such as spray drying, freeze drying, emulsification, coacervation, and nanoprecipitation have already been explored in biomedical and pharmaceutical sectors, their application in designing of agriculture pesticides/ food additive is not well explored. Nanoemulsions, nanoencapsulates, nanocontainers, and nanocages are some of the nanopesticide delivery techniques that have recently been studied in organic farming and food system for their effectiveness. Using these techniquesplant-derived bioactive compounds can be effectively delivered at desired rate either individually or as co-adjuvants to the available pesticides for pest management in organic and small scale farming system. Although, an efforts have already been started in research and the design of better carriers to improve efficacy of rational pesticide or preservatives; the challenges such as suitable processing operations and facilities to large scale application of botanicals at field level are still needed. The development of nanopesticides "involve either plant derived bioactive molecules or newer synthetic analogue with useful pesticidal properties" may become a key element for pest control in sustainable agriculture in the future.

Advancement in semiochemical-based invention: Push-pull strategies: The idea of manipulating natural enemy behaviors to manage economically important crop pests at field level has recently been introduced under the push-pull concept. Certainly, advancement in semiochemical based invention in pest management could play an important role in organic farming, small scale agri-industires, and would reduce the need of synthetic pesticide in field crop protection. Although, the push-pull strategies are successfully introduced in some part of the world, more research is needed on how to best achieve this concept for sustainable pest management.

CONCLUSION: In conclusion based on the foregoing, plant-derived products have significant potential in pest management and crop protection. The diversified use of plant-derived products and their active formulation in the pest management could have both economic and ecological benefits. Therefore, future research work should be directed towards the practical application of recently discovered bioactive compounds i.e. lab to field trial, to overcome new regulatory rules, and to make an effective formulation in light of synergistic action and cost efficiency. Hence, there is a strict need of collaborative research between research institutions and industries to develop an effective plant-derived pesticides having rapid toxicity, long life span, less /no toxic effect on consumer health, and environment with worldwide availability and acceptability.

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