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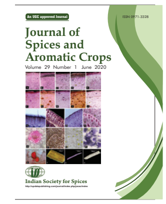

Biorational strategies for the management of insect pests of spice crops

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Abstract

Pest control strategies based on relatively non-toxic procedures that preserve the health of the ecosystem and minimize negative effects on beneficial organisms, and utilize microbial pathogens and their products, plant natural products, semiochemicals, biotechnological strategies and reduced-risk pesticides can be termed as 'biorational strategies'. This review consolidates the information available on the use of biorational strategies for the management of insect pests of spice crops such as *Piper nigrum* (black pepper), *Elettaria cardamomum* (cardamom), *Zingiber officinale* (ginger), *Curcuma longa* (turmeric), *Coriandrum sativum (*coriander), *Cuminum cyminum* (cumin) and *Foeniculum vulgare* (fennel). The review also identifies the current gaps in knowledge and the opportunities and challenges in using biorational strategies for the production of clean spices, reflecting the global concern over pesticide misuse.

Keywords: biorational management, insect pests, spices

Introduction

The term 'biorational' was first used by Djerassi *et al*. (1974) with respect to insect pest management using pheromones, insect hormones and hormone antagonists whose properties include specificity, lethality at low concentrations and low toxicity to non-target organisms. Plimmer (1985) introduced a process-oriented definition of 'biorational' and mentioned that 'biorational' is the exploitation of knowledge on plant or animal biochemistry to synthesize molecules that act at a particular site or block, a key step in a biochemical process. Ware (1989) included derivatives of biological origin such as bacteria, viruses, fungi and protozoa and chemical analogues of natural biochemical compounds such as pheromones and insect growth regulators that resemble chemicals of insect and plant origin as 'biorational'. Reddy (1996) mentioned that the term 'biorational' is derived from the two words 'biological' and 'rational', referring

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to pesticides of natural origin that have limited or no adverse effects on the environment or beneficial organisms. Reduced-risk pesticides that augment the effectiveness of IPM and have low effects on human health, non-target organisms and environment are also sometimes categorized as 'biorationals' (Uri 1998). Thus, pest management strategies involving the use of relatively non-toxic and selective procedures that preserve ecological health and minimize negative effects on beneficial insects, and utilize microbial pathogens and their products, plant natural products, semiochemicals, biotechnological strategies and reduced-risk pesticides could be termed 'biorational strategies'. Rosell *et al*. (2008), Horowitz *et al*. (2009) and Gogi *et al*. (2015) have overviewed the general concepts of biorational approaches to pest management. Khater (2012) has reviewed the chemical composition, mode of action, safety, and production of major groups of biorational insecticides. This review consolidates the information available on the use of biorational strategies for the management of insect pests of spice crops like *Piper nigrum* (black pepper) (Piperaceae), *Elettaria cardamomum* (cardamom), *Zingiber officinale* (ginger), *Curcuma longa* (turmeric) (Zingiberaceae), *Coriandrum sativum* (coriander), *Cuminum cyminum* (cumin) and *Foeniculum vulgare* (fennel) (Apiaceae) using microbial agents, natural products, semiochemicals, biotechnological approaches and reduced-risk insecticides. The review also identifies current gaps and opportunities and challenges in using biorational strategies for the production of clean spices, reflecting the global concern over pesticide misuse.

Exploitation of microbial agents

Microbial agents include viruses, bacteria, fungi, protozoans and nematodes and their products that are toxic to insects. Microbial pathogens generally enter through the integument or gut of the insect and multiply producing toxins resulting in pathogenesis and death of the host. Some of the recent reviews on the potential of microbial biopesticides and the availability of active substances that can be used in pest management include that of Koul (2011), Ramanujam *et al*. (2014), Ruiu (2018) and Kumar *et al*. (2019).

Viruses

Reports on viruses infecting spice crop pests are limited. Earlier, Rabindra *et al*. (1990) reported a nucleopolyhedrovirus (NPV) infecting *Eupterote cardamomi* (hairy caterpillar) (Eupterotidae) on cardamom from Western Ghats (Tamil Nadu). Recently, Senthil Kumar *et al*. (2015a) reported an epizootic caused by an NPV in field populations of *Spilarctia obliqua* (Arctiidae), a polyphagous insect pest that also infests turmeric and ginger sporadically, from Kerala. The isolate was tetrahedral in shape and transmission electron microscopy studies confirmed the SpobNPV isolate as multiple nucleocapsid NPV (MNPV). Based on morphological and molecular data, the virus was identified as a new species of MNPV belonging to the genus *Alphabaculovirus* (Baculoviridae). The isolate was highly virulent against third instar larva of *S. obliqua* as evidenced by a lower LC_{50} value of 4.37×10^3 OBs ml^{-1} The authors concluded that SpobNPV merits further field evaluation as a potential biological control agent of *S. obliqua*. An isolate of *S. obliqua* NPV (SpobNPV-Ambalavayal) was also found to be cross infective to *Olepa (Pericallia) ricini* (Erebidae) on cardamom and other horticultural crops (Senthil Kumar *et al*. 2020a).

Bacteria

Records of bacteria infecting spice crop pests are limited to *Enterobacter cloacae* (Enterobacterales) and *Pseudomonas* sp. (Pseudomonadales) isolated from larvae of *Udaspes folus* (leaf folder) (Hesperiidae) infesting ginger and turmeric, from Kasaragod (Kerala) (CPCRI 1974). The bacterial pathogen *Bacillus cereus* (*Bacillaceae*) has also been recorded on *Lasioderma serricorne* (cigarette beetle) (Ptinidae), a major storage pest (Thompson & Fletcher 1972).

Commercial products such as spinosad, abamectin, Bioasp and Dipel formulated from bacteria and *Streptomyces* sp. have been evaluated against insect pests of cardamom, ginger and turmeric. Spinosad is a natural fermentation product of *Saccharopolyspora spinosa* (Actinomycetales); abamectin is based on natural fermentation of *Streptomyces avermitilis* (Actinomycetales). Bioasp and Dipel are based on naturally occurring *Bacillus thuringiensis* subsp. *kurstaki* (*Bacillaceae*).

Trials conducted with insecticides and natural products against *Sciothrips cardamomi* (cardamom thrips) (Thripidae) at Appangala (Karnataka), indicated that spinosad 0.0135% was on par with the insecticides in reducing the damage on capsules when sprayed during February-March, March-April, April-May and September and October, along with cultural operations such as removal of dried leaf sheaths before undertaking the spraying operations; abamectin 0.0012% was on par with spinosad 0.0135% (Jacob *et al*. 2015a). Recent trials conducted at Mudigere, Sakleshpur (Karnataka), Pampadumpara and Myladumpara (Kerala) indicated that spinosad 0.0135% was as effective as insecticides in reducing the damage on the capsules at Sakleshpur and Pampadumpara. At Mudigere, though fipronil 0.005% was the best treatment, spinosad 0.0135% was also effective in reducing the pest infestation significantly (ICAR-AICRPS 2019).

Two commercial products of *B. thuringiensis* namely, Bioasp and Dipel were evaluated in the field at Peruvannamuzhi (Kerala) for the management of *Conogethes punctiferalis* (shoot borer) (Crambidae) on ginger and turmeric. All the treatments were effective in reducing the damage caused by the pest compared to control; however, Dipel 0.3% (five sprays at 21-day intervals during July-October) was the most effective treatment in both the crops (Devasahayam 2000 & 2002). Trials conducted against *C. punctiferalis* on ginger at Peruvannamuzhi indicated that spinosad 0.0225% was on par with insecticide treatments, when sprayed at 15-day intervals during the second fortnight of July to the first fortnight of November (Senthil Kumar *et al*. 2017). In turmeric, though the insecticide treatments were significantly superior to spinosad 0.0225%, the yield of fresh rhizomes in spinosad-treated plots was on par with the insecticide treatments (Senthil Kumar *et al*. 2019).

Entomopathogenic fungi

Earlier reports of naturally occurring entomopathogenic fungi on spice crops include *Verticillium intertextum* (Hypocreales) (Deshpande *et al*. 1972), *Penicillium fellutanum, Aspergillus parasiticus* (Eurotiales), *Purpureocillium lilacinum (Paecilomyces lilacinus), Fusarium oxysporum* (Hypocreales), and *V. lecanii* on *Pentalonia nigronervosa* (banana aphid) (Aphididiae) on cardamom from Kodagu (Karnataka) (Mathew *et al*. 1999); *Aschersonia placenta* (Hypocreales) (Muraleedharan 1985) and *Verticillium* sp. (Josephrajkumar & Murugan 2001) on *Kanakarajiella cardamomi* (cardamom whitefly) (Aleyrodidae); *Metarhizium anisopliae* (Hypocreales) infecting grubs, and *Beauveria bassiana* (Hypocreales) infecting adults of *Basilepta fulvicorne* (root grub) (Chrysomelidae) on cardamom from Idukki (Kerala); and *M. anisopliae* on *Holotrichia* spp. (white grubs) (Melolonthidae) on ginger from Sikkim (North East India) (Varadasan *et al*. 2000).

Metarhizium anisopliae and *B. bassiana* were highly pathogenic to *B. fulvicorne* in laboratory bioassays and also in the field indicating their potential as biocontrol agents against *B. fulvicorne* on cardamom (Varadarasan *et al*. 1993 & 1996). Mechanical collection and destruction of adults during their peak periods of occurrence and application of *M. anisopliae* mixed with fine cow dung has been recommended as a strategy for the management of *Holotrichia* spp. on ginger (Varadarasan *et al*. 2000). Laboratory bioassays with four entomopathogenic fungi from spice crop ecosystems against *P. nigronervosa* infesting cardamom indicated that *B. bassiana* and *Pochonia chlamydosporia* (*V. chlamydosporium*) were promising (Mathew *et al*. 1998).

Intensive surveys to document naturally occurring entomopathogens on spice crop pests were undertaken by ICAR-IISR, Kozhikode, during 2012-19 to identify promising isolates that could form the basis for development of suitable microbial pesticides. Among the newly recorded entomopathogenic fungi, the most promising was *Lecanicillium psalliotae* (Hypocreales) isolated from cadavers of *S. cardamomi*. Bioassays with purified conidial suspension resulted in up to 62.9% mortality at a dose of 1×10^7 conidia ml^{-1} (Senthil Kumar *et al*. 2015b). The fungus also exhibited multifarious plant growth promoting traits. Application of the fungus to cardamom seedlings significantly increased shoot and root length, shoot and root biomass, number of secondary roots and leaves and leaf chlorophyll content, suggesting its potential for exploitation in sustainable agriculture (Senthil Kumar *et al*. 2018).

Beauveria bassiana was isolated from *Sinoxylon anale* (auger beetle) (Bostrichidae) on *Pimenta dioica* (allspice) and *Syzygium aromaticum* (clove) (Myrtaceae) trees from Kozhikode (Kerala). Bioassays with the isolate indicated that the fungus was virulent against adult beetles as evidenced by the LC_{50} (3.6×10^6 conidia ml^{-1}) and ST_{50} values (6.8 days at a dose of 1×10^7 conidia ml^{-1} and 5.8 days at a dose of 1×10^8 conidia ml^{-1}, respectively). The fungus holds promise to be developed as a mycoinsecticide (Senthil Kumar *et al*. 2016).

Apart from these two potential entomopathogens, hyphomycetes fungi belonging to *Isaria* spp., *Lecanicillium* spp., *Beauveria* spp., *Paecilomyces* sp. and *Metarhizium* sp. infecting various spice crop pests (*Lepidosaphes* sp., *Marsipococcus* sp., *Protopulvinaria* sp., *Aulacaspis* sp., *Aspidiotus destructor, Marsipococcus marsupialis* (Diaspididae), *Busoniomimus majunathi* (Cicadellidae), *Sinoxylon* spp. (Bostrichidae), *C. punctiferalis* and *Zeuzera* sp. (Cossidae) were recorded (Senthil Kumar *et al*. 2020a).

Devasahayam *et al*. (2005) evaluated the pathogenicity of *B. bassiana, B. brongniartii, M. anisopliae* and *P. chlamydosporia* (obtained from spice crop ecosystems) against adult *Lanka ramakrishnai* (pollu beetle) (Chrysomelidae) in laboratory bioassays; however, none of the isolates were promising and the highest mortality (30%) was observed in beetles treated with *B. brongniartii*. Four isolates of microbial pathogens namely, *M. anisopliae, M. rileyi, L. lecanii* and *Aspergillus* sp. from other sources and four commercial products of *Paecilomyces* sp., *B. bassiana*, *L. lecanii*, and *M. anisopliae* were evaluated in laboratory bioassays against *Planococcus* sp. (root mealybug) (Pseudococcidae); however, none of the microbial pathogens or their products were effective (Devasahayam *et al*. 2006).

Laboratory bioassays with different concentrations of *B. bassiana* against *Hyadaphis coriandri* (coriander aphid) (Aphididae) indicated that the highest concentration (1×10^{10} conidia ml^{-1}) caused maximum cumulative mortality 7 days after treatment (Selvaraj *et al*. 2012). In fennel, evaluation of entomopathogenic fungi and botanicals for the control of *H. coriandri* indicated that highest population reduction after first spray was observed in *M. anisopliae* and *B. bassiana* treatments after second spray; highest yield was recorded in *M. anisopliae* application. Application of the entomopathogens in combination with neem oil did not exhibit synergistic effect (Kant *et al*. 2013a).

Protozoa

Protozoan parasites generally affect feeding and host reproduction rather than killing the pest outrightly, that result in subtle regulation of insect populations. Hence, they probably function more as classical biological control agents than as biological insecticides. However, a few species can be manipulated in some manner to increase their activity against insect hosts. The protozoan parasites recorded on pests of stored products include *Adelina tribolii* (Eucoccidiorida), *Farinocystis tribolii* (Neogregarinorida), *Gregarina cuneata* (Conoidasida), *Nosema oryzaephili, N. whitei* (Nosematidae) and *Lymphotropha tribolii* (Schizocystidae) on *Tribolium castaneum* (Ashford 1965; Burges *et al*. 1971; Burges & Weiser 1973); *Mattesia trogo-*

dermae (Neogregarinorida), *Adelina* sp. and *Pyxinia* sp. (Actinocephalidae) on *Trogoderma granarium* (Hall *et al*. 1971); and *M. oryzaephili*, *N. oryzaephili* and *N. whitei* on *Oryzaephilus surinamensis* (Burges *et al*. 1971). Henry (1990) has reviewed the potential of utilizing protozoan parasites for the management of forest tree, crop and storage pests such as *Trogoderma* sp.

Entomopathogenic nematodes

Eight species of entomopathogenic nematodes (EPNs) (three species belonging to *Steinernema* sp. (Steinernematidae), one to *Heterorhabditis* sp. (Heterorhabditidae) and four to *Oscheius* sp. (Rhabditidae) were documented from rhizosphere of ginger among which *S. ramanai* and *O. gingeri* were described as new species (Pervez *et al*. 2013; 2014a & b). The symbiotic bacterium associated with *Heterorhabditis* sp. was identified as *Photorhabdus luminescens* (Enterobacterales) based on morphological, biochemical and molecular studies (Pervez *et al*. 2015).

The infectivity of the eight native EPNs was tested against larvae and pupae of *C. punctiferalis*. Among them, *Heterorhabditis* sp. (IISR 01), *Steinernema* sp. (IISR 02) and *Oscheius* sp. (IISR 07 and 08) were the most virulent against larvae; *Oscheius* sp. (IISR 07) was the most virulent against pupae (Pervez *et al*. 2012). A study on the pathogenicity of four promising EPNs, *Heterorhabditis* sp. (IISR-EPN 01), *Steinernema* sp. (IISR-EPN 02), *Oscheius* sp. (IISR-EPN 08) and *O. gingeri* against *C. punctiferalis* larva, by dose response and time exposure assay and determination of median lethal dose (LD_{50}) and lethal time (LT_{50}) indicated that *Steinernema* sp. (IISR-EPN 02) and *O. gingeri* were more promising (Pervez *et al*. 2014c). These four promising isolates were evaluated against *C. punctiferalis* infesting ginger and turmeric under field conditions at Peruvannamuzhi. Among them, *O. gingeri* (IISR-EPN 07) and *Steinernema* sp. (IISR-EPN 02) treated plants showed minimum shoot damage in ginger and turmeric, respectively, which was on par with the insecticide (malathion 0.1%) treatment (ICAR-IISR 2016). A new low-cost artificial media for the mass production of infective juveniles of promising EPNs was developed. Malathion and chlorpyriphos were compatible with the four promising EPNs (IISR 2014).

In cardamom, *Heterorhabditis indica* (ICRI EPN-18) was recorded to infest grubs of *B. fulvicornis* in Idukki. Methods were standardized to culture infective juveniles in *Galleria* larvae and application of *Galleria* cadavers at the plant base resulted in significant control of the pest (Varadarasan *et al*. 2011). The infectivity of eight native EPNs from rhizosphere of ginger was tested against *B. fulvicorne,* among which *Heterorhabditis* sp. (IISR-EPN 01) and *O. gingeri* (IISR-EPN 07) were promising (Pervez *et al*. 2016). The infectivity of these eight native EPNs was also tested against larvae of *Euproctis* sp. (hairy caterpillar) (Erebidae) infesting ginger and *Lema* sp. (leaf feeder) (Chrysomelidae) infesting turmeric. All isolates except *Oscheius* sp. (IISR-08), were highly virulent to larvae of *Euproctis* sp. (Pervez *et al*. 2012). *Steinernema* sp. (IISR-EPN 02) and *O. gingeri* (IISR-EPN 07) were more virulent to larvae of *Lema* sp. (Pervez *et al*. 2014d).

Use of plant natural products

Plant-derived natural products or botanicals are part of defensive chemistry of plants that help them to defend against herbivores and pathogens. Plant products act as repellents, antifeedants and growth regulators, and also cause mortality in insect pests. Godfrey (1995) extensively reviewed the agricultural applications of natural products and synthetic compounds, their isolation, structure, biological activity and toxicology. Isman (2006) reviewed the use of botanical insecticides, deterrents, and repellents in agriculture and Gahukar (2011) reviewed the use of natural products in spices and condiment crops.

Several plant natural products and commercial neem products have been evaluated against major insect pests of spice crops. Among the plant extracts evaluated in laboratory bioassays for their antifeedant activity against *L. ramakrishnai* infesting black pepper, root bark extracts of *Uvaria narum* and *U. hookeri* (Annonaceae) (Babu *et al*. 1996), leaf extracts of *Strychnos nux-vomica* (Loganiaceae) and *Chromolaena odorata* (Asteraceae), and seed extracts of *Annona squamosa* (Annonaceae) (Devasahayam & Leela 1997) and *Capsicum* sp. (Solanaceae) (Devasahayam *et al*. 1998) possessed significant antifeedant activity. Among the commercial neem products evaluated, Neemark (azadirachtin 300 ppm), Neemazal-T/S (azadirachtin 10,000 ppm) and Neemgold (azadirachtin 300 ppm) were promising (Devasahayam & Anandaraj 1997). Laboratory bioassays of three compounds namely, crotepoxide, pipoxide and pipoxidechlorhydrin isolated from *P. attenuatum*, a wild *Piper* sp. resistant to *L. ramakrishnai*, indicated that antifeedant activity was significantly higher in crotepoxide and pipoxidechlorhydrin in no choice tests. Various combinations of the compounds did not enhance the antifeedant activity significantly (Devasahayam *et al*. 1997). The persistence of antifeedant activity of *Capsicum* extract (0.05% to 1%) studied against *L. ramakrishnai* in greenhouse bioassays indicated that *Capsicum* extract (containing 1% capsaicin) caused >90% feeding deterrence up to 14 days, after treatment. However, *Capsicum* extract 1% was not effective in reducing the damage caused by the pest to black pepper berries in the field when sprayed at fortnightly intervals during July to October (Devasahayam *et al*. 1997). Field trials conducted at Thiruvambady (Kerala) indicated that shade regulation in the plantation after receipt of pre-monsoon rains and spraying one round of quinalphos 0.05% (July) + three rounds of Neemgold 0.6% (azadirachtin 300 ppm) (August-October) or four rounds of Neemgold 0.6% (azadirachtin 300 ppm) (July-October) was effective and on par with each other for the management of *L. ramakrishnai* (Devasahayam *et al*. 2005).

Trials conducted in the greenhouse at Kozhikode indicated that neem oil 0.3%, Neemgold 0.6% (azadirachtin 300 ppm) and fish oil rosin 3% were promising in controlling *Lepidosaphes piperis* (mussel scale) and *Aspidiotus destructor* (coconut scale) infestations on black pepper and were safer to coccinellid predators indicating their potential use in IPM schedules (Devasahayam *et al*. 1998). Various neem and organic products were evaluated at Mudigere (Karnataka) against *L. piperis*, among which neem oil @ 5 ml L^{-1} and fish oil @ 3 g L^{-1} were promising and were as effective as insecticides (Naik *et al*. 2009). Field experiments conducted at Chintapalle (Andhra Pradesh), to evaluate the efficacy of various leaf extracts (5%) on *L. piperis* revealed that extracts of *Cleome gynandra* (Cleomaceae) and *Azadirachta indica* (Meliaceae) were more effective (Sreekanth 2013).

Alcoholic and water extracts of various plant species, neem-based products and other organic products were evaluated against *Planococcus* sp. (root mealybug) infesting black pepper in laboratory bioassays. Among the various extracts, alcoholic extracts of *A. indica* 3% and *Vitex negundo* 3% (*Lamiaceae*), tobacco extract 3%, custard apple seed extract 2% and agro-spray oil 3% were promising, resulting in over 75% reduction in pest population, 30 days after treatment (Devasahayam *et al*. 2006). Trials conducted in the field at Peruvannmuzhi indicated that an integrated strategy involving, planting root mealy bug-free rooted cuttings, removal of weeds in interspaces of black pepper vines during summer and drenching tobacco extract 3% or custard apple seed extract 2% was effective for the management of the pest during early stages of infestation (Devasahayam *et al*. 2006).

Various neem-based products such as neem cake (500 g $plant^{-1}$), neem seed kernel extract (NSKE) 4%, neem oil 0.03%, and commercial neem products such as Neemgold 0.03% (azadirachtin 300 ppm) and Eco-Neem+ 0.03% (azadirachtin 10,000 ppm), were evaluated at Mudigere (Karnataka) along with monocrotophos 0.045% and phosalone 0.07% against *S. cardamomi*; however, none of the neem products were effective (Naik *et al*. 2006). At Pampadumpara (Kerala), fish oil insecticidal soap (Na-based) 2.5% + tobacco extract 2.5%

significantly reduced the damage caused by the pest, though it was not on par with quinalphos 0.05% (Josephrajkumar *et al*. 2002). The bioefficacy of commercial neem formulations such as Nimbicidine (azadirachtin 300 ppm and 1500 ppm), Neemazal (azadirachtin 10,000 ppm and 50,000 ppm) and TNAU neem oil (azadirachtin 300 ppm) was compared with monocrotophos 0.072% against *S. cardamomi* at Lower Pulneys (Tamil Nadu). The trials indicated that the reduction in damage on the capsules was significantly higher in monocrotophos 0.072% treated plots followed by Neemazal (azadirachtin 50,000 ppm) and TNAU neem oil (azadirachtin 300 ppm) (Rajabaskar & Regupathy 2013). Later trials conducted with TNAU neem oil (azadirachtin 300 ppm), diafenthiuron 0.06% and profenofos 0.05% in different IPM modules indicated that sequential application of TNAU neem oil–diafenthiuron–diafenthiuron–profenofos–profenofos at 21-day intervals was the most effective schedule (Rajabaskar & Regupathy 2013). Trials conducted at Gudalur and Bodimettu (Tamil Nadu) indicated that the neem oil formulations, TNAU neem oil (acetic acid) 3% and TNAU neem oil (citric acid) 3%, were effective against the pest after three consecutive sprays at 15-day intervals. Neem oil 3% and the commercial neem product Vijay Neem 0.2% (azadirachtin 300 ppm) were also effective in controlling the pest. Organoleptic tests conducted on cardamom capsules sprayed with neem products revealed no significant difference in taste, aroma, and overall acceptability (Stanley *et al*. 2014).

Neem-based products such as neem cake (500 g $plant^{-1}$), NSKE 4%, neem oil 0.03%, and commercial neem products such as Neemgold 0.03% (azadirachtin 300 ppm) and Eco-Neem+ 0.03% (azadirachtin 10,000 ppm), were evaluated at Mudigere along with monocrotophos 0.045% and phosalone 0.07% against *C. punctiferalis*; however, none of the neem products were effective (Naik *et al*. 2006). At Lower Pulneys, trials with commercial neem formulations such as Nimbicidine (azadirachtin 300 ppm and 1500 ppm), Neemazal (azadirachtin 10,000 ppm and 50,000 ppm) and TNAU neem oil (azadirachtin 300 ppm) and monocrotophos 0.072% against *C. punctiferalis* indicated that the reduction in damage on the capsules was significantly higher in monocrotophos 0.072% treated plot followed by Neemazal (azadirachtin 50,000 ppm and TNAU neem oil (azadirachtin 300 ppm) (Rajabaskar & Regupathy 2013). Later trials conducted with TNAU neem oil (azadirachtin 300 ppm), diafenthiuron 0.06% and profenofos 0.05% in different IPM modules indicated that sequential application of TNAU neem oil–diafenthiuron–diafenthiuron profenofos–profenofos at 21-day intervals was the most effective treatment (Rajabaskar & Regupathy 2013).

Spraying neem oil 0.5% + Triton X-100 0.5% or Sandovit 0.5%, 2–3 times at fortnightly intervals was effective against nymphs of *K. cardamomi* on cardamom (Gopakumar & Kumaresan 1991). A chitin-based bio-pesticide (Eco-1) was also found to be effective against nymphs and adults of the pest (Ali *et al*. 2014). Laboratory bioassays of plant extracts and commercial neem products indicated that seed extract of *Annona squamosa* (Annonaceae), leaf extracts of *Lawsonia inermis* (Lythraceae) and *Leucas aspera* (Lamiaceae), rhizome extract of *Acorus calamus* (Acoraceae) and the commercial neem product Bioneem (azadirachtin 300 ppm) significantly affected the settling and colonization behaviour and multiplication of *P. nigronervosa* on cardamom. Trials laid out in the field at Kodagu (Karnataka) indicated that Bioneem (1.6%) (azadirachtin 300 ppm) and extracts of *A. squamosa* and *A. calamus* (5% each) were promising for the management of the aphid (Venugopal 1999).

Evaluation of neem oil 1% and the commercial neem product Nimbicidine 1% (azadirachtin 300 ppm) in the field at Peruvannamuzhi for the management of *C. punctiferalis* on ginger and turmeric indicated that the results were not consistent (Devasahayam *et al*. 2005). In ginger, mulching with mahaneem (*Melia dubia*) (Meliaceae) leaves (Lalnuntluanga & Singh 2008) or spraying quinalphos 0.05% + commercial neem product Ozoneem (azadirachtin

1500 ppm) (3 ml L^{-1}) (Mhonchumo *et al*. 2010) were suggested for the management of the pest at Nagaland. Dried leaves of *Chromolaena odorata* (Asteraceae), *Glycosmis pentaphylla* (Rutaceae), *Melia composita* (Meliaceae) and *S. nux-vomica* (Loganiaceae) were evaluated as storage materials for the management of *Aspidiella hartii* (rhizome scale) (Diaspididae) on ginger and turmeric at Kozhikode. Among the various materials, storage in dried leaves of *S. nux-vomina* and saw dust in 1:1 proportion was the most effective treatment after dipping the rhizomes in quinalphos 0.075% (Devasahayam *et al*. 2005).

The efficacy of neem products (neem oil, neem leaf extract and NSKE), insecticides and mixtures of neem products and insecticides was evaluated against *Hyadaphis coriandari* (coriander aphid) (Aphididae) at Tikamgarh (Madhya Pradesh); the incidence of the pest was the lowest with highest yield in the treatment with neem oil 1% (Gupta & Pathak 2009). At Kota (Rajasthan), among the neem products (commercial formulation of azadirachtin 1500 ppm, neem oil and NSKE) evaluated, the commercial formulation of azadirachtin 1500 ppm (5 ml L^{-1}) was the most effective treatment for the control of the pest as well as for increasing the seed yield (Chaudhary *et al*. 2015). Field experiments conducted at Ajmer (Rajasthan) for the management of *Systole albipennis* (seed wasp) (Eurytomidae) of coriander indicated application of all plant products (at 10-day intervals during flowering stage) showed significant reduction in seed damage at harvest, and increase in seed yield. Neem products were found superior over karanj (*Pongamia* sp.) (Fabaceae) products both in terms of seed infestation and seed yield at harvest. Among the neem formulations, neem oil 2% resulted in lowest seed damage and highest yield that was on par with NSKE 5% and neem oil 1%. Among the karanj products, karanj seed powder extract (KSPE) 5% was the most effective and was on par with karanj oil 2% and superior over other karanj formulations (Kant *et al*. 2013b).

In cumin, emulsified neem oil 2% was effective for the management of *Myzus persicae* (Aphididae) (Vir & Yadav 2007). At Jobner (Rajasthan), minimum incidence of aphid and maximum seed yield were recorded in cumin with soil application of vermicompost @ 2.5 t ha^{-1} + seed treatment with NSKE 5% + spray of NSKE 5% (Shekhawat *et al*. 2016). Application of sulphur compound of karanj extract 1%, gave maximum control of the pest and yield in fennel at Ajmer (Rajasthan) (Kant *et al*. 2013a).

Evaluation of dried leaf powders for protecting dry ginger rhizomes from infestation by *L. serricorne* indicated that storage of dry ginger in PET containers with leaf powder of *Glycosmis cochinsinensis* (Rutaceae) or *Clerodendron infortunatum* (Lamiaceae) or *A. indica* was promising in preventing the pest infestation (IISR 2003).

Semiochemical-based approaches

Semiochemicals are organic compounds that are utilized by insects to convey specific chemical messages that modify their physiology or behaviour. Semiochemicals are divided into two broad groups namely, pheromones that mediate interactions among individuals of the same species and allelochemicals that mediate interactions among individuals of different species. Kong *et al.* (2019) recently reviewed plant-organism interactions mediated by allelochemicals and signaling chemicals and their potential implications and applications in sustainable agriculture.

Pheromones

The occurrence of sex pheromones in *C. sahyadriensis* infesting cardamom has been demonstrated, and the calling behavior and attractiveness to the crude extract of females and synthetic blends investigated in the laboratory. The dose, age and ratio of the compounds had significant influence on the attraction of males to the females. A blend of E-10-hexadecenal and Z-10-hexadecenal at 90:10 ratio was the most attractive that was on par with 80:20 ratio. Trials conducted in the field at Mudigere, Sakleshpur and Lower Pulneys indicated the potential of using pheromones for management of the pest (Chakravarthy & Thyagaraj 1997, 1998; Rajbaskar & Regupathy 2012).

Sex pheromones have been identified in *L. serricorne* and *Stegobium paniceum* (drug store beetle) (Pitinidae) (Kuwahara *et al*. 1975; Chuman 1984) and aggregation pheromones in *Araecerus fasciculatus* (coffee bean weevil) (Anthribidae) (Singh 1993) that are major storage pests in many spices. These pheromones have been used for monitoring populations of storage pests in stores other than spices.

Allelochemicals

Planting of aromatic companion crops that may interfere with host plant location, feeding and oviposition, resulting in decreased pest abundance is an ecological engineering strategy to manage pests in many crops. Plants of *Eryngeum foetidum* (saw-toothed coriander) (Apiaceae) and *Kaempferia galanga* (galangal) (Zingiberaceae) were raised along with ginger in the field at Kozhikode to study the repellent action of these plants against oviposition by *C. punctiferalis*; however, these plants were not effective in preventing oviposition by the pest. Planting of *Curcuma zedoaria* (Zingiberaceae) (a related species resistant to *C. punctiferalis*) along with ginger in the field at Kozhikode was also not effective in preventing the pest infestation on ginger (Devasahayam *et al*. 2005).

Biotechnological manipulations

Major technological advances in chemistry, biochemistry, molecular genetics, physiology and behaviour in recent years have resulted in new products for insect pest management that are less hazardous to humans and the environment. These mainly include genetically engineered plants exhibiting resistance to pests, natural enemies with high tolerance to pesticides, improved formulations and delivery methods for biopesticides, and use of novel organisms.

Wolbachia *sp.*

Recent advances in biotechnology as a strategy for pest management includes the use of the endosymbiont bacterium, *Wolbachia* spp. that are involved in manipulation of the reproductive physiology of the host. The occurrence of *Wolbachia* sp. in *S. cardamomi*, was reported recently (Jacob *et al*. 2015b). Both male and female thrips harboured the same strain of *Wolbachia* sp. which belonged to subgroup *Con* under supergroup *B*. The incidence of *Wolbachia* sp. infection varied from 15.0% to 87.8% in various cardamom growing districts. DNA sequencing and phylogenetic analysis revealed that all the *Wolbachia* isolates clustered together indicating that all thrips were infected by the same *Wolbachia* strain (Jacob *et al*. 2015b). The role of *Wolbachia* sp. on the reproductive physiology of *S. cardamomi* was also studied. A method was standardized for removal of *Wolbachia* sp. from thrips by treating the insects with tetracycline-treated cardamom leaf bits and also by feeding with a mixture of tetracycline and sucrose. Egg hatchability in laboratory-bred F1 populations of thrips in which *Wolbachia* sp. was removed was reduced to 15.3%, compared to 53.7% in control. In F2 generation, the survivability of thrips from egg to adult was 36.6% compared to 53.7% in control (Senthil Kumar *et al*. 2020).

Protease inhibitors

Protease inhibitors are plant defence proteins, which can cause mortality in a wide range of insects. Expression of protease inhibitors can be induced in transgenic plants for protection against pest attack. The midgut protease profile of the gut lumen of *C. sahyadriensis* was studied and the conditions for optimal protein hydrolysis were determined to identify potential targets for protease inhibitors. Trypsin and elastase-like chymotrypsin were the prominent digestive proteases, and age-related modulation of midgut proteases existed for trypsin, chymotrypsin, elastase-like chymotrypsin and leucine aminopeptidase. Serine protease inhibitors such as aprotinin, soybean trypsin inhibitor and phenylmethanesulfonyl fluoride inhibited peptidase activity. Trypsin and elastase-like chymotrypsin were significantly inhibited by aprotinin under *in vitro* conditions. These studies indicated the potential of incorporating protease inhibitors into transgenic plants for pest management (Josephrajkumar *et al*. 2005, 2006, 2007).

Use of reduced-risk pesticides

Reduced-risk pesticides are pesticides that have low impact on human health and toxicity to non-target organisms and lower potential for developing pest resistance, and are thus more compatible with other integrated pest management procedures (Fishel 2019).

In spice crops a few reduced-risk pesticides have been evaluated in ginger and turmeric in recent years. In ginger, evaluation of reduced-risk insecticides along with conventional insecticides at Peruvannamuzhi indicated that spraying chlorantraniliprole 0.01% or flubendiamide 0.02% or cyantraniliprole 0.005% at 15-day intervals during the second fortnight of July to the first fortnight of November was more effective for the management of *C. punctiferalis* (Senthil Kumar *et al*. 2017). In turmeric, spraying chlorantraniliprole 0.01% or lambda-cyhalothrin 0.01% or flubendiamide 0.02% was more effective for the management of the pest (Devasahayam *et al*. 2010; Senthil Kumar *et al*. 2019). In India, chlorantraniliprole and flubendiamide are categorized as green label pesticides and considered as low-risk pesticides (KAU 2011). The U.S. Environmental Protection Agency has classified chlorantraniliprole, cyantraniliprole and lambda-cyhalothrin as reduced-risk pesticides. Flubendamide has been catergorized under category III with low order of acute toxicity (USEPA 2019). Chlorantraniliprole, flubendiamide and cyantraniliprole belong to the diamide class of insecticides which are relatively safe to insect natural enemies and are classified as slightly harmful to harmless as per IOBCs (International Organization for Biological Control) categorization against non-target natural enemies (Singh *et al*. 2016).

Future challenges and opportunities

Though biorational insecticides have emerged as a viable alternative to chemical insecticides for pest control, there are few challenges and opportunities in its widespread adoption especially in spice crops. Most of the spice crops are grown under tropical humid regions, providing ideal conditions for the use of microbial pathogens especially entomopathogenic fungi, for the management of insect pests. However, information on the epizootic potential of various isolates, their sporulation and dispersal in the ecosystem are to be generated. The feasibility of their commercial-scale multiplication on cheap substrates including crop wastes such as coir pith, coffee husk and tea wastes that are commonly available in plantation crop ecosystems also need to be studied. Though entomopathogenic fungi are known to exist primarily as insect parasites, their existence as endophytes, plant disease antagonists and plant growth promoters are increasingly being established. Endophytic establishment of entomopathogenic fungi in host plants to induce systemic resistance is a viable alternative to reduce the number of pesticide applications and also overcome their poor performance in the field due to various abiotic factors.

Plant natural products have been suggested as attractive alternatives to chemical insecticides for pest control because they pose little threat to the environment and human health. Though scientific literature on bioactivity of plant products to insect pests continues to expand, only a few molecules have been commercialized. Due to their fast degradation properties, plant products are generally short-lived necessitating multiple applications to achieve acceptable levels of control and rendering their use economically unfeasible. However, recent studies have reported enhancement in the efficacy of plant products and reduction in degradation under harsh environmental conditions with encapsulation of these substances. Thus, nanotechnology could contribute to the development of increased stability of these active agents and enhanced activity on target pests.

The use of plant products is bound to increase in future with increasing demand for organic food and growing awareness on pesticide misuse. Future research also needs to focus on development and evaluation of stickers and synergists to enhance the effectiveness of plant products in spice cropping systems in high rainfall regions.

Pheromones have been extensively used in insect control for detection and monitoring insect populations, mating disruption and mass trapping in many cropping systems. However, except in the case of *C. sahyadriensis* of cardamom, very little basic and field studies have been conducted on pheromones of insect pests infesting spice crops. Encapsulation of pheromones into nanoparticles as an advanced application method and use of controlled release nano porous materials as a novel carrier delivery method has received increased attention in recent years. These methods reduce the influence of the environment, prolong their duration of activity, and avoid contamination of active ingredients, thus improving their efficacy in the field.

Prospects for use of allelochemical-based crop protection strategies are dependent on understanding the sensory processes involved as to how host plants are identified by phytophagous insects and also the dynamics of plant host-herbivore-natural enemy interactions. Though allelochemicals have received increasing attention in recent years in many cropping systems, unlike other phytochemicals, the collection and identification of allelochemicals and design of new molecules based on their structure is a major challenge for their wide use in insect pest management. Studies on behavioral push-pull approaches using stimulo-deterrent strategies and ecological engineering techniques, is another potential area for research. Push-pull strategies use a combination of behavior-modifying stimuli to manage pest populations. Pests can be repelled away from a resource (push) by deterrent stimuli using volatiles, antifeedants or oviposition deterrents and simultaneously attracted (pull), using attractive stimuli, such as pheromones or trap crops facilitating their elimination. The main advantage of this strategy is that it can be easily incorporated into IPM systems using biorational approaches.

Biotechnology provides ample opportunities for effective and targeted insect-pest control through engineering of biological processes. In spite of successful identification of potential biocontrol agents, inconsistency of strains against specific insect pests under varied environmental conditions is a major issue. Characterization of genes encoding biocontrol properties of a biocontrol agent with respect to mechanism of action, and genetic engineering will help to enable development of new strains and strategies for their improvement and use. Gene silencing via RNA interference (RNAi) is another strategy that holds great promise for insect pest management in future. However, further studies are needed to improve the efficacy of RNAi-based strategies and to assess their associated safety risks. Though biotechnological interventions present significant opportunities for insect pest management in the future, due caution should be exercised while exporting products based on transgenic crops due to the stringent GMO regulations of many spice importing countries.

One of the significant factors affecting biological control of insect pests in most cropping systems is the use of harmful insecticides leading to negative impacts on natural enemies causing pest resurgence and secondary pest outbreaks. Hence there is a need to not only find alternate methods of control but also shift from traditional broad-spectrum chemicals to selective novel groups that have minimal side-effects on natural enemies and the environment. Most of the reduced-risk insecticides are also less toxic to honeybees which are the principal pollinators in crops like cardamom, coriander, cumin and fennel. Thus reduced-risk pesticide groups could be more efficiently incorporated into IPM schedules in spice cropping systems.

Conclusion

There is great demand for insecticides safer to natural enemies, non-target organisms and the environment, for production of clean crop produces including spices, reflecting the global concern over pesticide misuse. Spices being high value, export-oriented produce and mostly consumed in its raw form, it is of paramount importance that they are free of pesticide residues. Moreover, stringent standards set by the importing countries often result in rejection of the produce leading to severe losses to producers and traders. Hence, identification of safer alternatives for the management of spice crop pests is of paramount importance. Biorational insecticides have emerged as a viable alternative form of pest control to meet this demand. It is also important that biorational strategies are integrated with other ecofriendly strategies such as cultural methods, use of resistant lines, biocontrol agents and safer insecticides in a holistic manner to improve crop health and productivity.

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