scientific reports

OPEN

Current biological approaches for management of crucifer pests

Saini Mayanglambam[1,2], Kabrambam Dasanta Singh[1] & Yallappa Rajashekar[1]✉

Cabbage is considered as one of the most commonly found vegetables and it has been cultivated in large areas throughout the year. As it is mostly grown in large areas, higher rate of pest infestation likely to occur, which hinder its total production and consumption. However, continuous use of synthetic pesticides in agricultural pest management often leads to various negative impacts such as development of resistance by the pest, adverse effect on non-target organisms and hazardous effect on environment. These drawbacks led to an alternative approaches for control of crucifer pests that are cost effective, biodegradable, low toxic effect on non-target organisms and eco-friendly. This review brings together all the information of different biological practices for management of crucifer pests and list of botanical insecticides and entomopathogenic organisms that are being reported. This will help in establishing the knowledge of limited studies on pest management using different biological control methods to more challenging research and conveys the importance of pest management system for taking research forward.

Among the vegetables, Crucifers are important winter crop consist of cabbage, cauliflower, mustard, broccoli and radish. Cabbage, *Brassica oleracea* var. *capitata* L. is the main temperate crucifers crop that cultivates widely in different climatic regions around the world. Worldwide, India occupies the second position in the production of cabbage after China. Of the total area of vegetable grown in India, 5% is occupied by cabbage (State of Indian Agriculture, 2015–2016)[1]. Cabbage is considered as one of the most important group of vegetables and it has been cultivated in large areas throughout the years. Since cabbage is more intensively cultivated, it resulted in higher rate of pest infestation, which hinders its total production and consumption[2]. Some of the major pests of crucifers are *Pieris brassicae* L. (Lepidoptera: Pieridae)[3], *Plutella xylostella* L. (Lepidoptera: Plutellidae)[4], *Brevicoryne brassicae* L. (Hemiptera: Aphididae)[5] and *Trichoplusia ni*. Hübner (Lepidoptera: Noctuidae)[6].

Protection of vegetable crops from numerous insect pests primarily depends on the use of synthetic pesticides[122]. However, prolonged and excessive use of synthetic pesticides has led to several side-effects like development of resistance by the pest, adverse effect on non-target organisms and hazardous effects on environment. All these problems bring the sustainability of ecosystem to danger[7]. As the population of resistant pest and detrimental effects on environment rises, it requires constant support to search for an alternative control measures to reduce their spread. One promising way is to incorporate the use of biological sources such as botanical insecticides in pest management system which has resulted less negative impacts on ecosystem[8,9].

Botanicals insecticides are chemical compound derived from plants that has the properties to kill, inhibit and repel the target pest[9,10]. These substances that are being produced naturally can be extracted and used in the formulation of commercial insecticides. Using extracts of plant material like leaves, stem, root, bark and seeds as insecticidal substances for management of crop pest has been practised for two millennia and continue the same in organic farming[11]. Some of the repellent plants can produce toxic substances and play an important role to protect against insects and pathogens[12]. This paper reviews the management of crucifer pests using current pest management strategies such as biological control practices, botanical insecticides and entomopathogenic microorganisms.

Overview of pests of cabbage

Many insect pests hamper cabbage cultivation and the most destructive pest is *P. xylostella* which can reduce the yield of cabbage by 52% in India, if huge number of pests appeared in the field[13]. Other major insect pests on cabbage and cruciferous crops are *Crocidoloma pavonana* Fabricius (Lepidoptera:Pyralidae)[14],, *P. brassicae*[15], *Spodoptera litura* Fabricius (Lepidoptera: Noctuidae) and *T. ni*[16].They infested the crucifers mostly in dry seasons and larvae start infesting the crops from their young stage and attacked the head at maturity[17]. *C. pavonana* fed on

[1]Insect Bioresource Laboratory, Animal Bioresources Programme, Institute of Bioresources and Sustainable Development, Department of Biotechnology, Govt. of India, Takyelpat, Imphal, Manipur 795001, India. [2]School of Biotechnology, Kalinga Institute of Industrial Technology, Deemed To Be University, Bhubaneswar, Odisha, India. ✉email: rajacftri@yahoo.co.in

the under surface of the leaves by leaving the veins causing skeletonization of leaves. *P. xylostella* larvae initially fed on the leaves causing small holes and entirely damaged the cabbage. *T. ni* defoliates the leaves by burrowing through 3–6 layers of cabbage. *H. undalis* usually damage on outer surface of cabbage and continue feeding into the terminal bud damaging the entire cabbage plant[17,18].

Current biological control of Crucifer pests

Habitat management. Habitat manipulation or management is one of the most sustainable ways of managing pests by promoting their natural enemie[19].It involves different approaches like intercropping, push pull method and insectary plant. Intercropping can be achieved by planting secondary or tertiary crop near the main crop or by incorporating non crop plants for certain specific functions for example, providing nectar and pollen for predator and parasitoids[20]. There are many reports on effective intercropping control method such as plantation of tomato inside the cabbage plot reduced the population of many adult butterflies of *P. xylostella* and *P. rapae* as compared to the monoculture cabbage plot. It is likely due to confusing visual cues and volatiles receive from tomato which masks the cabbage. However, it was reported that there was inconsistency between the damage index and population of pest[21]. As suggested by Xu et al.[22] decreasing pest population in intercropping plots in turn increase the pest damage index in monoculture plot. The cause of this might be due to the variation in nitrate concentration of outer layers of cabbage leaves which is higher in intercropped plot than monoculture plot. Another study concluded that, *Ocimum gratissimum* L. can reduce the population of three cabbage pest [*H. undalis, P. xylostella* and *Spodoptera littoralis* Boisd. (Lepidoptera: Noctuidae)] when grow in an alternate row with cabbage[23] . In another study, using of onion and tomato as an intercropped plant with cabbage as host plant could be taken as the most reasonable and inexpensive pest management strategy when compared to other methods[21]. With these studies, intercropping of certain plants like tomato, tulsi etc. with cabbage can be used preferably as an alternative for synthetic pesticides in management of cabbage pests.

Regulating the planting period of crucifers. Regulating planting period of crucifers would be able to control certain insect infestations and can help in reducing the use of synthetic insecticides. Variables in climatic conditions play a significant role in the population of crucifer's pest since they have a short generation time and rapid reproductive rates[24]. It also greatly depends on the temperature which may lead to an increase in infestation by rapid rises of pest population or reducing mortality of pest[25]. Impact on crop performance by planting dates is because of the changed in abiotic and biotic factors. In the cabbage field plot, the pest population started increasing from February and the highest peak occurred in April. Multiplication of pests preferred the hot climatic condition (off-season) but in cold condition (Nov-Feb) very few insects infest the cabbage[26]. According to Tanyi[27] late plantation of cabbage (April) reduce the pest population of cabbage looper larvae, webworm larvae and *P. xylostella* when compared to normal and early plantings. This method is considered a feasible, cost-effective pest management strategy that can be implemented by the farmers. In a study, Viraktamath et al.[28] reported that *P. xylostella* highly damage the leaf of cabbage planted in the first week of January in comparison with those planted in the first week of December, but the head of cabbage were not marketable in both cases. From this study, it concluded that temperature plays an important role in regulating the pest population of crucifers as hot and dry condition increases the pest population as compared to pests. Increase in temperature leads to an increase in infestation by rapid rises of the pest population.

Push–pull strategies. In push pull method, one repellent plant is planted within the crop to repel the pest and another attractant plant species is planted in the surrounding field to attract the pest[20]. The "push–pull" strategy is a technique that brings together both negative and positive impulse to repel the pests from the host plant and consequently trap the herbivores by the trap plants grows at the surrounding of host target[29]. At present, this method has been implemented approximately by 70,000 agronomist[30,31]. Presently, the most effective technique of agricultural pest management, the push–pull method, was practiced successfully and developed in Africa[32]. It required low efforts and it is an organic agricultural pest management system[33]. The techniques include both the combined use of trap crops and intercrops. The plant used as trap crops and intercrops must be suitable for the farmers and should be able to damage the natural enemies[32]. Some of the repellent plants that have been used as a push for controlling stem borers in maize are *Melnis minutiflora* P.Beauv, *Desmodium unicinatum* Jacq.DC or *Desmodium intortum* Mill., that can pull away target pests to the trap plants mainly *Pennisetum purpureum* Schumach. or *Sorghum vulgare* var *sudanense* Hitchc[34]. An example of trap plant is *Barbarea vulgaris* W.T.Aiton, which was reported and can attract the cabbage pest, *P. xylostella* but there were complications in field management practices as the plant is not suitable growing in arable fields[35]. Another case is use of onion or tomato (Fig. 1) as an intercropped plant with cabbage as host plant could be taken as the most reasonable and inexpensive pest management strategy when compared to other methods. Successful method of intercropping method using onion and tomato is probably due to the confusing volatiles and visual signals that can in return repelled the cabbage pests[21].

Pheromone based product for cruciferous pest management. Pheromones are a low molecular weight volatile organic molecule produced by insect to produce a behavioral response from another individual of the same species[36]. More than 1,600 pheromones and sex attractants have been reported[37]. According to Witzgall et al.[38] Sex pheromones are mainly used to control the pest in an agricultural field. One of the advantages of using pheromone in pest management system is showing no adverse effects on non-target and beneficial insects as they have higher degree of specificity to one specific insect species only. Management of pest population can also be done by using synthetic pheromones where it can mask the natural pheromones produced by the lepidopteron pest and disrupt the olfactory communication of opposite sex which results in mating disruption. Mating

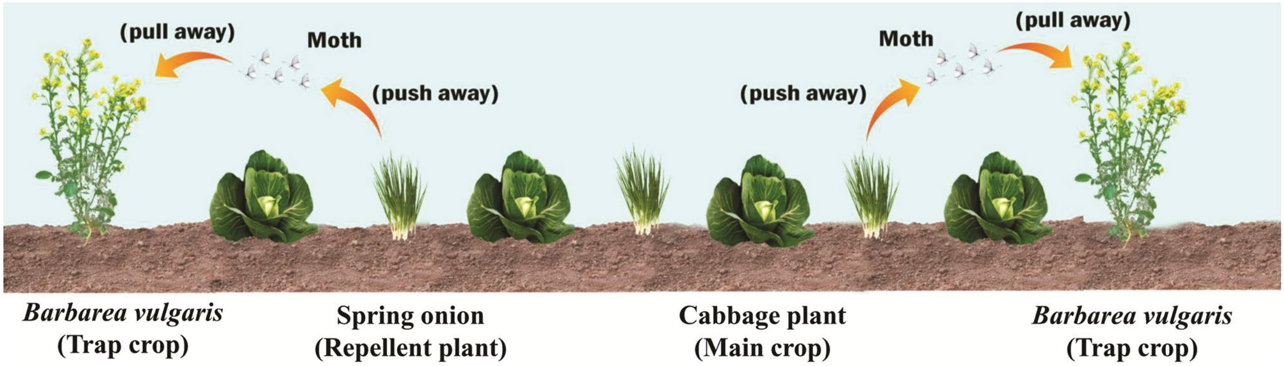

Figure 1. A schematic representation of the management of cabbage moth by using repellent "push" plant and trap "pull" plant. When Cabbage (maincrop) is planted with spring onion (repellent) non-host intercrop plant and simultaneously with attractive *B. vulgaris,* Yellow rocket cress (trap plant) as a barrier plant, it reduces the infestation of cabbage by cabbage moth. This occurred by repelling away the cabbage moth, that were trying to feed on the cabbage, from the push plant using stimuli that alter the host fragrance and at the same time pull away by the trap plant using highly attractive stimuli.

disruption using synthetic pheromone has been considered as a feasible pest management technique[39]. However the efficacy of mating disruption is highly dependent on population density of pest as large number of pest populations are more difficult to control than less populations[40]. It has been reported that DBM sex pheromones isolated from the female moths i.e., (Z11-hexadecenal, Z11-hexadecenyl acetate in the range of 8 + 2 to 4 + 6 and addition of 1% Z11-hexadecen-1-ol were used in mass trapping of male moths in a cabbage field[41].

Botanicals against crucifer pests control

India is among the leading country that gains insight in developing natural botanical insecticides as most of the people still focused on indigenous traditional knowledge for controlling insect pest in the field[42]. Botanicals are natural chemical compounds derived from plants[43].They showed different biological activities such as repellents, insecticides, fungicides and bactericides[42,44]. Some of the plants that have been reported to protect crucifer crops against insect pests are shown in (Table 1).

Botanical insecticides served as effective and safer alternatives of synthetic insecticides, as they are readily available and safer for the non-target organisms and for the environment[45,46]. Some common chemical compounds reported from plants are Pyrethrins, Nicotine, Rotenone, Azadirachtin, Limonene, Limone, Linalool, Citronellal, Artemisinin, Diterpene, Coumarins, Annonin[47,48]. According to 2012 report, Ministry of agriculture approved nine botanicals insecticides along with garlic and neem extracts[49]. Those seven botanical insecticides include *Cymbopogon* spp. Spreng., *Sophora* spp. L., *Annona squamosa* L., *Tripterygium wilfordii* Hook.F., *Apocynum venetum* L., *Eucalyptus globulus* Labil. and *Milletia pinnata* L. They have been commercialized by Ministry of Agriculture[50]. Studies have reported that azadirachtin from Neem, *Azadirachta indica* A.juss and lantanine from *Lantana camara* L. exhibit defensive mechanism against insect's pests. Azadirachtin is considered as one of the most effective botanical insecticide and helped in management of many agricultural pests[51,52]. As reported by Shah, F. M. et al[122] botanically derived commercial formulation NeemAzal was just as effective as synthetic insecticides in terms of pest suppression and marketable yield. Some of the insecticidal plant used in management of pests in cabbage and cauliflower are leaf extract of *Melia azedarach* L.[53], *Tagetes minuta* L., *Cymbopogon flexuosus* Nees ex Steud*, Acorus calamus* L., *Eupatorium adenophorum* Spreng and *Artemisia maritima* L.[54]. Although some agricultural organizations often recommended using botanical insecticides over synthetic pesticides there are some drawbacks like having poor scientific evidence on the efficacy and safety of botanical insecticides[55]. One of the factors that control the efficacy of the botanical insecticides mainly depends on concentration of active constituents and its varying contents[56]. Variable concentration of active constituents mainly resulted from the varying concentration of secondary metabolite contents which is caused by an extensive factor like the genotype of plants, different environmental factors and plant developmental stage[57]. Besides the above factor, an important factor could be due to the storage condition as the active constituents present in botanical insecticides may deteriorate gradually while storing[58]. Some other factors like a method of application of bioactive compound and a structural membrane of the target pest and its body conformation is responsible for altering the bioactivity of compounds and its toxicity[59]. It has been reported that the synergistic activity of plant essential oil constituents, may enhance the penetration effect into the insect integument. In a study of constituents of rosemary essential oil i.e., 1, 8-Cineole and camphor against *T. ni*, it was found out that mixture of 1, 8-Cineole and camphor oil gave higher toxicity than the one applied individually on *T. ni*[60]. In another study, positive synergistic effects between the constituents of lemon grass oil was shown greater insecticidal activity against the *T.ni* although some minor constituent like limonene were less effective than citral the main active compound[61] and it was also reported that the combination of three major components (thymol, p-cymene and linalool) of thyme oil which were obtained from *Thymus vulgaris* L. (Thyme) the binary mixtures have shown synergistic activity against the third instar larvae of *S. litoralis* [62].

Sl.No	Plant species (common name & Family)	Parts of the plant	Target pests	References
1	*Acorus calamus* L. (Sweet flag) Asteraceae	Leaf	*P. xylostella* Diamondback Moth & *Spodoptera frugiperda* Fall armyworm (Lepidoptera: Noctuidae)	Kumar et al.[74]
2	*Ageratum conyzoides* L. (White weed) Asteraceae	Leaf	*P. xylostella* & *B. brassicae* Cabbage aphid	Rioba and Stevenson[75]
3	*Alpinia galanga* L. Willd. (Siamese ginger) Zingiberaceae	Rhizomes	*S. frugiperda*	Datta et al.[76]
4	*Alpinia katsumadai* Hayata. (Blue ginger) Zingiberaceae	Seeds	*P. xylostella*	Hwang et al.[77]
5	*Annona cherimola* Mill. (Cherimoya) Annonaceae	Seeds	*S. frugiperda*	Castillo-Sánchez et al.[78]
6	*Annona squamosal* L. (Custard apple) Annonacea	Seeds	*P. xylostella*	Leatemia & Isman[79]
7	*Artemisia annua* (L.) (Sweet worm wood) Asteraceae	Seeds	*P. xylostella*	Okwute[80]
8	*Aspidosperma pyrifolium* Mart. & Zucc. (Pereiro) Apocynaceae	Leaf	*P. xylostella*	Torres et al.[81]
9	*Azadirachta indica* A Juss. (Indian lilac) Meliaceae	Leaf	*P. brassicae* Large Cabbage white	Sharma & Gupta[82]
10	*Bobgunnia madagascariensis (Desv.) (Snake bean plant) Fabaceae*	Fruit	*P. xylostella*	Mazhawidza & Mvumi[5]
11	*Bunium persicum* Boiss. (Black Jeera) Apiaceae	Fruit	*T. ni* Cabbage looper	Khanavi et al.[83]
12	*Cephalotaxus sinensis* (Rehder & E.H.Wilson) (Plum Yew) Cephalotaxaceae	Leaf	*P. xylostella*	Ma et al.[84]
13	*Clerodendrum inerme* L. (Glory bower) Lamiaceae	Leaf	*P. xylostella*	Yankanchi & Patil[85]
14	*Corymbia citriodora* Hook. (Lemon scented gum) Myrtaceae	Leaf	*P. xylostella*	Filomeno et al.[86]
15	*Cucurma longa* L. (Turmeric) Zingiberaceae	Rhizomes	*T. ni*	de Souza Tavares et al.[87]
16	*Cymbopogon citratus* (DC.) Stapf. (Lemon Grass) Poaceae	Leaf	*T. ni*	Tak and Isman[88]
17	*Cymbopogon schoenanthus* (L.) Spreng (West Indain Lemon grass) Poaceae	Leaf	*P. xylostella*	Sanda et al.[89]
18	*Dodonaea viscosa* (L.) Jacq (Hopseed bush) Sapindaceae	Seeds	*P. xylostella*	QIN et al.[90]
19	*Elettaria cardamomum* L. (Green cardamom) Zingiberaceae	Whole plants	*B. brassicae*	Jahan et al.[91]
20	*Eupatorium adenophorum* Spreng. (Crofton Weed) Asteraceae	Aerial part	*P. xylostella*	Adebisi et al.[92]
21	*E.adenophorum* Spreng. *&* *Lantana camara* L. (Lantana) Verbenaceae	Aerial parts	*P. brassicae*	Khan et al.[93]
22	*Apium nodiflorum* L.Lag. (Fools Water Cress) Apiaceae	Aerial parts	*T. ni*	Afshar et al.[94]
23	*Jatropha gossypifolia* L. (Cotton leaf) Euphorbiaceae	Leaf	*S. frugiperda*	Bullangpoti et al.[95]
24	*L.camara* L	Leaf	*B. brassicae*	Mvumi & Maunga[96]
25	*Maerua edulis* (Gilg & Gilg-Ben.) DeWolf. (Blue bush cherry) Capparaceae	Leaf	*P. xylostella*	Mazhawidza & Mvumi[5]
26	*Melia azedarach* L. (Chinaberry tree) Meliaceae	Leaf	*P. xylostella*	Kumar et al.[97]
27	*Melia volkensii* Gurke. (Melia) Meliaceae	Seeds	*T. ni*	Akhtar et al.[98]
28	*M.volkensii* Gurke	Seeds	*P. xylostella* &*T. ni*	Akhtar & Isman[99]
29	*Muntingia calabura* L. (Panama berry) Muntingiaceae	Fruits and flowers	*P. xylostella*	Bandeira et al.[100]
30	*Origanum vulgare* L. (Oregano) Lamiaceae	Aerial parts	*P. xylostella*	Nasr et al.[101]
31	*Otostegia persica* Boiss. (Tinjut) *Lamiaceae*& *Peganum harmala* L. (Wild Rue) Zygophyllacea	Seeds	*B. brassicae*	Shafiei etal.[102]
32	*Oxandra xylopioides* Diels. Annonaceae	Leaf	*S. frugiperda*	Castillo-Sánchez et al.[78]
33	*Panax ginseng C.A.MEYER* (Chinese ginseng) Araliaceae	Leaf and Stem	*P. xylostella*	Yang et al.[4]
34	*Pharbitis purpurea* L. (Morning glory) Convolvulacea	Seed kernels	*P. xylostella*	Xu et al.[103]
35	*Ricinus communis* L. (Castor bean) Euphorbiaceae	Seed kernels	*P. xylostella*	Kodjo et al.[104]
36	*Rosmarinus officinalis* L. (Rosemary) Lamiaceaea	Aerial parts	*T. ni*	Tak et al.[61]
37	*Satureja hotensis* L. *(Summer savory Meliaceae &Cuminum cyminum* L. (Cumin) Apiaceae	Leaf	*P. brassicae*	Khorrami et al.[105]
38	*Vitex negundo* (L.) (Chinese Chase tree) Lamiaceae	Leaf	*P. xylostella*	Yankanchi & Patil[106]

Table 1. List of some of the insecticidal plants used in management of crucifer pests.

Microbial control agent against crucifer pest

Microbial biopesticides are products developed from microorganisms like bacteria, fungi, nematode and viruses or its products that are used to control the agricultural pest and also play an important role as an alternative tool to chemical pesticides for their eco-friendly nature[63]. According to NBAIR 2017 report, minimum of 15 biopesticides based on microbes have been developed in India with 970 commercial formulations registered[64]. Some of the microbial control agents against crop pests are discussed here in Table 2.

Fungi species which are pathogenic to insect pests are called entomopathogenic fungi. The most commonly used entomopathogenic fungi are *Beauveria bassiana (Balsamo)Vuillemin, B. brongniartii (Sacc.)Petch, Metarhizium anisopliae (Metschn.)Sorokin, Lecanicillium lecnii (Zimmerman) Gams & Zare, Hirsutella thompsonii Fisher, Cladossporium oxysporium Berk & M.A.Curtis)* and *Isaria fumosorosea (Wize)*[65,66]. Based on the report

Sl.No	Entomopathogenic microbes	Target pest	Types of microbes	References
1	*Bacillus thuringinesis* Berliner *ssp* kurstaki	*T. ni*	Bacterium	Ramanujam et al.[107]
2	*Bacillus thuringinesis* var. galleriae	*Helicoverpa armigera* HübnerCotton Bollworm (Lepidoptera:Noctuidae) & *P. xylostella*	Bacterium	Singh et al.[108]
3	*Beauveria bassiana* – Myco Jaal	*P. xylostella.* & *P. brassicae*	Fungus	Ghosh et al.[109] Srinivasan et al.[110] & Singh et al.[111]
4	*Beauveria brongniartii*	*S. litura*	Fungus	Lin et al.[112]
5	*Cabbage looper* (TrniSNPV)	*T. ni*	Virus	Singh et al.[108]
6	*Chromobacterium subtsugae*	*P. xylostella*	Bacterium	Martin et al.[113]
7	*Diamond back moth GV* (PlxyGV)	*P. xylostella*	Virus	Singh et al. [108]
8	*Egyptian cotton leafworm NPV* (SpliNPV)	*S. littoralis*	Virus	Singh et al.[108]
9	Granulosis Virus	*P. rapae*	Virus	Ramanujam et al.[107]
10	*Heterorhabditis bacteriophora*	*P. xylostella*& *P. brassicae*	Nematode	Rodriguez et al.[114] & Abbas et al. [115]
11	*Isaria fumosoroseus*	*P. xylostella*	Fungus	Huang et al.[116]
12	*Nomuraea rileyi*	*S. litura*	Fungus	Lin et al.[112]
13	Nuclear Polyhedrosis Virus	*Mamestra brassicae L. Cabbage moth* (Lepidoptera:Noctuidae)	Virus	Kunimi[117]
14	*Photorhabdus luminescens*	*P. brassicae*	Nematode	Mohan et al.[118]
15	*Steinernema carpocapsae*	*P. xylostella*	Nematode	Baur et al.[119] & Sunanda et al.[120]
16	*Steinernema glaseri*	*P. brassicae*	Nematode	Abbas et al.[114]
17	*Xenorhabdus nematophila*	*P. xylostella*	Nematode	Razek et al.[121]

Table 2. List of some of the entomopathogenic microbes used in management of crucifer pests.

of entomopathogenic bacteria, the most commercially used microbial pesticide belongs to gram positive bacteria mostly in the genera of *Bacillus*, *Paenibacillus* and *Lysinibacillus*[67]. More than 30 products developed from the sub species *kurstaki* of *B.thuringiensis* are effective against bollworms, loopers and other lepidopterans and also two viruses namely Helicoperva armigera nucleopolyhedrovirus and Spodoptera litura mucleopolyhedrovirus were registered to control two lepidopteran pests i.e., *Helicoverpa* spp., *S. litura* and *S. exigua*[53].

Although microbial pesticides have many advantages for control of crucifer pest, several factors limit the commercial production, and their efficacy also varies among the stage of larvae, strains, environmental condition and target pests. The efficacy of these products is highly effective when applied to the young larvae (first and second instars larva) and reapplication when insect population increases[68–70]. Some of the factors that limit the commercialization of microbial pesticides include low microbial counts, as rapid production of entomophthoralean fungi species is quite low due to difficulty in development of conidia and its short-lived which makes impossible in creating a period of vast applications. For this one should try to increase the production of resting spores and competent mycelia of entomophthoralean species by developing effective methods which will ultimately increase the efficacy of these fungi[71]. Another factor is the shelf life of entomopathogenic microbes, where storage facilities are not yet developed in rural areas[72]. Poor solubility of the some of the formulations in water is also one of the challenges[73]. Despite of all the challenges, several methods need to be followed like enhancing the microbial production and formulation, learning the proper idea of microbial pesticides being incorporated into integrated systems and their relations with the external environment, accepting the advantages like efficacy, safety etc. while comparing with synthetic pesticides and approved[71].

Conclusions

As biological control of pest can be an alternative to synthetic pesticides, effectiveness and maintenance of developing control method for crucifer pests must be considered. Some of the criteria that should be encountered for developing a proper biological control methods are (1) adopting proper guidelines to the farmers about various approaches of pest management in a comprehensive manner, (2) providing awareness programme for the negative impacts of used of synthetic pesticides for better cooperation of the farmers (3) having proper taxonomical knowledge on insectary plants, trap crops and insecticidal plants and (4) maintained authentic research data during laboratory practices to be commercialised later. These approaches can provide the importance of the economic benefits of using biological control method over synthetic products and will gain insight of accepting the sustainable way of crucifer pest management. The ultimate challenge will be to adopt the use of biological pest management technologies in a cost effective manner so that farmer can easily access those approaches.

Received: 16 February 2021; Accepted: 19 May 2021
Published online: 04 June 2021

References

1. State of Indian Agriculture 2015-16, Government of India, Ministry of Agriculture & Farmers Welfare, Department of Agriculture, Cooperation & Farmers Welfare, Directorate of Economics and Statistics, New Delhi. https://eands.dacnet.nic.in/PDF/State_of_Indian_Agriculture,2015-16.pdf.
2. Amoabeng, B. W. *et al.* Tri-trophic insecticidal effects of African plants against cabbage pests. *PLoS One*. **8**(10), e78651 (2013).

3. Hasan, F. & Ansari, M. S. Effect of different cole crops on the biological parameters of Pieris brassicae (L.)(Lepidoptera: Pieridae) under laboratory conditions. *J. Crop Sci. Biotechnol.* **13**(3), 195–202 (2010).
4. Yang, H., Piao, X., Zhang, L., Song, S. & Xu, Y. Ginsenosides from the stems and leaves of *Panax ginseng* show antifeedant activity against *Plutella xylostella* (Linnaeus). *Ind. Crops Prod.* **124**, 412–417 (2018).
5. Mazhawidza, E. & Mvumi, B. M. Field evaluation of aqueous indigenous plant extracts against the diamondback moth, Plutella xylostella L. and the rape aphid, Brevicoryne brassicae L. in brassica production. *Ind. Crops Prod.* **110**, 36–44 (2017).
6. Akhtar, Y., Isman, M. B., Niehaus, L. A., Lee, C. H. & Lee, H. S. Antifeedant and toxic effects of naturally occurring and synthetic quinones to the cabbage looper. *Trichoplusia ni. Crop Prot.* **31**(1), 8–14 (2012).
7. Aktar, M. W., Sengupta, D. & Chowdhury, A. Impact of pesticides use in agriculture: their benefits and hazards. *Interdiscip. Toxicol.* **2**(1), 1–12 (2009).
8. Couto, I. F. S. *et al.* Botanical extracts of the brazilian savannah affect feeding and oviposition of *Plutella xylostella* (Linnaeus, 1758)(Lepidoptera: Plutellidae). *J. Agric. Sci.* **11**(5), 322–333 (2019).
9. Lengai, G. M., Muthomi, J. W. & Mbega, E. R. Phytochemical activity and role of botanical pesticides in pest management for sustainable agricultural crop production. *Sci. Afr.* **7**, e00239 (2020).
10. Hikal, W. M., Baeshen, R. S. & Said-Al Ahl, H. A. Botanical insecticide as simple extractives for pest control. *Cogent. Biol.* **3**(1), 1404274 (2017).
11. Isman, M. B. Botanical insecticides, deterrents, and repellent in modern agriculture and an increasingly regulated world. *Annu. Rev. Entomol.* **51**, 45–66 (2006).
12. Petacci, F. *et al.* Phytochemistry and quantification of polyphenols in extracts of the Asteraceae weeds from Diamantina, Minas Gerais State Brazil. *Planta. Daninha.* **30**, 9–15 (2012).
13. Krishnamoorthy, A. Biological control of diamondback moth Plutella xylostella (L.), an Indian scenario with reference to past and future strategies in *Proceedings of the International Symposium* (eds. Kirk, A. A. & Bordat, D.) 204–211 (Montpellier, France: CIRAD 2004).
14. Sulifoa, J. B., Fangupo, S. & Kant, R. Oviposition periodicity, egg morphology and life history of large cabbage moth *Crocidolomia pavonana* population in Samoa. *SPJNAS* **34**(2), 29–34 (2016).
15. Lal, M. N., & Ram, B. Cabbage butterfly, *Pieris brassicae* L.-an upcoming menace for Brassica oilseed crops in Northern India. *Cruciferae Newsletter* **25**. (2004).
16. Chalfant, R. B., Denton, W. H., Schuster, D. J. & Workman, R. B. Management of cabbage caterpillars in Florida and Georgia by using visual damage thresholds. *J. Econ. Entomol.* **72**, 411–413 (1979).
17. Mochiah, M. B., Baidoo, P. K. & Owusu-Akyaw, M. Influence of different nutrient applications on insect populations and damage to cabbage. *J. Appl. Biosci.* **38**, 2564–2572 (2011).
18. Tumutegyereize, J. K. Handbook on identification and management of pests and diseases of cabbage and other brassicas in Uganda. (2008).
19. Amoabeng, B. W., Johnson, A. C. & Gurr, G. M. Natural enemy enhancement and botanical insecticide source: a review of dual use companion plants. *Appl. Entomol. Zool.* **54**(1), 1–19 (2019).
20. Gurr, G. M., Wratten, S. D., Landis, D. A. & You, M. Habitat management to suppress pest populations: progress and prospects. *Annu. Rev. Entomol.* **62**, 91–109 (2017).
21. Warwick, H. R. I., & Wellesbourne, W. Control of Diamond back Moth (Plutella xylostella) on Cabbage (*Brassica oleracea* var *capitata*) using Intercropping with Non-Host Crops "E. Asare-Bediako," AA Addo-Quaye and A. Mohammed" Department of Crop Science, University of Cape Coast, Cape Coast, Ghana. *Am. J. Food Technol.* **5**(4), 269–274 (2010).
22. Xu, Q. C. *et al.* Relay-intercropping into tomato decreases cabbage pest incidence. *J Food. Agric. Environ.* **8**, 1037–1041 (2010).
23. Yarou, B. B *et al.* Efficacy of Basil-Cabbage intercropping to control insect pests in Benin, West Africa. *Commun. Agric. Appl. Biol.* **82**, 157–166(2017)
24. Abhishek, S. & Ashok, K. The diamond back moth, *Plutella xylostella* a problematic pest of Brassica crop. *J. Adv. Indian. Entomol.* **1**, 229–240 (2005).
25. Olesen, J. E. & Bindi, M. Consequences of climate change for European agricultural productivity, land use and policy. *Eur. J. Agron.* **16**, 239–262. https://doi.org/10.1016/S1161-0301(02)00004-7 (2002).
26. Dey, D., Routray, S., Baral, S. & Mahantheshwara, B. Effect of planting dates and botanical insecticides against major Lepidopterous pests of cabbage: a review. *Agric. Rev.* **38**(1), 60–66 (2017).
27. Tanyi, C. B., Ngosong, C. & Ntonifor, N. N. Effects of climate variability on insect pests of cabbage: adapting alternative planting dates and cropping pattern as control measures. *Chem. Biol. Technol. Agric.* **5**(1), 25 (2018).
28. Viraktamath, S., Reddy, B. S. & Patil, M. G. Effect of date of planting on the extent of damage by the Diamond back moth, *Plutella xylostella* on cabbage. *Karnataka. J. Agric. Sci.* **7**, 238–239 (1994).
29. Pickett, J. A., Woodcock, C. M., Midega, C. A. & Khan, Z. R. Push–pull farming systems. *Curr. Opi. Biotech.* **26**, 125–132 (2014).
30. Kergunteuil, A., Dugravot, S., Danner, H., Van Dam, N. M. & Cortesero, A. M. Characterizing volatiles and attractiveness of five brassicaceous plants with potential for a 'push-pull'strategy toward the cabbage root fly *Delia radicum. J. Chem. Ecol.* **41**(4), 330–339 (2015).
31. Khan, Z. R. *et al.* Achieving food security for one million subSaharan African poor through push—pull innovation by 2020. *Philos. Trans. R. Soc. B: Biol. Sci.* **369**(1639), 20120284 (2014).
32. Cook, S. M., Khan, Z. R. &Pickett, J. A. The use of push-pull strategies in integrated pest management. *Annu. Rev. Entomol.* **52**, 375–400 (2007).
33. Khan, Z. R. *et al.* Intercropping increases parasitism of pests. *Nature* **388**(6643), 631–632 (1997).
34. Khan, Z. R., Pickett, J. A., Berg, J. V. D., Wadhams, L. J. & Woodcock, C. M. Exploiting chemical ecology and species diversity: stem borer and striga control for maize and sorghum in Africa. *Pest Manag. Sci.* **56**(11), 957–962 (2000).
35. Parolin, P. *et al.* Secondary plants used in biological control: a review. *Int. J. Pest Manag.* **58**(2), 91–100 (2012).
36. Teal P.E.A. Sex attractant pheromones. in *Encyclopedia of Entomology* (ed. Capinera, J. L.) 3349-3354 (Springer, Dordrecht, The Netherlands 2004).
37. Witzgall, P., Lindblom, T., Bengtsson, M., & Toth, M. The Pherolist. (2004) http://www.pherolist.slu.se/pherolist.php. Accessed 23 July 2013
38. Witzgall, P., Stelinski, L., Gut, L. & Thomson, D. Codling moth management and chemical ecology. *Annu. Rev. Entomol.* **53**(1), 503–522 (2008).
39. Schroeder, P. C., Shelton, A. M., Ferguson, C. S., Hoffmann, M. P. & Petzoldt, C. H. Application of synthetic sex pheromone for management of diamondback moth, *Plutella xylostella*, in cabbage. *Entomol Exp. Appl.* **94**(3), 243–248 (2000).
40. Reddy, G. V. & Guerrero, A. New pheromones and insect control strategies. *Vitam. Horm.* **83**, 493–519 (2010).
41. Reddy, G. P. & Urs, K. D. Mass trapping of diamondback moth *Plutella xylostella* in cabbage fields using synthetic sex pheromones. *Int. J. Pest Manag.* **39**(4), 125–126 (1997).
42. Isman, M. B. Botanical insecticides, deterrents, and repellents in modern agriculture and an increasingly regulated world. *Annu. Rev. Entomol.* **51**, 45–66 (2006).
43. Isman, M. B. & Grieneisen, M. L. Botanical insecticide research: many publications, limited useful data. *Trends Plant. Sci.* **19**(3), 140–145 (2014).
44. Campos, E. V. *et al.* Use of botanical insecticides for sustainable agriculture: Future perspectives. *Ecol. Indic.* **105**, 483–495 (2019).

45. El-Wakeil, N. E. Retracted Article: Botanical Pesticides and Their Mode of Action. *Gesunde Pflanz.* **65**(4), 125–149 (2013).
46. Lengai, G. M., Muthomi, J. W. & Mbega, E. R. Phytochemical activity and role of botanical pesticides in pest management for sustainable agricultural crop production. *Sci. Afr.* **7**, e00239 (2020).
47. Bennett, R. N. & Wallsgrove, R. M. Secondary metabolites in plant defence mechanisms. *New Phytol.* **127**(4), 617–633 (1994).
48. Samarasekera, J. K. R. R. Insecticidal natural products from Sri Lankan plants (Doctoral dissertation, The Open University) **204**, (1997).
49. Bambawale, O. M., & Bhagat, S. O. M. E. S. H. W. A. R. Registration related issues in effective use of biopesticides in pest management. in Biopesticides in Environment and Food Security: Issues and Strategies (eds. Koul, O., Dhaliwal, G. S., Khokhar, S. & Singh, R.) 265–285 (Scientific Publishers, 2012).
50. Isman, M. B. A renaissance for botanical insecticides?. *Pest Manag. Sci.* **71**(12), 1587–1590 (2015).
51. Begum, S., Wahab, A., Siddiqui, B. S. & Qamar, F. Nematicidal Constituents of the aerial parts of *Lantana camara*. *J. Nat. Prod.* **63**, 765–767 (2000).
52. Baidoo, P. K. & Adam, J. I. The effects of extracts of *Lantana camara* (L.) and *Azadirachta indica* (A. Juss) on the population dynamics of *Plutella xylostella, Brevicoryne brassicae* and *Hellula undalis* on cabbage Sustain. *Agric. Res.* **1**(2), (2012).
53. Kumar, K. K. *et al.* Microbial biopesticides for insect pest management in India: current status and future prospects. *J. Invertebr. Pathol.* **165**, 74–81 (2019).
54. Reddy, S. E., Dolma, S. K. & Bhardwaj, A. Plants of himalayan region as potential source of biopesticides for lepidopteran insect pests. in Herbal Insecticides, Repellents and Biomedicines: Effectiveness and Commercialization (eds. Veer, V. & Gopalakrishnan, R.) 63-83 (Springer, New Delhi 2016).
55. Dougoud, J., Toepfer, S., Bateman, M. & Jenner, W. H. Efficacy of homemade botanical insecticides based on traditional knowledge A review. *Agron. Sustain. Dev.* **39**(4), 37 (2019).
56. Sarasan, V., Kite, G. C., Sileshi, G. W. & Stevenson, P. C. Applications of phytochemical and in vitro techniques for reducing over-harvesting of medicinal and pesticidal plants and generating income for the rural poor. *Plant Cell Rep.* **30**, 1163 (2011).
57. Figueiredo, A. C., Barroso, J. G., Pedro. L. G. & Scheffer, J. J. Factors affecting secondary metabolite production in plants: volatile components and essential oils. *Flavour Fragr J*. **23**(4), 213–226 (2008).
58. Yakkundi, S. R., Thejavathi, R. & Ravindranath, B. Variation of azadirachtin content during growth and storage of neem (*Azadirachta indica*) seeds. *J. Agric. Food Chem.* **43**(9), 2517–2519 (1995).
59. Tak, J. H. & Isman, M. B. Penetration-enhancement underlies synergy of plant essential oil terpenoids as insecticides in the cabbage looper *Trichoplusia ni*. *Sci. Rep.* **7**(1), 1–11 (2017).
60. Tak, J. H. & Isman, M. B. Enhanced cuticular penetration as the mechanism for synergy of insecticidal constituents of rosemary essential oil in *Trichoplusia ni*. *Sci. Rep.* **5**(1), 1–10 (2015).
61. Tak, J. H., Jovel, E. & Isman, M. B. Contact, fumigant, and cytotoxic activities of thyme and lemongrass essential oils against larvae and an ovarian cell line of the cabbage looper *Trichoplusia ni*. *J. Pest Sci.* **89**(1), 183–193 (2016).
62. Pavela, R. Acute, synergistic and antagonistic effects of some aromatic compounds on the *Spodoptera littoralis* Boisd. (Lep, Noctuidae) larvae. *Ind. Crops Prod.* **60**, 247–258 (2014)
63. Arthurs, S. & Dara, S. K. Microbial biopesticides for invertebrate pests and their markets in the United States. *J. Invertebr. Pathol.* **165**, 13–21 (2019).
64. NBAIR. ICAR-National Bureau of Agricultural Insect Resources, Newsletter,. Bengaluru. *India* **9**, 4 (2017).
65. Maina, U. M., Galadima, I. B., Gambo, F. M. & Zakaria, D. A review on the use of entomopathogenic fungi in the management of insect pests of field crops. *J. Entomol. Zool. Stud.* **6**(1), 27–32 (2018).
66. Sujeetha, J. A. R. P & Sahayaraj, K. Role of entomopathogenic fungus in pest management. in Basic and Applied Aspects of Biopesticides (ed. Sahayaraj, K.) 31–46 (Springer, New Delhi 2014).
67. Glare, T. R., Jurat-Fuentes, J. L. & O'callaghan, M. Basic and applied research: entomopathogenic bacteria. in *Microbial Control of Insect and Mite Pests* (ed. Lacey, L. A.) 47–67 (Academic Press, 2017).
68. Van Frankenhuyzen, K. Insecticidal activity of *Bacillus thuringiensis* crystal proteins. *J. Invertebr. Pathol.* **101**(1), 1–16 (2009).
69. Arora, N. K., Khare, E. & Maheshwari, D. K. Plant growth promoting rhizobacteria: constraints in bioformulation, commercialization, and future strategies. In *Plant Growth and Health Promoting Bacteria* (ed. Maheshwari, D. K.) 97–116 (Springer, Berlin, Heidelberg 2010).
70. Gupta, S. & Dikshit, A. K. Biopesticides: An ecofriendly approach for pest control. *J. Biopestic.*, **3**(1), 186–188 (2010).
71. Lacey, L. A., Frutos, R., Kaya, H. K. & Vail, P. Insect pathogens as biological control agents: do they have a future?. *Biol. Control.* **21**(3), 230–248 (2001).
72. Mishra, J., Tewari, S., Singh, S. & Arora, N. K. Biopesticides: where we stand? In *Plant microbes symbiosis: Applied Facets (ed. Arora, N. K.)* 37–75. (Springer, New Delhi 2015).
73. Aneja, K. R., Khan, S. A. & Aneja, A. Biopesticides an eco-friendly pestmanagement approach in agriculture: status and prospects. *Kavaka* **47**, 145–154 (2016).
74. Kumar, R. *et al.* Chemical composition, cytotoxicity and insecticidal activities of *Acorus calamus* accessions from the western Himalayas. *Ind. Crops Prod.* **94**, 520–527 (2016).
75. Rioba, N. B. & Stevenson, P. C. Ageratum conyzoides L for the management of pests and diseases by small holder farmers. *Ind. Crops. Prod.* **110**, 22–29 (2017).
76. Datta, R., Kaur, A., Saraf, I., Singh, I. P. & Kaur, S. Effect of crude extracts and purified compounds of Alpinia galanga on nutritional physiology of a polyphagous lepidopteran pest, *Spodoptera litura* (Fabricius). *Ecotoxicol. Environ. Saf.* **168**, 324–329 (2019).
77. Hwang, K. S., Kim, Y. K., Kim, Y. T., Lee, J. & Park, K. W. A tetracosatetraene as larvicidal compound isolated from *Alpinia katsumadai*. *Ind. Crops Prod.* **109**, 786–789 (2017).
78. Castillo, L. E., Jiménez, J. J. & Delgado, M. A. Secondary metabolites of the Annonaceae, Solanaceae and Meliaceae families used as biological control of insects. *Trop. Subtrop. Agroecosyst.* **12**(3), 445–462 (2010).
79. Leatemia, J. A. & Isman, M. B. Efficacy of crude seed extracts of *Annona squamosa* against diamondback moth, *Plutella xylostella* L. in the greenhouse. *Int. J. Pest Manag.* **50**(2), 129–133 (2004).
80. Okwute, S. K. Plants as potential sources of pesticidal agents: a review. in *Pesticides-Advances in Chemical and Botanical Pesticides* (ed. Soundararajan, R. P.) 10, 208–232. (Academic, Detroit 2012).
81. Torres, A. L., Barros, R. & Oliveira, J. V. D. Effects of plant aqueous extracts on the development of *Plutella xylostella* (L.) (Lepidoptera: Plutellidae). *Neotrop. Entomol.* **30**(1), 151–156 (2001).
82. Sharma, A. & Gupta, R. Biological activity of some plant extracts against *Pieris brassicae* (Linn.). *J. Biopestic.* **2**(1), 26–31 (2009).
83. Khanavi, M., Laghaei, P. & Isman, M. B. Essential oil composition of three native Persian plants and their inhibitory effects in the cabbage looper *Trichoplusia ni*. *J. Asia Pac. Entomol.* **20**(4), 1234–1240 (2017).
84. Ma, S., Jia, R., Guo, M., Qin, K. & Zhang, L. Insecticidal activity of essential oil from *Cephalotaxus sinensis* and its main components against various agricultural pests. *Ind. Crops Prod.* **150**, 112403 (2020).
85. Yankanchi, S. R. & Patil, S. R. Field efficacy of plant extracts on larval populations of *Plutella xylostella* L. and *Helicoverpa armigera* Hub and their impact on cabbage infestation. *J. Biopestic.* **2**(1), 32–36 (2009).
86. Filomeno, C. A. *et al. Corymbia* spp. and *Eucalyptus* spp. essential oils have insecticidal activity against *Plutella xylostella*. *Ind. Crops Prod.* **109**, 374–383 (2017).

87. de Souza Tavares, W., Akhtar, Y., Gonçalves, G. L. P., Zanuncio, J. C. & Isman, M. B. Turmeric powder and its derivatives from *Curcuma longa* rhizomes: insecticidal effects on cabbage looper and the role of synergists. *Sci. Rep.* **6**(1), 1–11 (2016).
88. Tak, J. H., Jovel, E. & Isman, M. B. Comparative and synergistic activity of *Rosmarinus officinalis* L essential oil constituents against the larvae and an ovarian cell line of the cabbage looper, *Trichoplusia ni* (Lepidoptera: Noctuidae). *Pest Manag. Sci.* **72**(3), 474–480 (2016).
89. Sanda, K., Koba, K., Poutouli, W., Idrissou, N. & Agbossou, A. B. Pesticidal propertties of *Cymbopogon schoenatus* against the Diamondback moth *Plutella xylostella* L (Lepidoptera: Hyponomeutidae). *Discov. Innov.* **19**, 220–225 (2006).
90. Qin, X. P., Zhao, H. Y. & Yang, M. L. Antifeeding activities of *Dodonaea viscose* seed extracts against *Plutella xylostella*. *Chin. Bull. Entomol.* 4, (2008).
91. Jahan, F., Abbasipour, H. & Hasanshahi, G. Fumigant toxicity and nymph production deterrence effect of five essential oils on adults of the cabbage aphid, *Brevicoryne brassicae* L. (Hemiptera: Aphididae). *J. Essent. Oil-Bear. Plants.* **19**(1), 140–147 (2016).
92. Adebisi, O., Dolma, S. K., Verma, P. K., Singh, B. & Reddy, S. E. Volatile, non-volatile composition and insecticidal activity of *Eupatorium adenophorum* Spreng against diamondback moth, *Plutella xylostella* (L.), and aphid *Aphis craccivora* Koch. *Toxin. Rev.* **38**(2), 143–150 (2019).
93. Khan, Z. R. *et al.* Management of witchweed, *Striga hermonthica*, and stemborers in sorghum, Sorghum bicolor, through intercropping with greenleaf desmodium *Desmodium intortum. Int. J. Pest Manag.* **52**, 297–302 (2006).
94. Afshar, F. H., Maggi, F., Iannarelli, R., Cianfaglione, K. & Isman, M. B. Comparative toxicity of *Helosciadium nodiflorum* essential oils and combinations of their main constituents against the cabbage looper, *Trichoplusia ni* (Lepidoptera). *Ind. Crops Prod.* **98**, 46–52 (2017).
95. Bullangpoti, V., Wajnberg, E., Audant, P. & Feyereisen, R. Antifeedant activity of *Jatropha gossypifolia* and *Melia azedarach* senescent leaf extracts on *Spodoptera frugiperda* (Lepidoptera: Noctuidae) and their potential use as synergists. *Pest Manag. Sci.* **68(9),** 1255–1264 (2012)
96. Mvumi, C. & Maunga, P. R. Efficacy of lantana (*Lantana camara*) extract application against aphids (*Brevicoryne brassicae*) in rape (*Brassica napus*) over varied periods of time. *Afr. J. Biotechnol.* **17**(8), 249–254 (2018).
97. Kumar, R., Sharma, K. C. & Kumar, D. Studies on ovicidal effects of some plant extracts against the diamondback moth, *Plutella xylostella* (L.) infesting cauliflower crop. *Biol. Forum. Int. J.* **1**(1), 47–50 (2009).
98. Akhtar, Y., Yeoung, Y. R. & Isman, M. B. Comparative bioactivity of selected extracts from Meliaceae and some commercial botanical insecticides against two noctuid caterpillars *Trichoplusia ni Pseudaletia unipuncta. Phytochem Rev.* **7**, 77–88 (2008).
99. Akhtar, Y. & Isman, M. B. Comparative growth inhibitory and antifeedant effects of plant extracts and pure allelochemicals on four phytophagous insect species. *J. Appl. Entomol.* **128**(1), 32–38 (2004).
100. Bandeira, G. N. *et al.* Insecticidal activity of *Muntingia calabura* extracts against larvae and pupae of diamondback, *Plutella xylostella* (Lepidoptera, Plutellidae). *J. King Saud Univ. Sci.* **25**(1), 83–89 (2013).
101. Nasr, M., Sendi, J. J., Moharramipour, S. & Zibaee, A. Evaluation of *Origanum vulgare* L. essential oil as a source of toxicant and an inhibitor of physiological parameters in diamondback moth, *Plutella xylostella* L. (Lepidoptera: Pyralidae). *J. Saudi Soc. Agric. Sci.* **16**(2), 184–190 (2017).
102. Shafiei, F., Ahmadi, K. & Asadi, M. Evaluation of systemic effects of four plant extracts compared with two systemic pesticides, acetamiprid and pirimicarb through leaf spraying against *Brevicoryne brassicae* L. (Hemiptera: Aphididae). *J. Vector Ecol.* **30**, 284–288 (2018).
103. Xu, X. R., Jiang, H. Y., Zhang, Y. N. & Feng, P. Z. Bioactivity of *Pharbitis purpurea* extracts against *Plutella xylostella*. *Pesticides-Shenyang-* **45**(2), 125 (2006).
104. Kodjo, T. A. *et al.* Bio-insecticidal effects of plant extracts and oil emulsions of *Ricinus communis* L. (Malpighiales: Euphorbiaceae) on the diamondback, *Plutella xylostella* L. (Lepidoptera: Plutellidae) under laboratory and semi-field conditions. *J. Appl. Biosci* **43**, 2899–2914 (2011).
105. Khorrami, F., Soleymanzade, A. & Forouzan, M. Toxicity of some medicinal plant extracts to *Pieris brassicae* and combined effects with Proteus® against *Brevicoryne brassicae*. *J. Phytopathol. Pest Manag.* 50–55 (2017).
106. Yankanchi, S. R. & Patil, S. R. Field efficacy of plant extracts on larval populations of *Plutella xylostella* L. and *Helicoverpa armigera* Hub. and their impact on cabbage infestation. *J. Biopestic.* **2**(1), 32–36 (2009).
107. Ramanujam, B., Rangeshwaran, R., Sivakmar, G., Mohan, M. & Yandigeri, M. S. Management of insect pests by microorganisms. In *Proc. Indian National Sci. Acad.* **80**(2), 455–471 (2014).
108. Singh, A., Bhardwaj, R. & Singh, I. K. Biocontrol Agents: Potential of Biopesticides for Integrated Pest Management in *Biofertilizers for Sustainable Agriculture and Environment* (eds. Giri, B., Prasad, R., Wu, Q. S. & Varma, A.) 413–433 (Springer, Cham. 2019).
109. Ghosh, S.K., Chaudhary, M. & Kumar P. Myco-Jaal: a novel formulation of Beauveria bassiana for managing diamondback moth (*Plutella xylostella*) in tropical and sub-tropical crucifer production systems. in The Sixth International Workshop on Management of the Diamondback Moth and Other Crucifer Insect Pests, Vol. 11(755), 153 (AVRDC-World Vegetable Center 2011).
110. Srinivasan, R., Sevgan, S., Ekesi, S. & Tamò, M. Biopesticide based sustainable pest management for safer production of vegetable legumes and brassicas in Asia and Africa. *Pest Manag. Sci.* **75**(9), 2446–2454 (2019).
111. Singh, K. I., Debbarma, A. & Singh, H. R. Field efficacy of certain microbial insecticides against *Plutella xylostella* Linnaeus and *Pieris brassicae* Linnaeus under cabbage-crop-ecosystem of Manipur. *J. Biol. Control.* **29**(4), 194–202 (2015).
112. Lin, H. F., Yang, X. J., Gao, Y. B. & Li, S. G. Pathogenicity of several fungal species on *Spodoptera litura Chin. J. Appl. Ecol.* **18**(4), 937–940 (2007).
113. Martin P. A., Hirose, E. & Aldrich, J. R. Toxicity of *Chromobacterium subtsugae* to Southern stink bug (Heteroptera: Pentatomidae) and corn rootworm (Coleoptera: Chrysomelidae). *J. Econ. Entomol.* **100**(3), 680–684 (2007).
114. Rodriguez, M. G. *et al.* Impact of entomopathogenic nematode applications on diamond back moth population. *Rev. Protec. Vegetal.* **28**, 158–160 (2013).
115. Abbas, W., Javed, N., Haq, I. U. & Ahmed, S. Pathogenicity of Entomopathogenic nematodes against cabbage butterfly (*Pieris brassicae*) Linnaeus (Lepidoptera: Pieridae) in laboratory conditions. *Int. J. Trop. Insect Sci.* **41**(1), 1–7 (2020).
116. Huang, Z., Ali, S., Ren, S. X & Wu, J. H. Effect of *Isaria fumosoroseus* on mortality and fecundity of *Bemisia tabaci* and *Plutella xylostella*. *Insect Sci.* **17**(2), 140–148 (2010).
117. Kunimi, Y. Current status and prospects on microbial control in Japan. *J. Invertebr. Pathol.* **95**(3), 181–186 (2007).
118. Mohan, S., Raman, R. & Gaur, H.S. Foliar application of *Photorhabdus luminescens*, symbiotic bacteria from entomopathogenic nematode *H. indica*, to kill cabbage butterfly *Pieris brassicae*. *Curr. Sci.* **84**(11), 1397 (2003).
119. Baur, M. E., Kaya, H. K., Tabashnik, B. E. & Chilcutt, C. F. Suppression of diamondback moth (Lepidoptera: Plutellidae) with an entomopathogenic nematode (Rhabditida: Steinernematidae) and *Bacillus thuringiensis* Berliner. *J. Econ. Entomol.* **91**(5), 1089–1095 (1998).
120. Sunanda, B. S., Jeyakumar, P. & Jacob, V. V. Bioefficacy of different formulations of entomopathogenic nematode *Steinernema carpocapsae* against Diamond back moth (*Plutella xylostella*) infesting Cabbage (*Brassica oleracea* var. *capitata*). *J. Biopestic.* **7**(2), 210–215 (2014).
121. Razek, A. A. S. Pathogenic effects of *Xenorhabdus nematophilus* and *Photorhabdus luminescens* against pupae of the Diamondback moth *Plutella xylostella*. *J. Pest Sci.* **76**, 108–111 (2003).

122. Shah, F. M. *et al.* Field evaluation of synthetic and neem-derived alternative insecticides in developing action thresholds against cauliflower pests. *Sci. Rep.* **9**(1), 1–13 (2019).

Acknowledgements

The authors wish to thank the Director, Institute of Bioresources and Sustainable Development, Manipur, India for his keen interest in this study and Department of Biotechnology for the funding and IBSD manuscript no. is IBSD/2020/01/013.

Author contributions

Conceptualization (all authors), methodology (all authors), data curation (S.M, K.DS.), formal analysis (all authors), visualization (K.D.S), writing–original draft (S.M, Y.R), writing–review and editing (all authors). All authors read and approved the final manuscript.

Competing interests

The authors declare no competing interests.

Additional information

Correspondence and requests for materials should be addressed to Y.R.

Reprints and permissions information is available at www.nature.com/reprints.

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.