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REVIEW ARTICLE

Sustainable Management Strategies and Biological Control in Apple Orchards – Indian Perspective

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Abstract

Sustainable horticultural practices address the global issues of food security, pest and disease management, soil health, water pollution, depletion of biodiversity etc. with environment–friendly approaches. Increasingly, the adoption of such strategies is benefitting agricultural production including in orchards. Even though several strategies such as Integrated Pest Management (IPM), disease and weed mitigation have been in use for the elimination of pests, diseases and weeds in apple orchards, they are still not the most favoured methods of control. There are various economic and acceptance concerns regarding their use, particularly in developing nations like India. A more viable system for apple orchards management, thus, should be adopted.

Here, we review various different approaches, including sustainable biocontrol methods, employed in the apple orchards. Use of genetically engineered pest-resistant varieties, bio-pesticides, plant-derived insecticides, sanitation methods and adoption of technology for evaluating the accuracy of these methods as well as monitoring of orchards are some of the management strategies included in the study. Further, conventional biocontrol practices, such as engaging natural enemies of harmful pests, use of companion plants or setting up of hedges and windbreaks for enhancing beneficial pest populations, application of compost for improving soil health and interplanting are also employed. Sustainable IPM methodologies can be integrated with biocontrol strategies leading to the development of environmentally feasible management of apple orchards. Such systems will not only reduce dependence on chemical control methods but will also minimize ecotoxicity. Drawing parallels between the biocontrol methods adopted in sustainable agri-production in other fruit orchards suggest other strategies that can be employed for sustainable apple production

Keywords

Apple orchards, Biocontrol methods, Integrated Pest Management, Sustainable management

Introduction

Human populations are dependent directly or indirectly on available agriculture and natural resources. Recent times have seen a tremendous increase in horticulture production including fruits, making India the second-largest producer of fruits in the world with an area of 6506 thousand hectares (ha) under fruit cultivation and annual production of about 100448 thousand metric tons (MT) in the year 2020 (https://www.statista.com/statistics/621278/fruit-production-by-type-india). In India, apples (*Malus pumila* Mill.) were cultivated on an area of 301 thousand ha with a production of 2783 thousand MT in the year 2020 (https://www.statista.com/statistics/621278/fruit-production-by-type-india) making India one of the top 10 producers of apples in the world (www.worldatlas.com/articles/top-apple-producing-countries-in-the-world.html). Central Asia, Asia Minor, the Caucasus, western China, Himalayan India and Pakistan are the primary centre of origin of *Malus* cultivars. Apples are predominantly grown in the four states of Jammu and Kashmir, Himachal Pradesh, Uttarakhand and Arunachal Pradesh followed by Kerala, Nagaland and Tamil Nadu. Even though India`s total contribution to the world apple production is only around 3% it is still a large contributor to the economic well-being of the Indian farmer. It remains a lucrative option as compared to other crops in the apple-growing states (1, 2). Several criteria affect the quality and quantity of apples. Some of these include good orchard management practices, conventional methods of apple production, limiting factors like changing climatic conditions (optimum climatic conditions requires 1200-1500 hrs of chilling below 7 °C depending on the type of cultivar) in the country, soil erosion and susceptibility to several diseases (https://www.agrifarming.in/apple-farming-information). Since apple orchards are perennial tree crop systems, they require high pesticide input (chlorpyrifos, fenitrothion, carbaryl, etc.) that can, in turn, lead to issues like ecotoxicity and pollution of both land and water ecosystems. Using synthetic pesticides like DDT, BHC etc. also leads to pest resistance and associated problems of biomagnification, bioaccumulation and secondary pest outbreak/resurgence (3). To minimize the losses and environmental pollution, various countries including India are taking to different methodologies like sustainable pest and disease management programs including biocontrol strategies for numerous fruits including apples (4). The 2030 Agenda for Sustainable Development was adopted by the United Nations Member States in 2015, which provides a shared blueprint for peace and prosperity. The agenda include efforts to be made to end hunger and poverty, reduce inequality and improve health, education and economic growth. Preservation of forests and oceans should be done while tackling climate change (https://sustainabledevelopment.un.org/post2015/transformingourworld). It has been recognized that the horticulture sector can make significant contributions towards sustainable development (5) by developing programmes employing suitable orchard management practices. Successful implementation of these programmes requires the integration of information from different sources and complicated tactical decisions (6, 7). Farmers and crop managers need detailed and comprehensive sustainability assessment practices for analyzing and defining orchard systems like the directed use of genetic resources in apple improvement programmes. Consumers today are gravitating towards organically grown produce and prefer to consume products grown using sustainable methods as opposed to industrially produced goods. The attention on biological control in the context of Integrated Pest Management (IPM) is increasing as there is a growing demand for high-quality and safe apple fruit produced without the use of chemicals. Sustainable practices under biological control minimize the resistance of pests to various methods of pest management (e.g., pest-resistant cultivars and pesticides), involve maximum use of renewable resources (e.g., natural enemies), improve cost-effectiveness and minimize the use of chemical pesticides that lead to both crop and environmental toxicity (8). Sustainability, thus, has been conceptualized to be of great use to organic growing systems (9). In this review, we explore various management strategies for controlling important pests and diseases and the potential of biocontrol as a sustainable management strategy in apple orchards (Fig. 1).

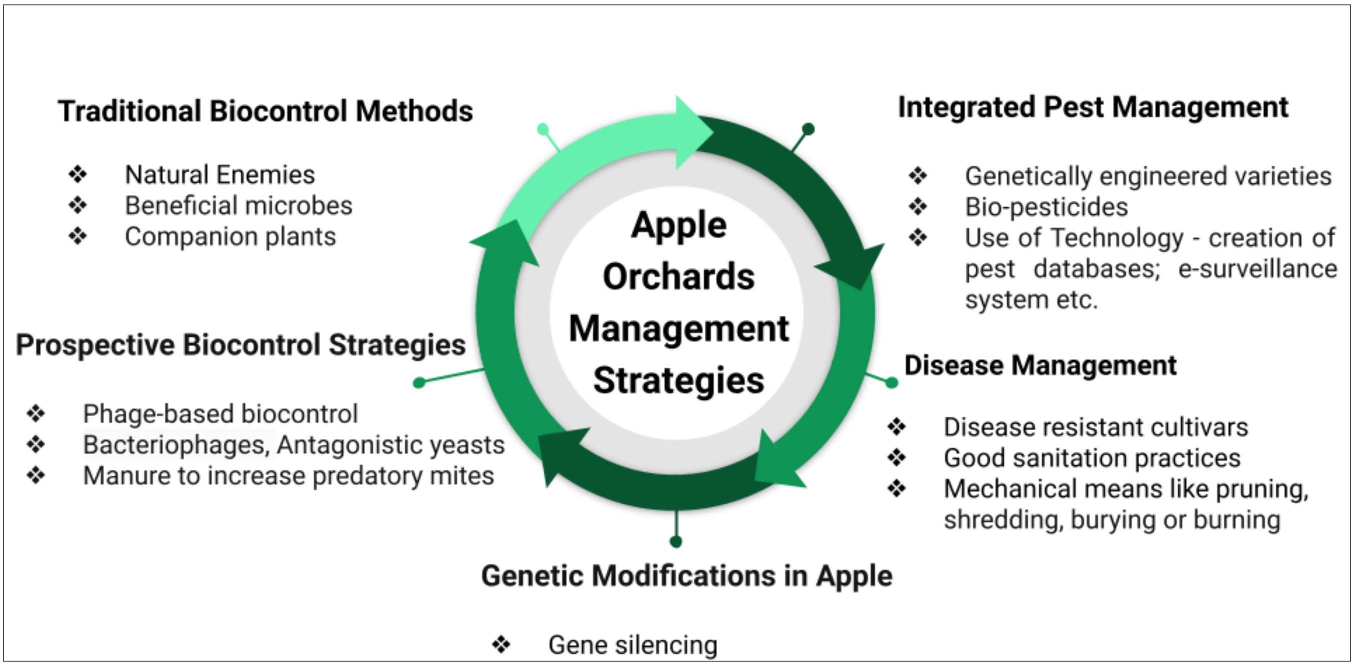

Fig. 1. Various Management Strategies adopted in Apple Orchards.

Integrated Pest Management (IPM)

In the Indian horticulture scenario, apple is an important industry but the introduction of different varieties of apple in the native apple-growing regions has also led to the emergence of exotic pests of apple that require control if the crop is to thrive and give economic returns (10). A set of practices known as Integrated Pest Management (IPM) were enforced in Indian agriculture by the National Agricultural Policy 2001. Creation of central pest databases, adoption of e-surveillance systems, survey and monitoring programs, use of biotechnology to create disease-resistant varieties, emphasis on the use of green pesticides, forewarning systems, shift to biological control methods and promoting the use of information technology are some of the initiatives being undertaken to promote IPM as a major plant protection tool in India (11). The strategies employed in the implementation of IPM in India are dependent on the type of pest that infests the crop and different techniques are used for each pest. Key pests of apple, damage caused and IPM strategies adopted for their control in India (12) are described in Table 1.

Sustainable IPM strategies

The main constraints faced by Indian farmers concerning the adoption of IPM have been primarily the high cost of IPM implementation, the emergence of resistant pests coupled with lack of knowledge and real-time information (24). To overcome these constraints various advances have been made in IPM methodologies like the increased use of genetically modified varieties that are resistant to pests (25), biopesticides (26), and technological advances such as Intelligent Decision Support Systems (IDSS) and Sustain OS that improves the accuracy of IPM methods. Both these systems analyze various parameters like the life cycle of pests, weather conditions of a given cultivar, environmental risk of a particular method, labor availability etc to come up with solutions specific to a particular apple orchard. Modification of earlier data to suit the present conditions and retaining this information are also hallmarks of these computer-aided agriculture programs (6, 7). Other methods involve e-pest surveillance and orchard monitoring like those which are currently being run by the National Research Centre for Integrated Pest Management (NCIPM).

Table 1. Key pests of apple, damage caused and their control by Integrated Pest management (IPM) in India.

Pests of Apple	Damage caused	Control Measures (IPM)	References
San Jose Scale (*Quadraspidiotus perniciosus*) is an exotic pest of apple and also infects other fruits like plum, peach and pear in the fruit growing regions of India.	It damages all above-ground parts of the plant by sucking sap and results in the appearance of distinct spots on the fruit resulting in poor quality produce.	1. Disinfection by burning all branches that may have harbored the scale during the winter months. 2. Spraying of the requisite chemicals is carried out before leaves appear in the trees and also if there is an appearance of the crawlers. 3. Parasitoids like *Encarsia perniciosi* and *Aphytis diaspidis* and predators like *Chilocorus* sp. are used to control the infestation levels. 4. Avoid planting of shade trees like willow, poplar etc. in and around fruit orchards as they act as secondary	13-15
Wooly apple aphid (*Eriosoma lanigerum*)	Infects both above and below-ground parts of the plant. Sucks the sap from the plant and creates large knots in the root.	1.Visual monitoring the aphid population. 2. Use of parasite, *Aphelinus mali.* 3. Sticky traps to track the migration cycles of the aphid. 4. Neem oil and chlorpyrifos as pesticides.	16
European red mite (*Panonychus ulmi)* and two-spotted mite (*Tetranychus urticae*)	Both types of mites cause damage to the leaves of the plant and lead to their bronzing. They also cause weakening of the fruit buds.	1.Monitoring the presence of eggs on twigs followed by removal and burning 2. Both winter and summer sprays can be done. 3. Use of predatory mites like *Amblyseius fallacis* and lady bird beetles. 4. Anthocorid bug, *Blaptostethus pallescens* has also shown promise as a future biological control agent.	17
Indian gypsy moth (*Lymantria obfuscate*) and Codling moth	Main damage to the apple trees is done by the caterpillars that feed on the leaves and cause defoliation. Repeated attacks by the caterpillars can lead to tree death.	1. Keeping track of the egg population, removing and destroying the eggs. 2. Using pheromone baited and delta traps. 3. Spraying if damage is seen in the orchards 4. Use of Nuclear Polyhedrosis Virus (NPV) as a pesticide 5. use of parasitoids like *Trichogramma embryophagum* and *T. caccia pallidum* that attack the eggs of the moth. 5. Removal of grasses grown around the tree helps to	15, 18-20
Stem borer (*Aeolesthes sarta*) and Apple stem borer (*Apriona cinerea*)	Signs of infestation are rotting tree bark, dust from exit holes due to grubs, dying limbs and yellowing of leaves are all due to infestation with the apple stem borer.	1. Burning of infested limbs and stems. 2. Spraying with pesticides, fumigants and insecticides and plugging of holes with petrol, odonil, mud etc. 3. Visual tracking to monitor the infection.	12, 21
Apple leaf miner (*Lyonetia clerkella*)	Causes extensive damage to the apple trees in Asia. The larvae attack the leaves and result in widespread defolia-	1. Pheromone-baited traps 2. Insecticides are used only when there is a wide spread attack by the leaf miner. 3. Eulophid parasitoids have been shown to attack the	22

Bark Beetle (*Scolytus nitidus*)	Damages the translocation of food and water in the bark leading to arrested growth. Attacked trees show reduced yield and foliage density.	1. Pheromone-baited, ethanol-baited and yellow sticky traps can be used. 2. Visual track of the infestation. 3. Insecticides should be used before egg laying on the bark by the adults. 4. Infested branches and stems should be removed and burnt. 5. Predatory species of the bark beetle can be used for biological control.	23

These programmes monitor pests and the data collected is shared with center experts who advise state agricultural departments that in turn forward the information to the farmers and help them take timely action. These sustainable IPM strategies help the farmers overcome the complexity associated with IPM methods and apply solutions that are safer for the environment.

Plant-derived insecticides and IPM

Plant-derived insecticides are increasingly becoming an integral part of IPM approaches due to their advantageous qualities like being less or non-persistent in the environment along with being non-toxic to other non-target organisms. Furthermore, their effectiveness, diversified modes of action and low cost of source materials make them easily acceptable to Indian farmers (27). It is estimated that more than 2500 plants belonging to nearly 235 families like *Apocynaceae, Asteraceae, Euphorbiaceae, Fabaceae, Meliaceae, Myrtaceae, Ranunculaceae and Rosaceae* contain promising biomolecules (28). Some of the more complex mixtures of various botanicals can be applied not only in IPM techniques but also to manufacture protective chemicals for the apple crop (29, 30). Most pesticide formulations available today comprise a neem base followed by pyrethrins and eucalyptus oil-based pesticides. All of these are registered and prescribed by the Central Insecticide Board and Registration Committee (CIBRC), Department of Agriculture and Farmers Welfare, India (27). The increased use of these naturally occurring botanical pesticides can help cater to the huge demand for organically grown apples. Moreover, further screening of native plants in and around apple growing areas for secondary metabolites like phenolics, terpenes, alkaloids, lignans and their glycosides can also help in identifying more plant-based insecticides.

Disease Management

Many diseases affect apple trees worldwide. Table 2 describes the major diseases of apples and the strategies adopted in their control.

Sustainable disease management strategies

In apple disease control, the choice of cultivar and rootstocks is of great importance. Resistant apple cultivars can reduce the use of chemical fungicides and minimize the need for forecasting weather (35). Some of the cultivars, which were relatively disease-resistant at the beginning of the 20th century, have now become susceptible to diseases (36), indicating that use of only resistant varieties is not sufficient. In the case of apple scab and powdery mildew use of chemical methods even though economically more beneficial is not able to contain the occurrence of both the diseases together. Also, the diseases might not occur during the same period and the cycle of the diseases are not always the same. However, dormant sprays and sanitation practices in combination can control various diseases in the orchards (37). In IPM strategy, sanitation practices are a fundamental approach to pest and disease control. For *Phytophthora sp.,* chemical fosetyl-aluminum completely controlled the disease and increased fruit yield and growth (34). Sanitation practices and the use of copper compounds can be used for the control of fire blight (38). To date, there is an emphasis on the use of copper and sulfur compounds for disease control in the cultivation of organic apples (39).

Integrating sprays of 1% mono-potassium phosphate (MPH) fertilizer with systemic fungicides can also be useful in mildew resistance management. Non-chemical control options include physical (mechanical) and sustainable biological control measures. Minimizing apple diseases via mechanical methods involves getting rid of infected above-ground parts of the plant by pruning, shredding, burying or burning them. These methods help to reduce the spread of disease and eradicate inoculum sources. A recent study in integrated and organic apple orchards showed that pruning did not save the plants from attacks by mildew (40). Not many biological control agents like natural antagonists of powdery mildew are available. Pycnidial fungi

Table 2. Diseases of apple and their control

Diseases	Causal Organism	Region	Control Measures	Reference
Apple Scab	*Venturia inaequalis*	India	1. Chemical: scheduled spraying of fungicides. 2. Resistant cultivars 3. Biological control 4. Cultural control	31
Powdery mildew	*Podosphaera leucotricha*	India	1. Fungicides (Proquinazid 20 EC) at 0.020 and 0.025% concentration. 2. Rootstock and varietal improvement.	32, 33
Collar rot	*Phytophthora cactorum*	India	1. Fungicide drenching, biocontrol using Trichoderma spp. 2. Rootstock and varietal improvement.	33

Crown gall	*Agrobacterium tumefaciens*	India	1. Use of rootstocks with low susceptibility. 2. Use of good cultural and sanitation practices.	34
Southern blight/ Sclerotius blight	*Sclerotium rolfsii*	India	1. Use of fungicides 2. Rootstocks like M.9	34
Fire Blight	*Erwinia amylovora*	India and many other parts of the world	1. Spraying with streptomycin. 2. Disinfection of tools with mercuric chloride after each use.	34
Apple mosaic disease	*Apple mosaic virus*	Widespread distribution throughout the world including India.	1. Use of certified virus tested planting material. 2. Using virus-free grafting scion.	34

from the genus *Ampelomyces* are one such example of natural antagonists that are used worldwide for biocontrol (41).

Genetic Modifications in Apple

Transgenic approaches for disease and pest management have not been explored in apples. Overexpressing the birch (*Betula pendula*) MADS4 transcription factor in apples by making use of the rapid crop cycle breeding methodology (42) were able to produce 18 advanced selections of the fifth generation from the line T1190 and 'Evereste' as the source of the fire blight resistance (Fb_E locus). The null segregants maintained the high level of fire blight resistance typical for 'Evereste' besides possessing a regular habitus. "Arctic Apples" are the first genetically modified apple approved by the FDA for US sale. In "Arctic Apple" Gene silencing was used to reduce the expression of polyphenol oxidase (PPO), which prevents enzymatic browning of the apple after it has been sliced open. The trait also includes an antibiotic resistance gene from bacteria that is resistant to the antibiotic kanamycin (43).

Weed Management

Another problem in the apple orchards is weed infestation. *Chenopodium album* L. *Amaranthus viridis* L., *Pers., Agropyron repens* L., *Cynodon dactylon* L., *Cyperus rotundus* L., *Bidens pilosa* L., *Sorghum halepense* L. and *Trifolium repens* L. are some of the common weeds found in Srinagar, Jammu and Kashmir, India. To control these weeds various methods have been employed like paddy straw mulch followed by glyphosate, atrazine followed by pendimethalin (44, 45). For chemical control of weed infestations in orchards, farmers mostly use two herbicides namely AFFINEX (5 g/l Carfentrazone-ethyl + 360 g/l glyphosate isopropylamine salt) and NASA 36SL (glyphosate). A small proportion of farmers also manually weeded their orchards. Weed interferences can be controlled with herbicides and proper cultural practices (38). Mulching is a common way of controlling weeds manually and it also reduces competition for resources in apple orchards. Mulch covers the soil surface and prevents weed seeds from germinating and suppresses the growth of emerging seedlings (46). Weed control methods adopted by farmers in apple orchards are diverse and include manual weeding, various mechanical and chemical methods. Combinations of mechanical and chemical (according to 45, the application of paddy straw mulch followed by chemical glyphosate reduced the weed growth and increased the soil quality, which, in turn increased apple tree growth and development) or mechanical and manual methods are also used by farmers. There were few -scale farmers whose orchards were grazed by cattle, to control weeds (38). In India, 44, 45 carried out studies on the control of various Monocot and dicot weeds in Srinagar, Jammu and Kashmir and concluded that the best results for weed management were obtained with the use of paddy straw mulch followed by glyphosate and by atrazine followed by pendimethalin. In another study based in the same region of Jammu and Kashmir, (47) showed that Oxyfluorfen followed by Glufosinate ammonium, Oxyfluorfen followed by Glyphosate, unpunched black polyethylene mulch and paddy straw mulch gave the best results for weed control.

Biocontrol Methods

Biocontrol or biological control is defined as "the use of a living organism to decrease the population density of another living organism". It can therefore be used in the management of diseases, weeds and pests. Biological control measures can either use macrobial agents like predatory insects and mites (insects that attack other insects as well as mite pests; parasitize other insects or nematodes) or 'microbial' agents (bacteria, viruses and fungi). For the biocontrol of weeds, different herbivorous insects and mites are used (48). In the sustainable production of apples and other crops, biocontrol of insect pests and diseases is the milestone. The sustainability of biocontrol will be enhanced as the ecology of orchards lends to the application of many management options. For decades the orchards remain in place favouring the evolution of a mature, stable, community of species used in biological control. Management practices like windbreaks, interplanting, mulches and partner plants have increased the population of natural enemies of insects and enhanced the rates of biological control. Temporal stability remaining undisturbed for 20 years or more and a multitude of habitats within a complex three-dimensional architecture are the characteristics of an Orchard (49). The combination of diversity in microhabitats and temporal stability creates opportunities to produce functionally diverse biodiversity that results in the biological control of numerous pests. All the components of the agroecosystem must be considered including the rhizosphere microbiome, detritus food web, plant communities in the apple orchard and the food web they support, as well as the surrounding habitats that provide both beneficial colonists and pests to the orchard as these components can contribute to the sustainability of biocontrol in the orchard.

Traditional Biocontrol Strategies

For developing a strategy for sustainable biocontrol in orchards diverse practices are available. To control pests, beneficial natural enemies have been used in apples since the late nineteenth century (50) which has led to sustainable biocontrol, but precaution should be taken to avoid introducing alien species that could disrupt the natural biocontrol of other pests. Natural enemies should be provided with adequate food, shelter, alternative hosts and habitat. In classical biological control, alien invasive pests were mostly brought under control by indigenous enemy species brought in from the country of origin of the pest. Successful application of biological control has been carried out against a wide variety of pests both in greenhouses and open fields.

For example, augmentative control has been successfully applied in Chinese apple orchards using different biological control agents like *Trichogramma dendrolimi*, *Aphelinus mali* and *Beauveria bassiana* (4).

Companion plants with no other economic value are generally used within a crop or orchards to attract beneficial organisms. Flowering plants are useful in attracting biocontrol agents into crop systems and orchards as they provide pollen, nectar, habitat, alternate food and alternate hosts. However, in experimental trials, it has been difficult to document enhanced rates of biocontrol with companion plants. It was observed that there were increased numbers of natural enemies and decreased fruit loss from codling moths (*Cydia pomonella*) and fewer pests (51). They believed the reduction in pests is due to the presence of alternate habitats and food in companion planting. Similarly in New Zealand increased parasitism of tortricid pests was found in orchards when buckwheat was used as a companion plant as compared to herbicide-treated orchards (52).

Hedges and windbreaks around orchards also contribute to the biocontrol of apple orchards through the same mechanisms as companion plants. They also enhance beneficial pest populations. Windbreak's deposit airborne arthropods (natural enemies and pests) on the leeward side of the hedge (53). However, in the orchard, suitable species selection for windbreaks is important as it harbors natural enemies for the pests (54, 55). For biocontrol of mites, hedgerows have been observed to be especially useful (54). The only limitation in the suitability of hedgerows and windbreaks is that the impact of biocontrol enhancement may not affect the entire orchard. As there is a limit to the dispersal of natural enemies just like in natural habitat (56).

For improving organic matter in the soil, tree growth, and other soil properties, compost is beneficial (57). Compost when used as mulch, can help in the sustainable biocontrol of weed and insect pests. It was observed that composted poultry manure has increased, the abundance of the ground-dwelling predators, and detritivore trophic level (58). It was also found plots mulched with straw, plastic, or pine bark have fewer predatory ground beetles as compared to herbicide-treated plots (59). In a mature apple orchard, a mulch of composted poultry manure decreased the number of both the spotted tentiform leafminer (*Phyllonorycter blancardella*) and the woolly apple aphid (*Eriosoma lanigerum*) (60). When compost mulch was used in the absence of herbicide, an interesting synergistic effect on the ratio of predators to herbivores was found (61). The ratio of predators to herbivores is a useful index on the sustainability of biocontrol. Composted animal waste as a mulch in apple orchards is an effective measure in the sustainability of biocontrol but adding more phosphorus to the soil should be avoided (62).

Another practice for sustainable biocontrol is interplanting more than one fruit species in an orchard. Different species of *Prunus* such as peach (*P. persica*) and cherry (*P. avium*) have extrafloral nectar glands on the petioles and leaves which provide nutrition for beneficial insects. In an orchard having cherry, peach and apple trees there was more diversity and abundance of predatory insects on apples than on apples in orchards without interplanting (63). Biocontrol of rosy apple aphid, *Dysaphis plantaginea,* in orchards with interplanting peach was significantly higher than in the apple monoculture (64). Moreover, in a study of an apple orchard using potted peach trees in the center, there was significantly higher biocontrol of spirea aphid on apple trees adjacent to the potted peach trees as compared to more distant apple trees (65). Interplanting apple orchards with peach trees may have a significant role in increasing biocontrol sustainability, but more research is required for its implementation (66).

Conventional Biocontrol Strategies that Continue to be Effective

Natural enemies, beneficial microbes and companion plants which attract natural predators are the most effective and sustainable bio-strategies. Enhanced pest control benefits were seen by the use of zoophytophagous predator populations and their varied compositions (67). Bacterial antagonists *Pseudomonas agglomerans* ACBP2, *Bacillus amyloliquefaciens* LMR2, *Brevibacterium halotolerans* SF3 and SF4 and *Bacillus mojavensis* SF16 are useful in controlling fire blight disease *Erwinia amylovora* (41). Predator abundance is also improved with the use of different aromatic plants like Catnip (*Nepeta cataria L.*) French marigold (*Tagetes patula L.*) and Ageratum (*Ageratum houstonianum Mill.)* (68). Flowering plants when blooming in apple orchards attracted predators such as Coccinellidae, Syrphidae and Chrysopidae (69).

Biocontrol Strategies Adopted in Other Fruit Orchards

Table 3 describes various biocontrol measures used in fruit orchards worldwide. Application of manure significantly increased population density of the predatory mites *Parasitus americanus, Stratiolaelaps scimitus* in Citrus orchards (70). Chicken manure and biopesticides are effective against plant-parasitic nematodes (26). Phage-based biocontrols were used to control Bacterial canker *Pseudomonas syringae pv. actinidiae* in Kiwifruit (73). Bacteriophages were also used in sweet cherry cultivation to control bacterial canker caused by *Pseudomonas syringae pv. syringae* (78). *Aspergillus pseudodeflectus* F13 and *Lecanicillium aphanocladii* F28' have high entomopathogenic potential against Olive fly, *Bactrocera oleae* Gmelin and the Olive psyllid, *Euphyllura olivina* Costa (79) Antagonist yeasts controlled the *Penicillium digitatum* in citrus fruit (81). All these biocontrol strategies have immense potential and can be explored in apple orchards in near future.

Table 3. Biocontrol management strategies in some fruit orchards

Biocontrol Method	Pest/ Disease/ Weed	Orchard type	Country/ Region	Reference
Zoophytophagous insect, the mullein bug, *Campylomma*	Spider mite	Apple	Quebec	67
Application of manure significantly increased population density of the predatory mites *Parasitus americanus,*	*Thrips Chrysoperla carnea Coccinella septempunctata*	Citrus	Tunisia	70
European earwig (*Forficula auricularia*)	*Drosophila suzukii*	Cherry orchard	Kent, England	71
Combination of mating disruption and CAPEX 2 gave successful control	Leafrollers	Apple	Northern Germany	72
Phage-based biocontrol	Bacterial canker *Pseudomonas syringae* pv. *actinidiae*	Kiwifruit		73
Weaver ants (Oecophylla smaragdina, Hymenoptera)	Insects pests	Asian mango and citrus orchards	Southern Vietnam	74
Foliage-dwelling spiders	*Psyllids*	Pear trees	Central Europe,	75
Chicken manure and biopesticides	Plant- parasitic nematodes	Citrus orchards.	Egypt	26
Neoseiulus californicus	Oligonychus punicae (Hirst) (Trombidiformes: Tetranychidae)	Avocado orchards	Mexico	76
Antagonistic bacteria (mainly species from *Pseudomonas* and *Bacillus* genus) and bacteriophages.	Bacterial diseases *Xanthomonas citri Xylella fastidiosa Candidatus Liberibac-*	Citrus orchards		77
Bacteriophages	Bacterial canker caused by *Pseudomonas syringae* pv. *syringae*	Sweet cherry cultivation	Turkey	78
Aspergillus pseudodeflectus F13 and *Lecanicillium aphanocladii* F28' have high entomopathogenic potential	Olive fly, *Bactrocera oleae* Gmelin and the Olive psyllid, *Euphyllura olivina*	Olive	Tunisia	79
Efficient bacterial antagonists *Pseudomonas. agglomerans ACBP2, Bacillus. amyloliquefaciens LMR2, Brevibacterium halotolerans SF3 and SF4* and *Bacillus mojavensis*	Fire blight disease *Erwinia amylovora.*	Apple	Morocco	41
Aromatic plant species – French marigold (*Tagetes patula* L.), Ageratum (*Ageratum houstonianum* Mill.) and Catnip (*Nepeta cataria* L.) positively influenced predator abundance	Herbivore pests in agroforestry ecosystems.	Apple	China	68
Parasitoids and predators	Targeted pests are the diaspidids and	Citrus	Morocco	80
Three flowering plants were used which attracted predators such as Coccinellidae, Syrphidae, and Chrysopidae	*Aphis spiraecola*	Apple		69
Antagonist yeasts	*Penicillium digitatum*	Citrus fruit	Chongqing	81
Pseudomonas strains were the most effective	Fire blight *Erwinia amylovora*	Pear	Northern Algeria	82

Challenges in Biocontrol and future perspective

As observed from the biocontrol methods adopted in different orchards, there is huge potential for sustainable biocontrol in apple orchards. However, different methods of biocontrol may not be compatible, and they may differ with different sets of environmental conditions. Many factors including diversity of surrounding habitats, differences in climate, pest community and local conditions need to be considered while selecting the appropriate method for optimizing biocontrol in apple orchards. Many fruit pests could not be controlled adequately by biocontrol methods alone. Such pests, therefore, require additional control methods like host plant resistance, behavioral tactics (e.g., attract and kill, mating disruption, trapping), or selective pesticides and insecticides (16, 17, 23). Integration of sustainable biocontrol methods with various other pest control and horticultural methods needs to be optimized for the successful development of a sustainable orchard system (66). Moreover, public interventions should be considered to promote the apple-producing sector. Farmers should be trained about pests, diseases and biocontrol methods along with the awareness of climate change. There should be information transparency and better communication among apple farmers on IPM and markets should be created for organic apple produce (38). Biological control practitioners' portfolios can include creating societal awareness about the benefits of environmentally friendly and sustainable pest management. Due to economic and technical, but more importantly attitudinal barriers, environmentally sound management for a wide variety of diseases and pests has not been adapted for apple orchards. Biological control methods being the most sustainable, environmentally safest and cheapest system of orchard management will drive the increasing demand for organic fruit production.

Conclusion

Apple crop is a substantial contributor to the economic well-being of the Indian farmer and is a profitable option as compared to other crops in the apple-growing states (1, 2). Apart from economic sustainability it also has a huge social and environmental impact. Moreover, it has an immense potential to be a 'future smart food' (83). Disease management and control of weed infestation in apple requires the adoption of sustainable methods as even today management in fruit orchards depends largely on only chemical control options. The focus needs to shift towards the inclusion of more biocontrol resources to manage diseases and weeds in apple orchards. The high cost of IPM implementation, the emergence of resistant pests coupled with lack of knowledge and real-time information are some of the major constraints associated with the successful employment of IPM. Basis the various means of control studied in this review, it is suggested that increased use of genetically modified varieties that are resistant to pests (25), biopesticides (26) and technological advances such as Intelligent Decision Support Systems (IDSS) and Sustain OS that improves the accuracy of IPM methods provide solutions to some of the challenges faced by apple growers. Plant-derived insecticides, can be another viable method of choice in controlling pests due to their environment-friendly and sustainable features. These can be identified by screening of native plants for secondary metabolites in and around apple growing areas. By exploring management strategies adopted in various fruit orchards across the globe, we suggest that there is a huge potential for sustainable biocontrol in apple orchards too. The integration of sustainable IPM with biocontrol methods should be the penultimate goal for apple growers as this will not only help in maintaining soil health in the orchards but will also aid in attaining Sustainable Development Goals of beating poverty and hunger despite changing climatic conditions all over the world. This area therefore deserves further attention and research efforts as it holds the potential for improving apple yield in a sustainable and environment-friendly manner.

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Authors contributions

JK and CDR conceptualized and conceived the idea. MAP, CDR, TG & JK compiled and formulated the manuscript. SG, NB, PM, RK contributed section material to build the review. All the authors edited the manuscript to its final form.

Compliance with ethical standards

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