Green pest management: A case study of *Aphidius colemani,* Viereck, a biological control agent

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Abstract
Biological control agents offer potential alternatives for managing insect pests, reducing synthetic chemical use and their impact on the ecosystem and preserving ecological principles. The horticulture sector produce faces continuous rejection from international markets due to pest presence and residue limits. Alternative tactics like parasitoid predators are being proposed to address the challenge of injudicious pesticide use. Exposure to toxic chemicals and environmental pollution leads to health complications. The current review points out more emphasis on biological control agents as a potential core part of integrated pest management (IPM) to tackle crop pests and reduce chemical use. Notably, the use of parasitoids able to manage insect pests of economic importance is less likely to develop resistance and subsequent impact on the environment.

Keywords: biological control agents, insect pests, aphids, pesticides, french beans

Introduction

Globally, crop production must significantly increase in a sustainable rhythm to adequately meet the food requirements of the actively growing population [32,36,84]. In contrast, Food and Agricultural Organization [FAO] [23] report in the Sustainable Development Goals' (SDGs) 2030 agenda cites the existence of enough food. According to Valk *et al*. [80] and Sharma *et al*. [73], globally, losses of up to 45% in quality and quantity of crop marketable products are attributed to pest effects, hence curtailing sustainable production as a "granary for food security". Combating food insecurity is an urgent strategy needed to reduce crop insects' damage concerning a safer environment, which would be mankind's most outstanding achievement in the 21st century. In East Africa, most horticultural crops have been severely affected by various pests, particularly aphids severity, consequently reducing income, marketable value and livelihood manifold [11,25,52,59]

Aphids (Hemiptera: Aphididae) are among the most serious economic groups of insect pests common to the Fabaceae family worldwide [7,70,71]. Most of them being phytophagous, with the armored capability of causing significant damage and loss amounting to about 500 million dollars annually [56]; they inflict plants directly either by sucking plant sap or wounding tissues [11], and indirectly by transmitting pathogens to healthy plants [2,21,17,62,85] with their fecal matter "honey dew" on the surface of plant foliage anchoring sooty mold growth that leads to low aesthetical resistance [12,25,22,11]. This translates into recurring yield losses for many horticultural crops like French beans (*Phaseolus vulgaris L.*), especially when control remedies are not executed on time.

French bean, (Fabaceae) with immature, tender green pods often referred to as green beans, snap beans, kidney bean, haricot bean, or string bean [5,53,55]. French bean origin is deemed to be Asia, the annual world production exceeds 17 million tons (MT), with India being the biggest producer in the world, Brazil leads in Latin America and the Caribbean, while DRC, Kenya, Tanzania, and Uganda lead in Africa respectively [54]. French beans, constitute approximately 52% of the value and 61% of the volume of total vegetable exports of all fresh horticultural exports in Kenya accredited for rural community growth and development through increased level of income and upscaling standards of living [61,52,24]. Dougoud *et al*. (2018) made a groundbreaking discovery that acknowledges the use of biological control agents (BCAs) as a key element of the integrated pest management (IPM) approach for the control of arthropod pests, particularly aphids in the crop system because of their ability to lower pest population densities. The biological control agent includes microbial, e.g., insect-parasitic nematodes, predatory, parasitic arthropods and microbial e.g., fungal, bacterial and viral pathogens. In Kenya, green pest management prioritizes on using biological control agents and has gained value and interest among farmers in agricultural production to increase productivity with less or no negative impact on the environment. This review aimed to evaluate the use of biological control agents specifically parasitoids and predators.

Methodology

This review used a monographic approach based on unpublished and published findings. An inclusive search approach was developed basically to identify different literature relevant to the topic of study. The search ranged from articles, journal papers, book and book chapters to government sector, development partner reports found in different search engines such as Elsevier, Wiley online and Springer from 1990 to 2021. Specific searching words such as "biological control of aphids and their impact on the quality, shelf life of French beans". This was purposely to document the different integrated biological control strategies used to manage insect pests, especially aphids, quality and productivity of French beans in Kenya. Out of 1045 papers and report, based on the relevance to the subject matter, only 80 original papers and 12 grey literatures were selected to conduct this study.

Overview of biological control agent

Biological control dates back to around 4,000 years ago (cats against rats) by Ancient Egyptians (Kwenti, 2017) [24]. Fascinatingly, the historical use of predatory ant (*Oecophylla smaragdina)* as biocontrol control agents against citrus insect pests (*Tesseratoma papillosa)* and later use of ladybird beetles (*Coccinella septempunctata*) against aphids and scales was first cited in China [24]. However, the conceptualization and use of biological control agents are of modern development presumed to be around the 1890s. Subsequently, Kwenti's[24] report recognizes the first successful use and movement of parasitoids to control weevil (*Conotrachelus menuphar*) in the United States by Charles V. Riley in 1870. An illustrative of this is the annual address to the Entomological Society of America by Microbiologist Dr Stephen A. Forbes' in 1915, who profoundly argued every born and unborn scientist to employ the use of the ecological principle in pest management to avoid generational misfortune [73].

Stern *et al.* [65] initiated the conceptual ideas of integrated pest control, darkness evolution of pest resistance outburst the concern about environmental safety, aimed at harmonizing the use of biological control with other methods and eventually 'gave birth' to integrated pest management [IPM]. IPM was based on three core principles to overcome the 3R. Firstly, to reduce residual accumulation; ii) pests' resistance or cross-resistance [32, 28], iii) pest resurgence [43]. Clausen *et al.*'s [23] report comprehensively defined IPM as the use of two or more pest management measures to protect the agroecosystem, environment, and human health without affecting yield. Insect biodiversity, especially Hymenoptera, avail a natural pest regulation cue through the predators (direct consumption) or parasitoids [using the pest's body as a host for developing parasitoid].

The successfulness of parasitoids as biological pest control in many agricultural crop systems is manifested by their capability to suppress up to 90% of their host's population and this ranks their use as a strategic IPM approach [19]. Starý and Stechmann, [78] found host specificity characteristics, adaptation and nectar as an alternative source of nourishment for parasitoid survival, increased searching ability and parasitism rate of most parasitoids.

Table 1: Major natural enemy (parasitic wasps) commercially used for aphid insect pest management

Major host aphid species	***Parasitoids***	**Empirical evidence**
Aphis gossypii and Myzus persicae, Aphis punicae, Hyalopterus pruni	*Aphidius colemani*	Messelink *et al.*[46], Messing & Rabasse [47], Prado *et al*.[65], Al-Khawass [3], Pourtaghi *et al.* [64], Rashki *et al.* [68], Zamani *et al.* [91], Vásquez *et al.* [82]
Myzus persicae, Lipaphis erysim, Acyrthosiphon pisum, Rhopalosiphum padi,	*Aphidius gifuensis Ashmead, Aphidius colemani Viereck, Aphidius ervi Haliday, and Aphidius matricariae Haliday*	Byeon *et al.* [13,14], Hemidi and Laamari [29], Khan *et al.* [37] Kinyanjui *et al.* [38] Kumar *et al.* [40], Mohammed and Hatcher [49], Starý [76], Starý and Erdelen [77], Stary and Schmutterer [78], Völkl *et al.* [83], Wei *et al.* [88], Ward et. [86], Yano, [90], Zamani *et al*,. [91,92]
Myzus persicae, Macrosiphum Euphorbiae, Rhopalosiphum padi, Sitobion avenae, and *Metopolophium dirhodum*	*Aphidius Colemani and Aphelinus asychis,* Lysiphlebus testaceipes *and* Diaeretiella rapae	Adisu *et al.* [1], Byeon *et al.* [13,14], Ceolin Bortolotto *et al.* [16], Rakhshani,[66], Sengonca *et al.* [72], Wei *et al.*,[88]
Macrosiphum euphorbiae	*Aphelinus abdominalis*	Blümel & Hausdorf [9], Kumar *et al.* [40,41], Shrestha *et al.* [74].
Aphis spiraephaga Muell, Diuraphis noxia and Melanaphis sacchari	*Aphidius colemani, Diaeretiella rapae and A. platensis*	Heddle *et al.* [28], Mercer *et al.* [45], Rakhshani [66] Rakhshani *et al.*[67]
Aphis gossypii, Rhopalosiphum padi, Myzus persicae, Aphis donacis and Aulacorthum solani	*Aphidoletes aphidimyza and Aphidius colemani*	Cheng *et al.*,[18], Guo *et al.*, [27], Higashida *et al*,. [30], Meadow *et al.*,[44], Mottaghinia *et al.* [51], Prado *et al.* [65], Watanabe *et al.* [87], Yamane *et al.* [89], Yano, [90]
Myzus persicae, Pentalonia nigronervosa, Hyalopterus pruni, *Aphis fabae,*	*Aphidius transcaspicus Telenga and Ephedrus cerasicola*	Stary and Schmutterer [79], Starý and Stechmann, [78], Yano, [90]
Aphis fabae, Aphis craccivora; Acyrthosiphon pisum, Eriosoma lanigerum, Capitophorus inulae, Aphis punicae, Aphis gossypii. Rhopalosiphum maidi, Aphis rumicis, Uroleucon ambrosiae, Hyperomyzus lactucae, Uroleucon compositae	*Aphelinus mali, Aphidius colemani, Aphidius ervi, Binodoxys angelicae, Diaeretiella rapae, Praon yomenae Lysiphlebus confusus, Lysiphlebus fabarum, Hyperomyzus lactucae*	Ahmed *et al.* [2], Boivin *et al.* [10] Cannon *et al.*,[15], Hemidi and Laamari,[29], Messelink *et al.* [46], Monique *et al.* [50], Rakhshani, [67], Monique *et al.* [50], Wei *et al.* [88]

Parasitic wasps

Parasitic wasps are small wasps that attack other arthropods [42]. They are generally referred to as parasitoids. Reuter's 1913, classical review introduced the word 'parasitoid' with a definition that differentiates it from predators, parasitic wasps lay their eggs on or within their host, their larvae eventually kill their hosts by feeding on the bodies (its hosts) to complete their life cycle [31,42,60,69]. Additionally, Li *et al.* [63] and Cusumano *et* *al.* [34] reaffirmed the latter definition of parasitoids as wasps that lay their eggs directly into the aphid, and their larvae or progeny develop inside the host, resulting in a mummified host. The latter added that they attain nourishment and kill their host to complete their life cycle as they form mummies and are more host-specific insects than predators. Utmost insect parasitoids are wasps or flies, hence the name parasitic wasps.

Parasitoids have been reported to regulate aphids' devastation in many crops naturally. Most insect parasitoids play an important role in the natural management of pest arthropod populations and the suppression of plant damage [19]. They can parasitize their hosts up to 90% thus reducing their population level below the economic injury level [34]. Parasitoids play a more prominent role in balancing the ecosystem than any other predators, for example, parasitoids in the order of Hymenoptera can regulate the population of their hosts in nature so that a stable state of self-regulation is maintained in the ecosystem [19,65]. This has been evidenced in controlling *M. persicae* and cotton aphids that infest greenhouses [63,65,91]. Their use presents an enormous opportunity to reduce pesticide use [58,59], reduce the cost of production [63], and overcome the 3R as they are host-specific and therefore require one host to complete their life cycle. Thus, pparasitoids appear to be more effective if synchrony exists between the parasitoids, companion crop and the host.

Aphidius species (parasitoids use)

Aphidiinae (Ichneumonoidea: Braconidae) family consist of over 400 active species world over that are capable of parasitizing and suppressing aphid populations [29,69]. Aphidius species comprise of koinobiont solitary parasitoids, considered highly efficient and extensively used biological control agents (BCA) against aphids [67]. Aphidius adults undergo complete metamorphosis; they are small wasps less than 3 mm long. The female adult parasitizes the aphid by laying its eggs inside the host. During their larval development stage, they obtain nourishment within the aphid body. As the larva matures, the aphid is eventually killed and mummified, usually turning tan or golden in color. The adult parasite chews inside the mummified aphid to find point of exit.

Aphidius colemani is considered one of the commercially successful and effective parasitoids in suppressing the aphid population in the aphidiinae subfamily [6,37,33]. This has been evidenced in control of M. persicae and cotton aphids that infest the greenhouse [63,65,91]. Their use presents an enormous opportunity to reduce pesticide use [58,59], reduce the cost of production [63], and overcome the 3R as they are host-specific and therefore require one host to complete their life cycle. If widely used, this can lead to the realization of SDGs 2030 agenda proposed by FAO [23] which advocates for the use of ecological principles to enhance and sustain product quality and production patterns. Reuter’s 1913, classical review introduced the word ‘parasitoid’ with a definition that differentiates it from predators, parasitic wasps develop on or within their host, their larvae kill their hosts to complete their life cycle [60,69], unlike the predators which attack, kill and sometimes ingest their prey. Nevertheless, due to secondary parasitoids (hyperparasitoids), super-parasitoids, toxic pesticides, intraguild competitions, and extremely unfavorable conditions that negatively affect their dispersal and synchrony with target pests, parasitoids in the fields aren't always as successful as they should be [43,48,69]. Presently, emphasis on the use of parasitoids as IPM strategy tool, yet access and availability to them by most growers in developing countries has been sorely impeded by import restrictions, quality of products, and suitability with climatic conditions.

Arguably, there is greater urgency for alternative strategies to manage pests. This has fueled extensive studies to explore better compatible and control methods with the environment. In this context, bolstering use of IPM is on the brink of reducing pesticide use and strengthening a sustainable productivity system inclusively reliant on knowledge and understanding of agroecology that builds a healthy environment [80]. Use of natural enemies in East Africa and Kenya has gained insightful strength in response to the market demands of pesticide residue-free products on international and local markets. For this reason, many floricultures, olericulture, pomiculture and Ornamental, and landscaping sectors have embraced the integrated use of natural enemies.

Aphidius colemani

Aphidiinae (Ichneumonoidea: Braconidae) and Aphelinidae (Chalcidoidea) are the most common hymenopteran parasitoids that aggressively attack various aphid species such as *Aphis fabae, Aphis gossypii, Rhopalosiphum padi*, and *Myzus persicae*. Aphidiinae species being the most abundant and active species, can parasitize over 400 aphid species [29,75]. Aphidius colemani Viereck is solitary koinobiont endo-parasitic wasp with a host range of over 41 aphids species, is presumed native to India or Pakistan [13,35,47,65], and this contradicts [4,8] report from which they constructively argued out the origin to North America. *Aphidius colemani* are also considered highly efficient and extensively used biological control agents (BCA) against aphids [67]. Aphidius species comprises of. *Aphidius colemani* is considered one of the commercially successful and effective parasitoids in suppressing the aphid population in the aphidiinae subfamily [6,37,33]. The *Aphidius colemani* is considered prime biological control agents that farmers can embrace. In ideal conditions, *Aphidius colemani* can manage the aphid population to levels comparable to the results of pesticide application and is safer to the environment, and less time-consuming to apply [39]. If embraced, the excruciating pesticide side effects would become history. Conversely, findings by Hemidi and Laamari [29] re-emphasize the magnificent role of parasitoids in maintaining terrestrial food webs and the tri-trophic interaction that leads to a stable ecosystem.

Use of *Aphidius colemani* in insect management

Aphidius has been extensively used in the control of aphid colonies and is cited as a significant biological control agent (BCA) for in and outdoors. This is due to their instinctive unique abilities, especially of *Aphidius colemani*, like being able to detect plant responses when attacked by aphids and the attractive aroma of honeydew (aphids fecal excretes) produced by the aphids upon feeding on the plant [69,81]. Additionally, adult females are pro-ovigenic (once deposited, all their eggs mature into adults before exiting the host), prolific (capable of laying eggs daily) and heightened invasion frequency even under low host population [13,17]. Nickolus *et al*. [57] argued that Aphidius species comprise the most beneficial aphidiinae subfamilies. According to Hwang *et al*. [18], Aphidius colemani has been successful in controlling the green peach aphid and the cotton aphid (Aphis gossypii) (Myzus persicae) compared to its very close relative *Aphidius plantensis* with a more wider host range like *Aphis nerii*, *Rhopalosiphum padi*, *Capitophorus elaeagni*, *Brachycaudus helichrysi*, and *B. tragopogoni* in addition to *Aphis gossypii* and *M. persicae*. Several parasitic wasps have been used to control aphids as illustrated in the table 1 below.

Table 2: Registered biological control agent imported into Kenya between 2016 and 2021

Biological control agent	Biological control agent	Primary target pests
Aphidius transcaspinus	Parasitoid wasp	Aphids
Coccidoxenoides perminutus	Parasitoid wasp	Mealybugs
Diglyhus isaea	Parasitoid wasp	Diptera leaf miners
Encarsia formosa	Parasitoid wasp	Whiteflies
Eretmocerus eremicus	Parasitoid wasp	Whiteflies
Aphidius colemani	Parasitoid wasp	Aphids
Amblyseius californicus	Predatory mite	Mites
Amblyseius cucumeris	Predatory mite	Mites, Thrips
Amblyseius swirskii	Predatory mite	Whiteflies
Hypoaspis miles	Predatory mite	Thrips
Phytoseilus persimilis	Predatory mite	Mites
Amblyseius californicus	Predatory mite	Mites
Steinernema carpocapsae	Insect-parasitic nematode	Lepidoptera
Steinernema feltiae	Insect-parasitic nematode	Soil-pupating pests
Bacillus thuringiensis var. aizawai	Bacterial pathogen	Lepidoptera
Bacillus thuringiensis var. kurstaki	Bacterial pathogen	Lepidoptera
Paecilomyces fumosoroseus	Fungal pathogen	Aphids, whiteflies
Beauveria bassiana	Fungal pathogen	Wide range of pests
Lecanicillium lecanii	Fungal pathogen	Aphids, whiteflies
Metarhizium anisopliae	Fungal pathogen	Mites
NPV of Helicoverpa armigera[b]	Viral pathogen	Cotton bollworm

Challenges in the use of parasitoids

Prado *et al*. [65] argued that parasitoids' invasion success requires the ecological theory to hold true and for this to happen, and interaction expressed by $r < aP^*$ should be achieved. Where r = prey growth rate, a = attack rate per predator per unit prey, and P^* = predator abundance at equilibrium. However, parasitoids in the fields are sometimes not as successful as they should be because of secondary parasitoids (hyperparasitoids), super-parasitoids, toxic pesticide used, intraguild competitions, extreme unfavorable conditions which adversely disrupts their dispersal and synchrony with target pests as detailed in figure 1 [20,43,48,69]. Presently, there is a prime emphasis on the use of parasitoids as an IPM strategy tool, yet import restrictions, quality of products, and suitability with climatic conditions have sorely impeded access and availability to them by most growers in developing countries. Adoption of the use of parasitoids among farmers is still low because of a lack of adequate knowledge about the parasitoids, how to manage them, accessibility and the cost of buying. Arguably, the use of natural enemies such as parasitoids to manage pests in East Africa and Kenya has tremendously gained insightful strength in response to the market demands of pesticide residue-free products on both international and local markets. This has fueled extensive studies to explore better compatible and control methods with the environment. In this context, bolstering the use of IPM is on the brink of reducing pesticide use and strengthening a sustainable production system inclusively reliant on knowledge and understanding of agroecology that builds a healthy environment [80]. For this reason, the floriculture, olericulture, pomiculture and Ornamental, and landscaping sectors have embraced the integrated use of natural enemies.

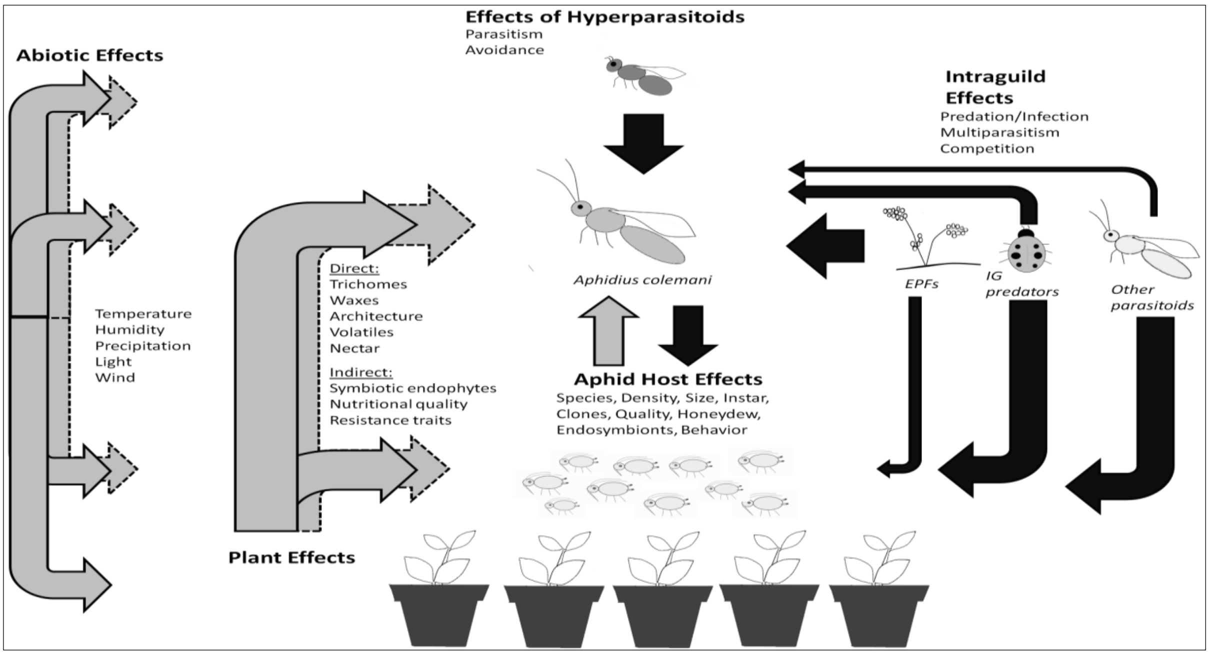

Fig 1: Ecological principle that affects the effectiveness of *A. colemani* parasitoid, Full black arrows indicate positive or negative effects on either the wasp or the pest. The dashed grey arrow indicates the indirect positive. Adopted from Prado *et al*. [65]

Presently, the world over, there is a prime emphasis on the use of parasitoids as IPM strategy tool, yet access, availability to them by most growers in developing countries has been sorely impeded by import restrictions, quality of products, and suitability with climatic conditions. Illustrative studies by Grzywacz *et al*. [26] and Sharma *et al*. [73] documented heavy and harmful use of synthetic chemicals since the 1950s thus tabling concern about their adverse effects. This has pushed for the prerequisite rebirth for natural control measure use such as the use of biological control agents to level insect pest damage to counteract the rejection, filed lawsuit complained and banned by several destined markets due to low standards with residual above limits required by the consumer protection act in those countries. Most products are from developing countries, triggering concern and awareness for integrating biological control agents to alleviate the root cause of indiscriminative use of synthetic chemicals. Arguably, the use of natural enemies such as parasitoids to manage pests in East Africa and Kenya has tremendously gained insightful strength in response to the market demands of pesticide residue-free products on both international and local markets. However, adoption of the use of parasitoids among framer in Kenya is still low because of inadequate knowledge about the parasitoids, how to manage them, accessibility and the cost of buying [26]. This has fueled extensive studies to explore better compatible and control methods with the environment. In this context, bolstering the use of IPM is on the brink of reducing pesticide use and strengthening a sustainable production system that is inclusively reliant on knowledge and understanding of agroecology that builds a healthy environment [26,80].

Conclusion
The need for sustainable agriculture and ecological restoration is driving policy changes to restrict chemical pesticide use. Horticultural firms are adopting natural enemies as an alternative approach. This could be adopted by countries with economic growth in agriculture. Adopting biological control measures or green pest management such as the use of natural enemies, parasitoids combined with integrated pest management approaches that are user friendly to farmers as well as offer sustainable solutions, reduce reliance on chemical pesticides, and transform agricultural practices sustainably.

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