Biological control of desert locust (*Schistocerca gregaria* Forskål)

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Abstract

Desert locust (*Schistocerca gregaria* Forskål) is one of the most serious agricultural pests in the world due to its voracity, speed of reproduction, and range of flight. We discuss the current state of knowledge on its biological control using microorganisms and botanical extracts. *Metarhizium flavoviride* was among the first fungus to be recognized as a bio-control agent against desert locust in the laboratory and field conditions. Nevertheless, its oil formulation adversely affected non-target organisms, hence led to further research on other microorganisms. *Metarhizium anisopliae* var. *acridum* (syn. *Metarhizium acridum*) is an environmentally safer bio-pesticide that has no measurable impact on non-target organisms. However, there are various shortcomings associated with its use in desert locust control as highlighted in this review. Bacterial pathogens studied were from species of *Bacillus*, *Pseudomonas*, and *Serratia*. Botanical extracts of 27 plant species were tested against the locust but showed varied results. *Azadirachta indica* and *Melia volkensii* were the most studied plant species, both belonging to family Meliaceae, which is known to have biologically active limonoids. Out of the 20 plant families identified, Apiaceae was the most represented with a frequency of 21%. However, only crude botanical extracts were used and therefore, the active ingredients against desert locust were not identified. Through a comprehensive research, an integrated pest management strategy that incorporates these bio-controls would be a realistic option to control desert locust infestations.

Keywords: bio-control, bio-pesticides, desert locust, microorganisms, botanical extracts

Review Methodology: Research questions were raised using PICO (population, intervention, comparison, and outcomes) and then validated to ensure that they had not been addressed by any other publications. In this case, P-desert locust, I-Bio-control, C-use of chemical pesticides, and O-success of application. A systematic review was then carried out using various keywords. The following search engines and databases were used: Google, Google Scholar, PubMed, ScienceDirect, FAO Desert Locust Information Service, CABI, and HINARI. Titles and abstracts were screened followed by full-text downloading and analysis. Some authors were contacted for full publications where only the abstracts were available.

Introduction

Desert locust (*Schistocerca gregaria* Forskål) is one of the most serious agricultural pests in the world due to its voracity, speed of reproduction, and range of flights, which can cause huge damage to all plant species [1]. A single swarm can comprise of up to 80 million locusts per square kilometer and can fly more than 100 km in the direction of prevailing winds to cover an area of about 1200 square kilometers per day [2]. If left uncontrolled, desert locust can invade a total area of 28 million square kilometers, which is approximately 20% of the earth's surface [3]. In 1 day, the swarm is capable of consuming the same amount of food as approximately 35,000 people, with each locust consuming about its own weight of green vegetation [4]. The plagues are associated with great economic losses hence require urgent attention to safeguard livelihoods and the environment.

Desert locust invasion is usually restricted to the semi-arid and arid deserts of Africa that receives less than 200 mm of rainfall annually [5]. In 1986–1989, desert locust plague affected 43 countries after heavy rains. This plague ended mainly because of control operations and unusual winds that blew swarms across the Atlantic Ocean [6]. A similar swarm was witnessed from 2003 to 2005 where more than 20 countries suffered with an estimated 80–100% loss of crops especially in sub-Saharan Africa [7]. During this time, control operations treated nearly 130,000 per square kilometers of the locust infestation area. The operation took 2 years and spent more than US$ 400 million to end the plague [6]. Between 2019 and 2020, exceptional locust breeding was observed in the horn of Africa [4]. This magnitude of invasion had not been witnessed for more than 70 years in East Africa. A prediction model demonstrated that vast areas of Kenya, northeastern regions of Uganda, and some regions of Southern Sudan were at high risk of providing a breeding environment for the locust [8]. The onset of long rains season in East Africa would also remarkably increase the swarms, threatening food security and livelihoods [4]. This rapid and sudden upsurge could be attributed to erratic climatic behavior that is triggered by global warming [9]. However, predictions are mainly based on ecological aspects but should also integrate the social, economic, and cultural aspects for effective control measures.

Desert locust is able to change its behavior and physiology in response to environmental conditions, transforming the swarms from harmless solitary insects to destructive cohesive ones [10]. This feature allows locusts to survive some of the harshest environmental conditions on earth. Seasonal migration of the desert locust is influenced by various factors such as rainfall, temperature, wind, and vegetation [11]. Favorable conditions for breeding are moist soils to depths of 10–15 cm, moist bare areas for egg-laying, and green vegetation for hopper development [12]. Sparse and erratic seasonal rains support phase change from their solitary lifestyle to a group lifestyle (gregarious phase) that develop into an upsurge and eventually into a plague [13]. These density-dependent changes are adaptations for migration under heterogeneous environmental conditions. For instance, a research study estimated the density of gregarization of desert locust hoppers in vegetation and reported that vegetation cover and height were the only characteristics that could enhance prediction of locust phase status [14]. A related study reported that low cover and dry vegetation led to a low density of gregarization while dense and green vegetation favored a high density of gregarization, probably due to a dispersion rate of the individuals. Another experiment explored the influence of vegetation patterns on gregarization and showed that when the distribution of the vegetation was patchy, the locusts were more active, experienced higher levels of crowding and became more gregarious [15]. This demonstrates that vegetation distribution influences individual behavior and phase state and plays a major role in population level responses. In a survey for early detection and control of desert locust in Sudan, locust densities varied according to the amount and distribution of rainfall and longevity of the annual green vegetation [16]. If these conditions are unfavorable, the swarm migrates until it encounters favorable breeding conditions, which may be thousands of kilometers away [12]. Effective preventive management strategy should therefore not only rely on the knowledge of the pest biology and ecology but also on the environmental factors associated with its spread.

Repeated outbreaks of desert locust in Africa have prompted the use of chemical pesticides as the main preventive and control measures. Most of the locust control measures carried out over the years have used conventional chemical insecticides (organochlorines, organophosphates, carbamates, and pyrethroids) that are usually neurotoxic to the locust [17]. Although chemical pesticides may provide an effective means of control due to prolonged activity of the spray residue, increased attention has been raised concerning environmental damage and human safety [18]. After treatment with chemicals, death of insects occurs within hours, making it difficult to monitor the effects of spray applications especially for highly mobile species [19]. As an upsurge starts, only a few locusts are aggregated into treatable targets and hence spraying leaves out many individuals that continue the upsurge and become aggregated at high densities [13]. Some chemical insecticides have been effective at preventing desert locust outbreaks at very early stages of invasion under Saharan condition but they simultaneously induce heavy mortality in some non-target insect groups [20]. Besides, the outbreaks occur in environmentally sensitive areas especially wetlands, near human settlements and to some extent in the protected areas with numerous migratory birds [21]. In East Africa, current management strategy for desert locust swarms is aerial spraying with chemical pesticides, which has affected humans, livestock, and the environment [8]. The concern regarding use of chemical pesticides provides impetus for investment in alternative means of control that are environmentally friendly and sustainable, such as bio-pesticides [13, 22] even though much remains to be done in terms of research and implementation.

Successful control of desert locust will require the development of an integrated pest management program using a variety of products that can be applied with a range of techniques that are appropriate in different habitats and circumstances [23]. This must be associated with reduced pesticide application, economic costs, environmental risks, and duration and extent of the locust threat [24]. Proposed products include bio-pesticides from plants and microorganisms. They are recommended because of their high specificity, very little adverse impact on the environment, and are non-toxic to humans and livestock when used at recommended doses [25]. A simulation model suggested that applying even a conservative rate of control from the beginning of an upsurge as part of early intervention would further reduce the size of upsurges and plagues and would contribute to better management of desert locust populations [23].

Use of microorganisms as bio-control agents

Only a few fungal and bacterial pathogens have been reported to show their efficacy against the desert locust (Table 1). Entomopathogenic fungi are potentially the most versatile bio-control agents due to their wide host range and natural occurrence, which makes them less damaging to the environment [42]. They are also slower acting than chemicals thus best suitable during early infestations. Entomopathogenic fungi and nematodes can be more effective when applied on the soil surface rather than spray treatment [38].

Early research on the use of fungi as a bio-control agent against desert locust was focused on *Metarhizium flavoviride*. The fungus was tested in both laboratory and field conditions and showed significant results. Treatments were made using oil formulations that improved the efficacy as compared to water-based formulations. For example, formulations of *M. flavoviride* in cottonseed oil showed superior performance to water-based suspensions at low humidity hence applicability in less humid environments [43]. In a laboratory experiment, adult desert locusts inoculated with *M. flavoviride* reduced their daily food consumption and died within a period of 5–14 days [33]. The results concur with those reported on significant reduction in flight activity and food consumption on the 3rd day after application, with a 100% mortality occurring on the 6th day after treatment [34]. When *M. flavoviride* oil formulation was tested in the field, the treated locusts showed a reduction of hopper bands into small groups with maximal daily mortality at 10–11 days in the open field and 6–10 days in cages [19]. A similar study in the field showed a population reduction of adult locusts by 90% in 10 days after application. In dense vegetation, the formulation resulted in 70% control within 14 days after application [35]. However, a major concern with an oil formulation of *M. flavoviride* is its effects on non-target organisms especially bees [44], and therefore, safety testing on such non-target organisms should be considered.

Various publications have focused on the use of entomopathogenic fungus *M. anisopliae* as a bio-control agent against many species [45]. *Metarhizium anisopliae* var. *acridum*, commonly known as *Metarhizium acridum* in modern science [46], is an environmentally safer commercial bio-pesticide that has been developed for ultra low volume spraying [13]. The bio-pesticide kills about 70–90% of treated locusts within 14–20 days with no measurable impact on non-target organisms [47]. The fungus produces destruxins in mycosed insects that kills locusts even before the fungus has established itself. Furthermore, the pathogen is unable to compete effectively with the saprophytic flora and hence fails to sporulate [13]. Various laboratory and field trials have demonstrated the efficacy of *M. anisopliae* var. *acridum* on desert locust

Table 1. Species of microorganisms studied as bio-control agents against desert locust.

No.	Microorganism	Effect on desert locust	Reference
1.	*Metarhizium anisopliae* var. *acridum* Driver & Milner	Increased acidic phosphatase (AcP) for autophagy and defense	[26]
		Altered behavioral changes	[27]
		Changed biochemistry and antimicrobial defenses	[28]
		Less energy reserves and poor flight capability	[29]
2.	*Metarhizium anisopliae* var. *acridum* + Pheromone Phenyl Aceto Nitrile (PAN)	Reduced feeding and mobility	[30]
3.	*Metarhizium anisopliae* var. *acridum* + *Paranosema (Nosema) locustae* (Protozoa)	Mortality happened sooner than those infected with only one of the pathogens	[31]
4.	*Metarhizium anisopliae* var. *acridum* + *Beauveria bassiana* (Bals-Criv) Vuill.	Significant reduction in total proteins and hemocyte counts	[32]
5.	*Metarhizium flavoviride* Gams & Rozsypal	Reduction dispersal of hopper bands into small groups	[19]
		Reduced daily food consumption	[33]
		Significant reductions in flight activity and food consumption	[34]
		High mortality in sparse vegetation than in dense vegetation	[35]
6.	*Metarhizium robertsii* J.F. Bisch., S.A. Rehner & Humber	Produced Destruxin A which inhibited fever	[36]
7.	*Serratia marcescens* Bizio (Bacteria)	Induced fever	[37]
8.	*Beauveria bassiana, Entomophthora*, and *Steinernema carpocapsae* (Nematode)	High mortality rates, although the nematode was more effective than fungi in less time	[38]
9.	*Bacillus weihenstephanensis* and *Pseudomonas* sp. (Bacteria)	Showed the highest insecticidal activities against desert locust nymphs	[39]
10.	*Pseudomonas aeruginosa* (Schroeter) Migula (Bacteria)	Pathogenic bacterium of the desert locust	[40]
11.	*Bacillus cereus* (Bacteria)	High insecticidal activity	[41]

although the results are highly variable. For example, treatment of desert locust with the fungi increased acidic phosphatase (AcP) (a lysosomal enzyme that plays a role in autophagy, cell turn over and defense) activity on day three after inoculation with the fungus. This was accompanied by a decline in the total hemocyte, plasmatocytes, and coagulocytes [26]. However, desert locusts usually undergo thermoregulation (behavioral fever) during an infection to improve their immune system [37], although this declines after continuous application. A laboratory study examined the effects of fungus on survival and reproduction in adult desert locust under various temperature conditions [27]. Mortality rates were varied upon thermal conditions where it was more that 90% at 10 days after treatment under constant temperature and 66% at 70 days after treatment under thermoregulatory conditions. Topical application of *M. anisopliae* var *acridum* on the desert locust resulted in changes in the biochemistry and antimicrobial defenses of the hemolymph from the second day post application [28]. The fungus stimulated the hemolytic aggregation indicating an overall stimulation of the immune system, which declined by day four of application. A similar study assessed the effect of *M. anisopliae* var *acridum* on energy reserves and flight capability in desert locust and found a decline in carbohydrate and lipids in the hemolymph 3 days after inoculation [29]. This indicates that the poor flight capability of mycosed locusts is partly due to a reduction in energy reserves. However, desert locusts reared under crowded conditions are significantly more resistant to the fungi that solitary locusts due to elevated antimicrobial activity at the gregarious phase [48]. These behavioral changes may enable the locust to adapt to new environments hence the need for further research on the use, testing and monitoring of the formulations.

The performance of *M. anisopliae* var. *acridum* against desert locust can be improved by combining the fungus with other bio-controls. For instance, when the fungus was combined with the pheromone Phenyl Aceto Nitrile (PAN), the solution caused a 100% mortality of desert locust within 2 weeks and this could reduce cost and environmental hazards [30]. Another study combined the fungus with microsporidian *Paranosema (Nosema) locustae* and showed that locust nymphs treated with both pathogens died more quickly than those infected with only one of the pathogens [31]. However, this study concluded that application of *M. anisopliae* might diminish the natural persistence of *P. locustae*. On the other hand, the combined effect of *M. anisopliae* with *Beauveria bassiana* achieved a significant reduction in total proteins and hemocyte counts of the desert locust on the 9th day of application [32]. Although these results indicate that a combination of effective microorganisms may be useful while considering integrated pest management strategy of the desert locust, more research is necessary to assess the interactions of these microorganisms.

Several studies have shown the potential of bacteria as a bio-control agent against the desert locust. For example, desert locust fevered when infected with *Serratia marcescens* and this "behavioral fever" greatly delays the progress of mycosis [37]. Other bacterial pathogens isolated from the gut contents of desert locust, which showed the highest insecticidal activities against the locust nymphs were *Bacillus weihenstephanensis*, *Pseudomonas* sp., *Pseudomonas aeruginosa*, and *Bacillus cereus* [39–41]. These strains could be potential bio-control agents in controlling desert locust nymphs.

A workshop held in Senegal in 2007 on the future of bio-pesticides in desert locust management made various recommendations to ensure rapid integration of bio-pesticides into operational desert locust management [49]. However, much remains to be implemented with various shortcomings associated with the use of *Metarhizium* in desert locust control. The following are the main ones:

i. They are highly susceptible to the damaging effects of solar radiation [50] keeping in mind that desert locust mostly invades areas that have harsh climatic conditions. To enhance survival, spores can be coated with water-soluble materials (anti-UV) that protect toxins and spores from solar radiation [50].
ii. Performance of the fungus may be affected by environmental factors such as humidity and temperature [51, 52].
iii. *Metarhizium* has a narrow host range (only locusts and grasshoppers) as compared to chemical pesticides hence more expensive in terms of research, development, and registration costs [53].
iv. Use of mycopesticides may have a possibility of causing health effects to immune-compromised persons exposed to high doses through production and use [54].
v. They are slower acting than chemical pesticides and thus inappropriate for emergency situation [18], though they may have a major role in an integrated control strategy.
vi. Sporulation of the fungus takes a long period of time and requires conditions that are not always found in the field [55].

Use of botanical extracts as bio-control agents

Several studies have reported the use of botanical extracts as potential bio-pesticides against desert locust. In this review, a total of 27 plant species belonging to 20 families were identified as tested against desert locust (Table 2) but had varied results. *Azadirachta indica* and *Melia volkensii* were the most studied plant species, both belonging to Family Meliaceae, which is known to have biologically active limonoids [56]. These were followed by *Calotropis procera*, *Fagonia bruguieri*, and *Peganum harmala*. The most represented plant family was Apiaceae with a frequency of 21%. However, most of these studies used crude extracts and the active ingredients against desert locust were not identified.

Table 2. List of plant species that have been tested as bio-control agents for desert locust.

No.	Scientific name	Common name	Family	Frequency (%)
1.	*Azadirachta indica* (A. Juss.) Brandis	Neem	Meliaceae	16.40 (10)
2.	*Melia volkensii* Giirke	Melia	Meliaceae	11.48 (7)
3.	*Calotropis procera* (Aiton) W.T. Aiton	Sodom apple	Apocynaceae	6.56 (4)
4.	*Fagonia bruguieri* D.C	Fagonia	Zygophyllaceae	6.56 (4)
5.	*Peganum harmala* L.	Wild rue	Nitrariaceae	6.56 (4)
6.	*Nerium oleander* L.	Oleander	Apocynaceae	5.00 (3)
7.	*Allium cepa* L.	Onion	Amaryllidaceae	3.28 (2)
8.	*Petroselinum sativum* Hoffm.	Parsley	Apiaceae	3.28 (2)
9.	*Cuminum cyminum* L.	Cumin	Apicaceae	3.28 (2)
10.	*Schouwia purpurea* (Forssk.) Schweinf.	Saharan crucifer	Brassicaceae	3.28 (2)
11.	*Jatropha curcas* L.	Physic nut	Euphorbiaceae	3.28 (2)
12.	*Ocimum basilicum* L.	Basil	Lamiaceae	3.28 (2)
13.	*Nigella sativa* L.	Black seed/cumin	Ranunculaceae	3.28 (2)
14.	*Zygophyllum gaetulum* (Emb. & Maire)	Caper beans	Zygophyllaceae	3.28 (2)
15.	*Ammi visnaga* (L.) Lam	Toothpick weed	Apiaceae	1.64 (1)
16.	*Solenostemma argel* (Delile) Hayne	Argel	Asclepiadaceae	1.64 (1)
17.	*Matricaria chamomilla* L.	Chamomile	Asteraceae	1.64 (1)
18.	*Cleome arabica* L.	The stinker	Capparidaceae	1.64 (1)
19.	*Pelargonium radens* H.E. Moore	Radula	Geraniaceae	1.64 (1)
20.	*Origanum vulgare* L.	Oregano	Lamiaceae	1.64 (1)
21.	*Linum usitatissimum* L.	Flax, linseed	Linaceae	1.64 (1)
22.	*Eucalyptus* L'Hérit spp.	Myrtle	Myrtaceae	1.64 (1)
23.	*Zizyphus lotus* (L.) Desf.	Jujube	Rhamnaceae	1.64 (1)
24.	*Rhizophora mucronata* Lam.	Mangrove	Rhizophoraceae	1.64 (1)
25.	*Carum carvi* L.	Caraway	Apiaceae	1.64 (1)
26.	*Citrus aurantium* L.	Orange	Rutaceae	1.64 (1)
27.	*Gaultheria procumbens* L.	Wintergreen	Ericaceae	1.64 (1)

Plant alkaloids have been reported to affect desert locust in different ways. For instance, azadirachtin from *A. indica* has an anti-feeding activity that inhibits feeding and molting [57]. The alkaloid has been formulated to produce a commercial anti-feeding product that controls a wide range of plant pests without harming beneficial insects [58]. Anti-feeding activity of *A. indica* against desert locust has also been well studied [58–60]. The activity varied in *A. indica* (79.62%), *Jatropha curcas* (78.92%), and *Solenostemma argel* (56%) against the desert locust with a significant mortality of 43.39%, 40.54%, and 20.70%, respectively, after 7 days of treatment. Further, cold-pressed *A. indica* seed oil resulted in molting disturbances and morphogenetic defects of the wings, legs, and antennae [61]. When *Nigella sativa* extracts were compared with those of *A. indica*, *N. sativa* caused a decrease in the body weight but with no mortality [58]. The effects of *Calotropis procera*, *Zygophyllum gaetulum*, and *Peganum harmala* on survival, feeding, and reproduction in desert locust showed that all the alkaloids extracted from the plants reduced food intake, increased weight loss, and caused a significant mortality [62]. Alkaloids extracted from *C. procera* and *Z. gaetulum* prevented sexual maturity both in males and female while those of *P. harmala* reduced female fecundity and hatching rate. Both *C. procera* and *P. harmala* generated 100% mortality within a few days after treatment and portrayed symptoms similar to those of insects treated with insecticides [63–65]. A similar study on the effect of *C. procera*, *Schouwia purpurea*, and *Zizyphus lotus* alkaloids on the desert locust observed morphological changes, molting inhibition and anti-feeding effects with a significant mortality ranging from 45% to 53% on day five after treatments [66]. In a different experiment, fruit extracts of *Ammi visnaga* promoted the acidic phosphatase (AcP) activity and reduced alkaline phosphatase (AlP) activity in fat bodies of adult desert locust. This was attributed to presence of couramins and furocoumarins [67]. Extracts of *Fagonia bruguieri* also inhibited growth and development of Desert locust by intervening with the process of metamorphosis [68, 69]. Meanwhile, desert locust nymphs treated with *Nerium oleander* leave extracts could not molt, had reduced food intake, and had a cumulative mortality rate greater than 50% from the fourth day of application and 100% mortality at the 12th day of application [70]. Extracts derived from different parts of the *Rhizophora mucronata* have insecticidal and antifeedant activity against the locust [71]. *Melia volkensii* extracts also have a growth inhibiting anti-feeding properties against desert locust and other insect pests [72]. Field tests have shown that the crude powder of *M. volkensii* has effective control resulting from acute toxicity, retarded growth, and 80% malformations, which led to 100% mortality after 14 days [56, 73]. These botanicals have shown their potential as bio-pesticides but are still at the experimental stage as far as desert locust control is concerned.

Several studies have confirmed that essential oils are effective against desert locusts and could be used as natural controls. A novel mixture of plant oils that had high toxic effects on desert locust after a single spray treatment was developed [55]. It was a combination of three essential oils of *Carum carvi*, *Citrus aurantium dulcis*, and *Gaultheria procumbens.* Interestingly, a mean mortality rate of 80% was observed within 24 h after treatment. Furthermore, essential oils extracted from 10 different plant species were tested against desert locust by topical application [74]. Oil from *Allium cepa* proved to be the most toxic to the locusts followed by *Petroselinum sativum*. Other plants studied were *Pelargonium radula*, *Cuminum cyminum*, *Ocimum basilicum*, *Origanum vulgare*, and *Matricaria chamomilla,* which showed different effects against the locust. Combining the oils resulted in different types of interactions although their efficacy was not tested in the field.

Conclusion

Control and management of desert locust plagues is difficult mainly due to unpredictability of outbreaks, influence of the environment, and the breadth of the areas across which they are spread. In many regions, synthetic pesticides remain the most effective and efficient for large-scale control operations of desert locust. Millions of dollars are spent on these preventive control measures that are still unable to completely prevent locust plagues from developing. Biological controls are an alternative but can take several days for locusts to die after being treated. However, an integrated pest management strategy that incorporates rational use of chemical pesticides with biological options would be a realistic option. This would require implementing natural-risk management plans for locust outbreaks as well as considering the benefit and cost of proposed control measures and their environmental and health impact.

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