

Review Article

Desert locust and its management in Nepal: a review

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ABSTRACT

Locusts are among the most dangerous agricultural pests. They are a group of short horned grasshoppers belonging to Acrididae family and are hemimetabolous insects. This group of grasshoppers have a unique character of changing habits and behaviors when they aggregate in a group and this habit is catalyzed by different environmental factors. In the adult stage, gregarious locusts migrate from one place to another in a swarm. Desert Locust, *Schistocerca gregaria* (Forsk.) is one of those locusts which cause damage to different types of crop which fly in the direction of wind up to a distance of 150 km. Because of polyphagous feeding habits and swarming in a plague (large group of adults), this pest is considered as the hazardous migratory pest. These pests entered Nepal for the first time in 1962 and then in 1996. In 2020 the pest entered the country from India on three different dates 27th June and continued till 29th (5 districts), 12th July (1 district), and 16th July (2 districts). The swarms migrated to 53 districts and caused the considerable loss in agricultural and field crop in 1118 hectare. These pests are monitored on the basis of environmental factors and many tools and practices such as eLocust3, SMELLS (Soil Moisture for Desert Locust Early Survey), P-locust and SUPARCO Disaster Watch Desert Locust Situation Alert are being used. Their control is critical to food security. Many tools and techniques are integrated for prevention and management of these pests to minimize damage in the existing crops where they migrate. These are physical methods, cultural methods, use of botanicals, green muscle, PAN (phenylacetone nitrile) and chemicals. Effective preventive management strategy relies on an improved knowledge of the pest biology, more efficient monitoring and control techniques.

Keywords: eLocust3, Green muscle, Gregarious, PAN, Plague, Upsurge

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INTRODUCTION

Locusts are the group of different species of short horned grasshoppers belonging to the family Acrididae (Order: Orthoptera). These are a special type of grasshoppers having the capacity of

changing their habits and behavior when in large numbers and are regarded as a major threat to agriculture from the beginning of human civilization (Steedman, 1990; Joshi *et al.*, 2020). Locusts are generally differentiated from grasshoppers with their swarm forming ability, body shape, size and color changing morphological characters (Symmons & Cressman, 2001). When adult locusts are in large numbers, they show gregarious behaviour called swarms. Similarly, gregarious behaviour shown by larval stage (hopper) are called as bands (Steedman, 1990; Symmons & Cressman, 2001). Some of the species of locust capable of forming large migrating swarms are Desert locust *Schistocerca gregaria* (Forsk.) (Forsal), African migratory locust *Locusta migratoria migratorioides* (Fairmaire & Reiche), Red locust *Nomadacris septemfasciata* (Audinet-Serville), Bombay locust *Nomadacris succincta* Johannson), Brown locust *Locustana pardalina* (Walker) and Tree locust *Anacridium* spp (Steedman, 1990). Grasshopper species can also form bands under certain circumstances. Major band forming species are *Melanoplus* (Stål), *Acridoderes* (Bolívar), *Hieroglyphus* spp.(Krauss) Depending upon the species nature of swarms varies *Oedaleus senegalensis* (Krauss) forms loose swarms (Symmons & Cressman, 2001) while tree locust (*Anacridium* spp.) barely forms a band (Symmons & Cressman, 2001). Desert locust (*Schistocerca gregaria* Forsal) is considered as the most dangerous migratory pest among the locust species because of its ability to reproduce rapidly, migrate long distances and devastate crops (Steedman, 1990; Cressman, 2016; Joshi *et al.*, 2020; FAO, 2020a). Swarms of desert locust can fly large distances up to 150 km in the direction of wind (Zhang *et al.*, 2019) containing a group of millions and billions of individuals (FAO, 2020b). Moreover, bands formed by *S. gregaria* hopper can march up to 1.5 km in a day (FAO, 2020b). They cause substantial damage to the crops and are considered as devastating pests but since they are edible, they can be used as alternative nutritive food and feed (Mariod *et al.*, 2017). However, the negative effects of eating the chemically treated swarms cannot be forsaken and it is not consumed.

Despite the recent and further possible locust invasion in Nepal, there is no systematic review conducted to assess the details of invasion and its possible control measures. This review has 4 objectives: 1) to explicit Desert locust, 2) to understand its status in Nepal, 3) to understand its outbreak, plague and upsurge, 4) to clarify its different management process. In this review, we give an overview of biology of desert locusts which clearly describes the different stages of the lifecycle of the locust and the behavioral changes that make a solitary locust into gregarizing swarms. We assess the damages caused by the locusts that entered in year 2020 in Nepal recently from different reports by Plant Quarantine and Pesticide Management Centre, under the Ministry of Agriculture and Livestock Development, Nepal and outline a map using ArcGIS. We review the traditional control strategies with different recent control strategies in detail. These methods can be applied in combating desert locust plague. Finally, we discuss that locusts are insects which can be used as human food and as dietary source for animal feed but if not monitored and controlled, these migratory transboundary pests bring serious devastation.

Biology of desert locust

The life cycle of desert locusts completes in three successive stages: egg, nymph and adult with an average of 3-5 months (Cressman, 1998). However, the time period in each stage varies according to weather and ecological changes (Steedman, 1990; Cressman, 1998).

Egg

The adult female *S. gregaria* lays many eggs which are bound together by a frothy secretion in batches called egg pods usually in bare moist sandy soil (Symmons & Cressman, 2001; Steedman, 1990). The female can lay one to four egg pods in its whole lifetime (Latchininsky *et al.*, 2016). Furthermore, the number of eggs in egg pods vary from 20 to above 100 and it decreases with successive laying (Steedman, 1990) so in the first laying nearly 149 eggs are laid and it decreases to nearly 122 eggs in second laying and it goes on decreasing (Roffey and Popov, 1968). Whereas gregarious phase locust lay less eggs than solitarius, generally 70 to 80 in first laying, 50 to 60 in second and less than 50 in third laying (Steedman, 1990). Egg pods are laid after 7 to 30 hours of copulation which consist of 80 to 158 eggs (Cressman, 1998). Initially eggs are yellow in colour which later on turn brown in soil (Steedman, 1990). Moreover, females generally do not lay eggs unless they find moist soil up to 5 to 10 cm depth from surface which they check by probing soil with their tip of abdomen in soil (Symmons & Cressman, 2001). While probing they check warmth, salinity, hardness and moisture of the soil (Steedman, 1990). Also, the soil moisture and temperature play an important role in egg development (Eltoum *et al.*, 2014) as they need to absorb water from the soil of their own weight for the first five days (Steedman, 1990).

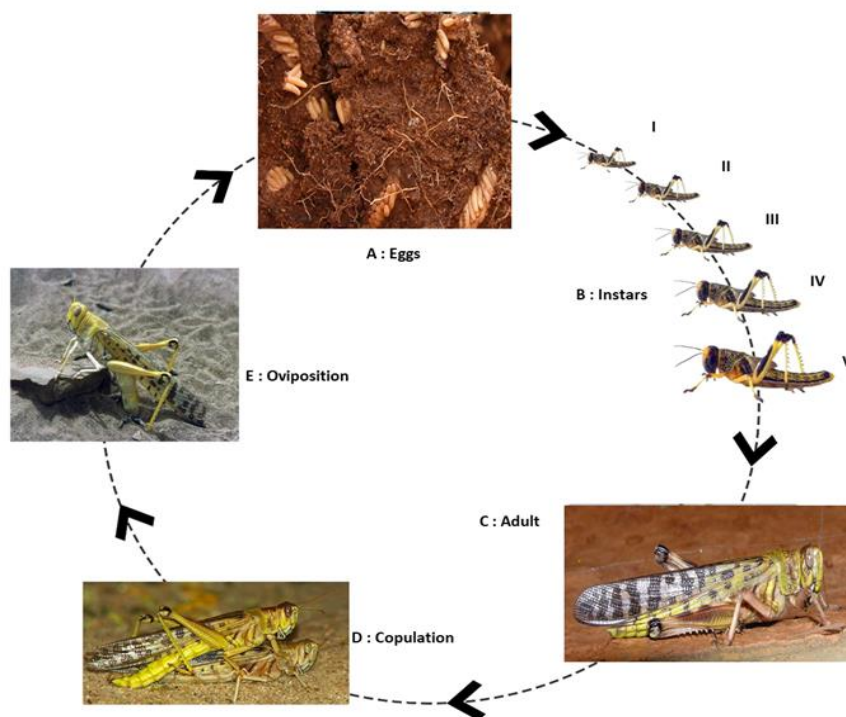


Figure 1: Life Cycle of Desert Locust. A: eggs of Desert locust (DAFWA, 2013); B: five larval instars also known as hopper (Ghoneim *et al.*, 2009); C: Mature adult desert locust (Pingstone, 2005); D: Mating of male and female (Kellard, 2007); E: female laying eggs (Kooyman, 1994).

After finding the required moisture in soil, female locust bores the soil with a valve at its abdomen tip and deposits egg pods at a depth of 5 to 10 cm (Symmons & Cressman, 2001). They lay eggs generally at night after 1.5 to 6 hours of sunset at a depth of 10 cm when upper soil is moist (Roffey & Popov, 1968) whereas the hatching period of the egg is generally two

weeks but it varies according to temperature regimes (Cressman, 1998; Roffey & Popov, 1968). So, these eggs in summer at high temperature hatch in 24 to 30 days but in winter it increases to 45 to 55 days (Eltoum *et al.*, 2014).

Nymph

This stage starts with hatching an egg into a nymph called hopper (Symmons & Cressman, 2001). *S. gregaria* hopper develops in about 30 to 40 days which undergoes five to six stages (Cressman, 1998). In these stages, solitary hoppers shed their skin for five to six times and five times in gregarious hoppers (Joshi *et al.*, 2020) which is called as moulting and the stages between moulting is called as instar (Symmons & Cressman, 2001). The first instars after hatching are white colored and get changed into black within 1 to 2 hours (Steedman, 1990). Furthermore, with change in instars color its body structure and size also get changed so finally in fifth instar, it is bright yellow with black colored pattern but it varies with temperature (Steedman, 1990; Joshi *et al.*, 2020).

Similarly, the time period for the completion of five instars also varies with temperature which at 32°C completes with an average duration of 5, 4, 4, 5 and 8 days, respectively (Claeys *et al.*, 2003). After the completion of fifth (or sixth) moulting wingless hopper gets developed into a winged adult and this new winged adult is called fledgling (Symmons & Cressman, 2001; Steedman, 1990). After the development of fledging from hopper, moulting stops which is termed as final moult. Moreover, wings formed in fledging are soft wings so they cannot fly as they need to be dry and hardened to fly (Symmons & Cressman, 2001). The total time period from egg stage to fledging generally takes 40 to 50 days (Cressman, 1998; Symmons & Cressman, 2001). Large number of locust mortality takes place in this stage especially in the first instar than other stages and it occurs mostly due to lack of water resource, predation by ants and cannibalism (Cressman, 1998).

Adult

Fledgling develops into an immature adult which later develops into a mature adult. The wings of fledgling get hardened in ten days and it changes into an immature adult (Symmons & Cressman, 2001). The young adult (fledgling), under optimal condition develops into an adult in 3 to 8 weeks but if the condition is unfavourable (like cool, no sufficient rain) then they remain in larval stages for six months or more (Cressman, 1998; Steedman, 1990).

The colour of an immature adult varies from light to dark pink colour according to weather and becomes sexually mature in a few weeks or months (Steedman, 1990). The beginning of maturation is indicated by the disappearance of pink color from hind tibia and the mature adult colour changes to yellow in which male adults are brighter yellow coloured than female (Steedman, 1990). Moreover, in the adult stage the weight increases gradually however size doesn't increase (Symmons & Cressman, 2001; Steedman, 1990). The immature solitary adult is pale grey whose colour on maturation changes to pale yellow (Steedman, 1990). Similarly, immature gregarious is bright pink coloured which on maturation changes to bright yellow (Steedman, 1990).

Most of the eggs laid undergo natural mortality which occurs when eggs dry up by heavy winds, destroyed by continuous flood, soil temperature above 35°C, presence of natural predators and entomopathogens (Symmons & Cressman, 2001). Entomophagous insects like *Stomorhina lunata* Fabricius (Calliphoridae), *Systoechus* spp. (Bombyliidae) and *Trox procerus* Har.

(Trogidae) are the major cause of mortality of gregarious phase locust eggs but it causes very less damage to solitarius phase locust eggs (Greathead, 1966). Hence, though an adult female lays a large number of eggs but only 16 to 20 adults are produced from an adult female in its single generation (Symmons & Cressman, 2001).

Behavioural phase change in locust

Locusts show phase polyphonic character in which they can induce two or more phenotypes within individuals of the same genotype (Applebaum & Heifetz, 1999; Pener & Simpson, 2009). So, in the past for many years desert locusts were considered to be two different insects until a Russian scientist Boris Uvarov in 1920 confirmed it as a single species (Cressman, 2016). Solitarius locusts can change themselves to a gregarious one and change their preferences from isolation to seeking conspecifics (Topaz *et al.*, 2012). Gregarious locusts are very mobile and remain gathered into a crowd or mass whereas solitarius ones are inactive and avoid each other and have creeping gait (Pener, 1991; Roessingh *et al.*, 1993; Simpson *et al.*, 1999; Pener & Simpson, 2009). During night, the solitarius are active but gregarious are mostly active at day (Ely *et al.*, 2011; Rogers *et al.*, 2014). Body colour of solitarius nymphs serves as camouflage in its natural environment (Tanaka *et al.*, 2012) whereas gregarious locusts produce colour pattern which serves as warning coloration (aposematism) to vertebrate predators, signalling that the locust is toxic prey by virtue of feeding on noxious plant (Sword *et al.*, 2000). F/C ratio (length of hind femur/width of head or caput) of gregarious is smaller than solitarius whereas E/F ratio (Elytron/femur) is larger in gregarious (Stower *et al.*, 1960; Uvarov, 1966; Symmons, 1969; Kilpatrick *et al.*, 2019).

Based on mixture of different behaviours and activities (Tanaka & Nishide, 2013), isolated reared *Schistocerca gregaria* when crowded, begun to show behavioural gregarization within 1 hour and completed after 4-8 hours (Roessingh & Simpson, 1994; Islam *et al.*, 1994; Anstey *et al.*, 2009; Pener & Simpson, 2009). Geva *et al.* (2010) also found the change in behavioural phase already after 30 min of crowding. For the desert locust *Schistocerca gregaria*, the most potent stimulus is tactile i.e. repetitive stroking of half of anterior (outward-facing) surface of a hind femur functions as a crowding indicator whereas the ineffective site is the ventral distal region with few tactile hairs (Simpson *et al.*, 2001). It can be explained that the population of solitarius locusts will more likely gregarize in patchy and compact clumps of vegetation than where the vegetation is spread evenly but sparsely (Despland *et al.*, 2000). Mechanosensory stimulation of leg nerves produces much of serotonin flow in the metathoracic ganglion, and initiates gregarious behavior (Rogers *et al.*, 2014). However, experiments carried out by Guo *et al.* (2013) found that injection of serotonin transits the isolated gregarious nymphs of migratory locust to solitary phase which contradict to the findings that serotonin initiates swarming behaviour of the desert locust (Anstey *et al.*, 2009).

Also, olfactory stimulation and appropriate visual stimulation together from other locusts can also induce the partial behavioural gregarization (Roessingh *et al.*, 1998). Dillon *et al.* (2000) found that *Pantoea agglomerens*, a bacterium that dominates the locust hind gut is mainly responsible for producing guaiacol and phenol in fecal pellets of locust and these compounds, when smelled, help locust to form swarms.

Maternal effects can also be seen on phase characteristics of locusts (Simpson & Miller, 2007; Maeno & Tanaka, 2008). Crowded mother for the first time produces gregarious offspring

while gregarious phase female in alone condition produces hatchlings that express solitarius phase behaviours (Roessingh *et al.*, 1994). These are mainly mediated by the chemical that mother adds to the egg foam plugs surrounding her eggs in the soil (McCaffery *et al.*, 1998).

Current status of locusts

Locust attack in Nepal in 2020

As per the Ministry, the first locusts attack in Nepal was reported in 1962. However, in 1996 Nepal experienced the worst locust invasion where 80 percent of crops were destroyed by swarms in Chitwan. Partial damage of crops was recorded from Makwanpur, Mahottari and Bara districts (IANS, 2020). Locust swarm entered Nepal on 27th of June 2020 and was recorded from Bara, Parsa, Sindhuli, Sarlahi and Rupandehi district (MoALD, 2020). Two swarms continuously entered Nepal on consecutive days i.e. on 28th and 29th of June (Jha, Sah, & Muniappan, 2020).

The second phase of swarm entered from Dang on 12th July 2020. This swarm flew to Pyuthan, Gulmi, Baglung and Syanjya districts. The swarm also entered through Nawalparasi (PQPMC, 2020a). On 16th July, two different groups entered Nepal from Banke and Kanchanpur. The swarm which entered from Banke travelled to Surkhet, Dailekh and Jajarkot districts. Damage of maize and mango trees was recorded from Surkhet. The second swarm which entered the very day via Kanchanpur got scattered and some parts of the swarm even reached India while few parts of the swarm reached Dadeldhura and Baitadi (PQPMC, 2020b; 2020c).

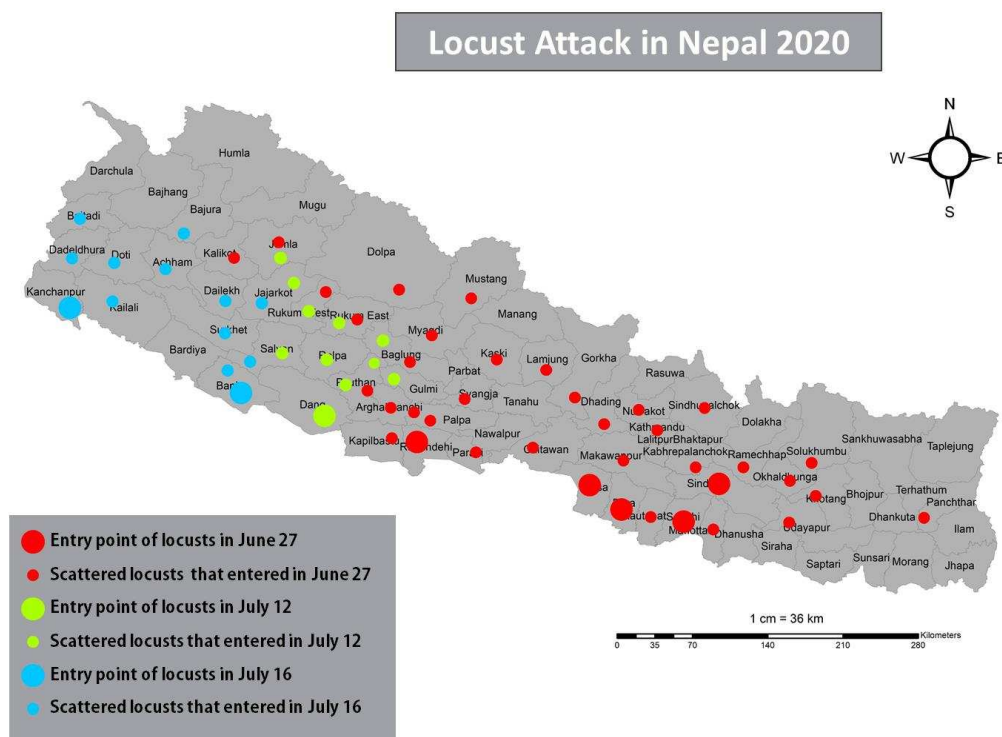


Figure 2: Locust attack in Nepal, 2020

Thus, the entered swarm expanded to 53 districts within 10 days (Karki, 2020). Damage of crops was noticed from 12 districts by infestation (Republica, 2020a) where damage was remarkably high in 5 districts (Karki, 2020). Plant Quarantine and Pesticide Management Centre (PQPMC) under the Ministry of Agriculture and Livestock Development reported crop damage of 1,118 hectares of land due to attack of locust swarm. Crop damage in Dang, Pyuthan, Makwanpur, Arghakhanchi and Palpa was observed in a land area of 580, 283, 100 and 50 hectares, respectively. Maize fields across the country faced extensive damage by locust attacks (Republica, 2020b). In Sindhuli and Rolpa also minor damage in corns was caused by locusts (Karki, 2020). Damage of crops by locust in various districts is shown in Table 1.

Table 1: Districts and crop damaged by locust swarm

S. N.	District	Damage	Area
1.	Dang	Maize and vegetables	580 ha
2.	Pyuthan	Maize, soybean and Rice	283 ha
3.	Makwanpur	Maize, fruits and vegetables	105 ha
4.	Argakhanchi	Maize and vegetables	100 ha
5.	Palpa	Maize	50 ha
6.	Dadheldhura	Maize	Minimal damage
7.	Rolpa	Maize	Minimal damage
8.	Surkhet	Maize and fruits	Minimal damage

Source: PQPMC, 2020d; IANS (2020)

Impact of climate change on locust swarm

Climate plays a major role in insect distribution in the world and so it has been anticipated that changing climate will also likely change pest outbreak patterns (Wang *et al.*, 2019). FAO has already stated that the pest outbreak is an ‘unprecedented threat’ to food security and livelihoods in regions that are already vulnerable to climate change (Mission, 2020). Similarly, these locust outbreaks also depend on climate as they require moist soil for egg incubation, they prefer to migrate to those areas where recently rainfall has occurred in order to get plenty of green vegetation to feed and breed (Tratalos *et al.*, 2010). So the region with exceptional weather events due to climate change becomes more susceptible and gets heavy damage by locust swarms outbreak (FAO, 2020b).

Also, these swarms are getting more prevalent in the present context due to increase in deforestation, industrialization, urbanization and all other human activities which increase greenhouse gases mainly methane and carbon dioxide on earth. This increased concentration of carbon dioxide gases results in enhancement of rainfall, soil moisture level, vegetation growth (Claussen *et al.*, 2003) which increases the size of the locust swarm and its outbreak frequencies (Tratalos *et al.*, 2010). Moreover, from autocorrelation analysis and autoregressive integrated moving average (ARIMA) analysis it has been observed that endogenous factors and rainfall play role in determining the size of the territory occupied by locust swarms and hopper bands across the entire range of the species (Tratalos *et al.*, 2010). These locusts outbreak frequency are also affected with change in frequency of both flood and droughts as during decades it has been observed that it becomes highly abundant in increased frequencies of both flood and droughts (Jiang *et al.*, 2005; Stige *et al.*, 2007). Unusual weather and climate causing locust outbreak can be easily illustrated with year 2020 as the outbreak has been regarded as one of the worst in the last 25 years (FAO, 2020c). As this outbreak occurred due to unusual climatic condition like successive heavy rains and cyclones in the Empty Quarter in the Arabian

Peninsula in May and October 2018 which resulted into favourable conditions for three generation breeding and numerous swarms started to leave those area in early 2019 in order to cause outbreak (FAO, 2020c).

Monitoring and locating the hot spots

Mainly desert locusts are found in deserts and semi-arid areas. When the condition becomes favourable in these places i.e. ground becomes moist and rainfed drains become abundant, massive breeding and swarm formation takes place. They favour the place with annual precipitation between 0 – 400mm (Le *et al.*, 2019) and for the development of eggs, rainfall of at least 20mm in a short period is required (Pedgley, 1980). For oviposition, females usually lay eggs in sandy soil with moisture between 5 and 25% at a certain depth (Piou *et al.*, 2018). For development of hoppers, green vegetation is required. Those areas, where rain has just prompted lush green vegetation, can support hoppers (nymphs) to become adults leading to outbreaks (Cressman, 2016). They can rapidly reproduce and multiply 20-folds every three months if provided appropriate environments (FAO, 2020). So, early monitoring and intervention should be done for effective locust control.

Monitoring programs to track down the locust help in surveillance and mapping of hotspots for locusts. Remote sensing techniques and use of different satellite images are now able to detect the locust bands and/or potential habitat by estimating the rainfall, wind direction, vegetative cover and soil condition (Cressman, 2013). Existing tools and practices mainly include eLocust3, SMELLS (Soil Moisture for Desert Locust Early Survey), P-locust and SUPARCO Disaster Watch Desert Locust Situation Alert (UNOOSA, 2020). eLocust3, a latest update of elocust series, is based on handheld tablet. It helps national survey and control officers to collect data and send it via satellite to ground monitoring centres in real time (Cressman *et al.*, 2016; Bajiou, 2018).

Preventive and control measures for locusts

Traditional methods

Farmers, before the availability of new and advanced technology, have developed a variety of physical and cultural methods to protect their crops from the locusts. These methods are practiced especially when the infestation or hopper bands are small. Some of them are killing or trampling the bands, ploughing or burning the egg infested field & trapping the hoppers in pits or trenches and killing them (Sharma, 2014). When a huge swarm of locusts are about to land in cultivated areas, the best way is to chase them away. Local people use fire, clouds of smoke and loud sounds to repel them from descending in the field. Gorden *et al.* (2014) reported that tympanal movement and electrophysiological response of locust is between 4 and 8 kHz. They have the ability to distinguish between low frequencies (conspecific) and high frequencies (like predatory echolocating bats) (Robert, 1989). Acoustic and electronic devices that pulses ultrasounds can be used to deter large swarms of desert locusts (Ibrahim *et al.*, 2013). Also, people use nets to protect small nurseries and kitchen gardens. Medicated nets, which are sprayed with garlic or neem oil are also effective to repel different insects including locusts and grasshoppers (Kaur, 2017). However, these traditional methods work well when the swarms and crop areas are small.

Botanical methods

Botanicals mainly include plant derived products. They are broad spectrum pesticides, safe to the environment & non-target animals, less toxic, cheap & easily available. Resistance by pests against them is very slow and less common (Raghavendra *et al.*, 2016). Most widely used botanical products include pyrethrum, rotenone, neem and essential oils. Others include ryania, nicotine, sabadilla, garlic oil, capsicum oleoresin which are used in limited (low volume) regional use (Hernández Escalona, 2006).

Neem

Major components of neem include azadirachtin, salanine, meliantriol and nimbin. They are tetranortriterpenoid compounds (Patel *et al.*, 2016). Neem is mainly popular for its repellency, antifeedant, metamorphosis disturbances, hormonal regulation & fertility inhibitor (Baumgart, 1995; Nisbet *et al.*, 1996; Nisbet, 2000; Roychoudhary, 2016; Bashir & Elshafie, 2017). In 1959, German Entomologist Heinrich Schmutterer witnessed a locust plague in Sudan and found that except all green plants, neem trees were the only remaining plants which weren't defoliated by locusts (National Research Council, 1992). Abdelbagi *et al.* (2019) in their experiment found that neem seed products slow down the development severely in 2nd and 3rd instars. Some 2nd instar individuals didn't moult, some died as overaged 2nd instars whereas some moulted to 3rd instars and died overaged without further moulting. They also found reduction in food intake ranging from 52 to 99% against the immatures. These results are in line with many other researches (Wilps *et al.*, 1992; Mordue & Blackwell, 1993; Abdelrheem, 2015). In addition to this, mortality rate of locust was also found greater when neem was used as oil formulation with *Metarhizium* fungus (Haroon *et al.*, 2011; Bashir & Elshafie, 2017; Paula *et al.*, 2019).

Linseed Oil

Linseed oil is a drying oil. It polymerizes and hardens over time (Lazzari & Chiantore, 1999) which makes it a good botanical controller of locust. It is reported that gregarious *Schistocerca gregaria* (Forsk.) and *Locusta migratoria* (Linnaeus) when treated with linseed oil mixed with saturated solution of bicarbonate lost their mobility due to hardening of linseed emulsion and also stopped feeding the treated wheat seedlings after the spray (Abdelatti & Hartbauer, 2020). High levels of linolenic acid (53.21%), oleic acid (18.51%), linoleic acid (17.25%), palmitic (6.58%) & stearic acid (4.43%) are found in linseed oil (Gruia *et al.*, 2012). Saturated fatty acids like oleic acid and linoleic acid are also known to be necromones i.e. death recognition chemicals and are the chemical cues that are produced by dead social insects like ants, bees, termites which are recognized by their swarm members and make them remove the corpse from the colony. (Yao *et al.*, 2009). This makes linseed oil a perfect candidate for disrupting the swarm formation of locusts. But more research and experiments are further needed in this topic.

It is reported that *Nerium oleander* when given as a diet showed inhibitory effect on ovarian development of desert locust (Bagari *et al.*, 2015). Other includes garlic extracts/oil *Allium sativum* (Linnaeus), cumin *Cuminum cyminum* (Linnaeus), jatropha oil *Jatropha curcas* (Linnaeus) as essential plant oils against the locusts (Bashir & El shafie, 2013; Mansour & Abdel-Hamid, 2015; Mansour *et al.*, 2015). Further research efforts are needed in the use of these botanical pesticides and also on screening more plants & isolating the novel bioactive molecules.

Green muscle

Extensive use of chemicals leading to environmental impacts (to human and non-target organisms) have urged the need for alternative strategies, such as pest control with biological control agents. *Metarhizium anisopliae* (Metchnikoff) var. *acridium*, an acridid-specific fungal pathogen, is the most promising biological agent for controlling locust and grasshopper (Lomer *et al.*, 2001; Hunter *et al.*, 2016). Normally it grows naturally in the soil (Hu & St. Leger, 2002) and is parasitic to insects (Maniania, 1991). They are effective, persistent with low vertebrate toxicity and are also used in environmentally sensitive areas such as water ways, rare and endangered species (Hunter, 2005). Organic agriculture which excludes chemical pesticides, are also using the fungus as a control agent (Hunter, 2004). They have a more restricted host range (Hunter, 2005; Hu *et al.*, 2014). Experiment done by Long & Hunter (2005) shows the fungus don't affect the locust's natural enemies like generalist robber flies (Diptera: Asilidae), *Ommatius* spp, *Promachus* spp and Bombyliid flies (*Anastoechus chinensis* Paramonov).

Some commercial products such as Green Guard (in Australia) and Green Muscle (in Africa) have been developed (Hunter, 2005). Fungus of isolate IMI330189 were developed by LUBISO in Africa and then isolate F1985 by CSIRO & the APLC in Australia (Hopper *et al.*, 1995). But high mortality of Australian migratory locust, *Locusta migratoria* (L.) treated with Australian isolate (Hunter *et al.*, 2001) shows higher mortality rate than African isolate tested against grasshoppers in China (Li *et al.*, 2000). Furthermore, a new biocide NOVACRID (*Metarhizium acridum* Driver & Milner strain EVCH077) is also available (Matthews, 2019). It is registered in Uzbekistan at the dose rate of 0.05 kg/hectare (Tufliyev, 2019). Many tests and trials are ongoing to check the efficiency of this new biocide in other countries.

Efficiency of the fungus mainly depends on application time, doses, methods & environmental conditions. Commercially, it is in dry spore powder technical concentrate (TC) which should be suspended in an oil formulation (SU). Application rate of 0.5-2l/ha is a reasonable volume whereas spore application rate is 100g/ha making 100g in 0.5-2l as per Green Muscle User Handbook. Generally young and early nymphal instars are more susceptible than older nymphal instars and must be targeted to prevent them from becoming adults and check the reproduction and dispersal of adults (Klass *et al.*, 2007). For migratory pests like locust, ULV (Ultra Low Volume) sprays with oil-based formulations of the conidia are appropriate (Rachadi, 2010). Within the temperature range of 28-33°C, the conidia of *M. anisopliae* var. *acridium* germinates and also produces conidia in higher proportion increasing the virulence of the fungus (Diedhiou *et al.*, 2014). However, due to behavioural fever response by locust, it increases its body temperature and higher temperature inhibits the development of the fungus reducing the mortality of the host (Clancy *et al.*, 2018). But this doesn't make the locust completely free from the pathogen (Sangbaramou *et al.*, 2018). Regardless of its slow action, *Metarhizium anisopliae* Metchnikoff var. *acridinium* can be an effective control method against the locust in an area to be polluted by heavy chemical pesticides.

Chemical control

Previously, organochlorines like Dieldrin were widely used to control the locusts as barrier spraying (Rachadi & Foucart, 1999). But after the ban of dieldrin in 1995, current locust operations use chemical insecticides of classes organophosphates, carbamates, pyrethroids, phenyl pyrazole and benzoylurea (Dobson, 2000). These include broad spectrum insecticides

(Arthurs, 2008). Pesticide Referee Group (PRG), an independent advising body of FAO, recommends different pesticides especially for locust control. According to PRG, neurotoxic insecticides should be only used as a last resort whereas *Metarhizium acridum* (Driver & Milner) comes in first priority and insect growth regulators in second. Those chemical pesticides discussed and recommended by the Desert Locust Taskforce of the Ministry of Agriculture and Livestock Development-Government of Nepal for control of locusts are listed in the table 2 below (PQPMC, 2020).

Table 2: Chemical pesticides recommended by Desert Locust Taskforce of the Ministry of Agriculture and Livestock Development-Government of Nepal for control of locusts

Recommended Pesticides	Pesticide (kg) a.i/ ha	Pesticide (mL) in one-liter water	Pesticide (mL/ ha)	Pesticide solution (liter/ha)
Malathion 50% E.C.	0.925	3.0	1850	600
Lambda-cyhalothrin 5% E.C.	0.002	0.77	400	600
Chlorpyrifos 20% E.C.	0.225	1.88	1125	600
Deltamethrin 2.8% E.C.	0.125	0.75	450	600
Deltamethrin 11% E.C.	0.125	0.20	120	600

The hoppers (young instars) are more susceptible to pesticides than the adults (Rachadi, 2010). So spraying operation should be carried out during the initial stages but problems like non-approachable and unseen mass breeding sites of locusts may occur (Symmons & Cressman, 2001). Different methods used in chemical control are described below (Wiktelius *et al.*, 2003).

Barrier spraying

In this technique, pesticides are sprayed in parallel strips of vegetation separated by an unsprayed area between the strips (Wiktelius *et al.*, 2003; FAO, 2005). Marching bands of locusts are controlled by this technique (Matthews, 1977). After the ban of dieldrin, this preventive strategy was thought to have become weak (Skaf *et al.*, 1990). But after the launch of chemicals such as IGR or fipronil has reintroduced the barrier treatment method as these chemicals are persistent (Cooper *et al.*, 1995; Rachadi & Foucart, 1999; Lecoq, 2000). This technique is popular due to: i) fast treatment of larger areas, ii) low volume of chemicals is used, iii) untreated areas are present which lowers the impact on the environment (Lecoq, 2001).

Aerial spraying

Aerial spraying is mostly done by agricultural aircrafts. They may be piloted manually or remotely. Small remotely piloted aircrafts or drones also known as UAVs (Unmanned aerial vehicles) are popular nowadays. UAVs, in agriculture, are mainly used for monitoring and spraying of chemicals over fields (Huang *et al.*, 2009). In aerial spraying, chemicals are usually applied as ULVs (Ultra Low Volume) formulation. It is applied about 0.5 – 1.0 liter/hectare. The chemicals are mixed in oil rather than water to prevent easy evaporation. Droplets of size about 40µm- 120µm are carried by wind and are applied 90° to the prevailing wind direction. Emission height of 5 – 10m depending on speed of wind should be adjusted (Dobson, 2001). In addition to this, EC (Emulsifiable Concentrate) formulation is also used in some cases. But

it is in large drop size and distributes unevenly with more water requirement (Wiktelius *et al.*, 2003). Aerial spraying is favored because of: i) less volume of chemicals is required, ii) more chance of pesticides remaining in vegetation and locusts rather than ground, iii) less exposure to operator, iv) application in timely & highly spatially – resolved manner.

Ground spraying

For ground spraying of locusts and grasshoppers, both portable sprayers and vehicle-mounted sprayers are used. Portable sprayers are mainly carried manually in hands or on the back of the user/operator. It is used for spraying in small areas. Vehicle-mounted sprayers are attached to the small truck, on tractors, or on the bed of a pick-up truck. It is used for spraying in large areas. Generally, ULV insecticide formulations are applied but EC formulations are used sometimes (FAO, 2020b).

Baiting

Baiting includes the insecticides impregnated in a carrier which are scattered among or in the path of locusts. Hoppers and settled adults are killed from stomach poisoning as they eat the bait. But mainly it is suitable for marching hoppers when there is minimal yearly vegetation and much exposed ground (Moharana *et al.*, 2020). Efficiency of baits mainly depends upon its palatability. Substrates/carriers mainly used are wheat bran, maize bran, saw dust & horse manures. Some attractants like molasses are also used to increase the acceptance of baits (Barbara & Capinera, 2003). Carbamates like bendiocarb and propoxur are widely used (Steedman, 1990). Bait incorporating IGRs, teflubenzuron & diflubenzuron resulted in failed moulting and distorted wings shape in locusts (Waktola, 1997). Cumin used as bait formulation showed toxicity against the desert locusts (Mansour & Abdel-Hamid, 2015). Dose rates ranging from 5 to 15kg/ha for marching hopper bands to over 50kg/ha for settled hoppers and adults are recommended (Dobson, 2001). Baits have significant environmental benefits over liquid insecticides. They don't need precise targeting and don't drift like in ULVs during aerial spraying. With a longer residual effect, it also doesn't need much water like liquid formulations which may be suitable for arid and desert areas. But it requires more formulations than ULVs, is laborious in preparing and transportation and risks to livestock as they eat the bait. Also, baits are not suitable carriers for entomo-pathogenic fungus (Latchininsky & VanDyke, 2006). Mainly bait kills the insects when it is ingested but for the fungus to work, contact of spores with cuticles is needed.

Dusting

Insecticides in dust formulations are spread over the locusts. Basically, inert materials like powdered chalk, talc and sands are used in the mixture. They can be distributed by using dusting bags, hand-blower or machine powder-duster. (Dobson, 2001). This technique is only effective when carried out in moist/ humid conditions and in first instar hoppers remaining in dense numbers (Steedman, 1990). But, in present, many countries rarely use this method and Pesticide Referee Group also doesn't recommend it anymore (Dobson, 2000). Large quantities should be used for controlling and acting poorly against later instars and adults. There is also the poison inhaling risk to the operator.

Synthetic insecticides are essential for control of locusts but only when other practices are unable to do it. Chemicals are applied in a wide variety of environments and its exposure poses a significant potential hazard to people, plant and non-targeted animal health. Non-judicial

application of synthetic insecticides may also develop resistance in pests and increase more risks to the environment (Ahmad *et al.*, 2020). Chemical pesticides used for locust control also pose more or less serious effects on specific groups of non-targeted animals. Therefore, improvement in the selectivity and efficiency of chemicals and also further research and improvement should be done to overcome the ecotoxicological problems.

Use of phenyl acetonitrile (PAN)

Prominent volatile emissions by mature desert locusts include mainly anisole, benzaldehyde, veratrole, phenyl acetonitrile (PAN) and 4 vinyl veratrole in which PAN is found in highest level (Mahamat *et al.*, 2020).

Table 3: Control Strategies of desert locust

Preventive and control measures	Description	References	
Traditional methods	Killing or trampling the bands, Ploughing or burning the egg infested field, Trapping the hoppers in pits	(Sharma, 2014).	
	Loud sounds, Acoustic and electronic devices	(Ibrahim <i>et al.</i> , 2013)	
	Using nets sprayed with garlic or neem oil	(Kaur, 2017)	
Botanicals methods	Neem -Consists tetranortriterpenoid compounds which are known for repellency, antifeedant, metamorphosis disturbances, hormonal regulation & fertility inhibitor property.	(Patel <i>et al.</i> , 2016), (Baumgart, 1995; Nisbet <i>et al.</i> , 1996; Nisbet, 2000; Roychoudhary, 2016; Bashir & Elshafie, 2017).	
	Linseed Oil - Helps in disrupting the swarm formation of locusts.	(Abdelatti & Hartbauer, 2020), (Bagari <i>et al.</i> , 2015)	
	Garlic extracts/oil <i>Allium sativum</i> (Linnaeus), cumin <i>Cuminum cyminum</i> (Linnaeus), jatropa oil <i>Jatropha curcas</i> (Linnaeus) as essential plant oils against the locusts	(Bashir & El shafie, 2013; Mansour & Abdel-Hamid, 2015; Mansour <i>et al.</i> , 2015)	
	Green muscle: <i>Metarhizium anisopliae</i> (Metchnikoff) var. <i>acridium</i>	(Lomer <i>et al.</i> , 2001; Hunter <i>et al.</i> , 2016)	
	(Diptera: Asilidae), <i>Ommatius</i> spp, <i>Promachus</i> spp and <i>Bombyliid</i> flies (<i>Anastoechus chinensis</i> Paramonov).	(Long & Hunter, 2005)	
	locust's natural enemies like generalist robber flies (Diptera: Asilidae), <i>Ommatius</i> spp, <i>Promachus</i> spp and <i>Bombyliid</i> flies (<i>Anastoechus chinensis</i> Paramonov).	(Long & Hunter, 2005)	
	Green Guard (in Australia) and Green Muscle (in Africa)	(Hunter, 2005)	
	Fungus of isolate IMI330189 , isolate F1985 by CSIRO & the APLC in Australia.	(Hopper <i>et al.</i> , 1995)	
	NOVACRID (<i>Metarhizium acridum</i> Driver & Milner strain EVCH077)	(Matthews, 2019)	
	ULV (Ultra Low Volume) sprays with oil-based formulations of the conidia	(Rachadi, 2010)	
	Chemical control	chemical insecticides of classes organophosphates, carbamates, pyrethroids, phenyl pyrazole and benzoylurea	(Dobson, 2000)
		PAN -suppresses cellular immune response in <i>S. gregaria</i> leading to high mortality rate.	(Khemais <i>et al.</i> , 2020)

PAN acts as growth inhibitory signal in microbe-microbe interactions (Kai *et al.*, 2007; Junker

et al., 2011) and as repellent signal in plant-insect interactions and some other insects like locusts (Seidelmann *et al.*, 2005; Irmisch *et al.*, 2014) may functions as a conspecific communication signal. It is concluded as a courtship-inhibiting pheromone used when sperm competition occurs among desert locusts (Seidelmann & Ferenz, 2002). It is produced by mature adult males of desert locust when they are crowded by the other mature males (Seidelmann *et al.*, 2000). It is found that when exposed in low relative doses, the locusts were arrested closer but further away at high relative doses (Rono *et al.*, 2008).

During the dual choice olfactometer tests, gregarious nymphs tend to move and remain in the zone suffused with paraffin oil but excludes the zone with PAN at or above the dose equivalent to 10 locust's emission moment (Wei *et al.*, 2019). Bashir *et al.* (2016) reported that use of PAN in combination with fractional doses of pesticides gave more control efficiency than the individual pesticides. The experiments conducted by Khemais *et al.* (2020) observed that PAN treatment suppresses cellular immune response in *S. gregaria* leading to high mortality rate. Also, IGR (Insect Growth Regulator) teflubenzuron combined with PAN revealed a negative impact on the feeding of nymphs (Mohamed *et al.*, 2011). They become confused and disoriented resuming solitary behavior and losing their appetite while others turn cannibal and eat one another (Bashir & Hassanali, 2010). In addition, PAN has a synergistic effect on *M. anisopliae*, an entomopathogenic fungus (Kooyman, 2003). In an experiment carried out by Bal *et al.* (2015), it is found that afternoon application of Green Muscle with PAN caused more mortality rate of nymphs of *S. gregaria* than them alone. Khemais *et al.* (2020) also found that joint application of PAN and the fungus, even in 50% reduction in recommended dose, showed a promising alternative for the control of the locusts. The overall management strategies discussed can be summarized in Table 3.

Beneficial aspects of locusts

Locusts as Food and Feed

Entomophagy, a practice of eating insects, has been followed in the long past by humans. According to a report "Edible insect: future prospects for food and feed security" published by FAO, top insect orders consumed worldwide are: Coleoptera (31%); Lepidoptera (18%); Hymenoptera (14%); Orthoptera (13%) and Hemiptera (10%) (Huis *et al.*, 2013). Locusts have grabbed the attention of people from its nutritionally rich composition and sensory appeal (Mariod *et al.*, 2017) and have been eaten throughout history. They have been recognized as delicacy food in many African, Middle Eastern and Asian countries. They are prepared either roasted, fried, boiled or grilled and are believed to taste like prawn and females filled with eggs are more flavored (Huis *et al.*, 2013). They can be captured in cool hours of day when they are less active and are easy to catch (Abbas *et al.*, 2020). Orthopterans have the FCR (feed conversion ratio) of 1.7kg (Rumpold and Schlüter, 2013) and are a popular source of protein and other essential nutrients. Desert locusts have energy content of 179 kcal/100 g and protein content of 14 – 18 (g/100g fresh weight) (Mariod, 2020). They consist of fat (11.5g/100 g fresh weight basis) in which 53% is unsaturated and are also enriched with minerals like sodium, potassium, calcium, phosphorus, zinc, magnesium and iron. (Abul-Tarboush *et al.*, 2010).

In addition, locusts can also be used as good potential feed for livestock, especially for poultry (Khan, 2018) and fishes (Tran *et al.*, 2015). They can be fed as live insects for free-range chickens & ducks or dried & ground for broilers & fishes (Heuzé & Tran, 2016). A shift from

conventional protein sources towards locust meals, mostly for protein and fat, could turn devastation of locusts into productive and alternative feed. Locust meal was reported to have 52.3% CP, 12% EE, 19% CF and 10% ash during the proximate analysis (Adeyemo *et al.*, 2008). However, it is deficient in lysine (Gibril, 1997).

Despite the fact that locusts are edible, one major factor to consider is the safety of locusts as food and feed. Some of the hazards associated with use of insects include pesticide residue, pathogens, anti-nutritive factors and allergens (Huis *et al.*, 2013). Chlorinated pesticides were found in the laboratory analysis of residual pesticides in edible locusts in Kuwait (Saeed *et al.*, 1993) so chemically controlled locusts shouldn't be used in diet. Instead, insects sprayed with botanical formulations like linseed oil can be collected and used in diet as they contain omega – 3 fatty acids and have higher linolenic acid content (Abdelatti & Hartbauer, 2020). And chemical pesticide sprayed locusts should be avoided as they pose a major health risk.

Harmful aspects of locusts

Damage caused by desert locust

Desert locusts are polyphagous insects which feed on various parts of plants such as leaves, shoots, flowers, fruit, seeds, stems, and even bark. Crops and non-crop plants including cereals, vegetables, fruit trees, sugarcane, cotton, pasture grasses, and weeds are eaten by the insect. Single insect is estimated to consume green vegetation equivalent to their body weight (2 g) in a day (Showler, 2013). It is reported that in a day a small 1 sq. km swarm consumes the same amount of food as 35000 people (FAO, 2020). The damage caused by locusts is even mentioned in the Bible and Quran. The swarms are more dangerous as they are capable of creating large populations, dense bands and can migrate many hundreds and even thousands of kilometres in a very short period of time which make them capable of causing heavy damage in a very short period (Lecoq, 2003). So, these pest outbreaks can create critical conditions for food security and livelihoods of people in affected areas (Long *et al.*, 2019). As these swarms can affect a large portion of the world such whole continents get affected and among them Africa is most susceptible to locust attack (Cressman, 2016).

Overview on desert locust plagues

Desert locust (*S. gregaria*) outbreak and plague evolution are generally episodic in nature as they take place through different recession periods and invasion periods alternating with each other (Zhang *et al.*, 2019). They are normally found scattered in solitarious phase in arid and semi-arid desert areas which can be called as recession areas (Symmons & Cressman, 2001; Roffey *et al.*, 1970; Ceccato *et al.*, 2007). The recession area for desert locust is about 16 million square kilometres in nearly 30 countries (Symmons & Cressman, 2001) which includes the deserts of North Africa, the Middle East, and Southwest Asia desert areas (Cressman, 2016). Locusts in these recession areas tend to avoid each other except while mating and are in low numbers (Simpson *et al.*, 1999). This period of time to which desert locusts remain in low numbers in the solitarious phase is called the recession period. In the rarest event some of the places in recession areas receive unusual heavy rainfall which encourage locusts to multiply and increase their number rapidly which under favorable conditions can increase up to 16 to 20 times in every 3 months (Cressman, 2016). After some time when rainfall stops, desert habitats start to dry out and the huge number of locusts are forced to feed on scarcely available vegetation in small areas and come close to each other (Cressman, 2016). Bouaichi *et al.* (1996)

laboratory & semi field experiment and Kennedy (1939) field observation concluded that the provision of small patches of resources can lead to gregarious behavior so the hopper present in those recession areas starts forming small group and finally fuse to form bands of hopper and swarms of adult (Cressman, 2016). After the several months of simultaneous multiplication, concentration and gregarious outbreak of locust takes place in which bands and swarms of locust are formed (Symmons & Cressman, 2001; Roffey & Popov, 1968) and the swarms can travel thousand kilometer in a week (Steedman, 1990). Moreover, upsurge of locust takes place with subsequent outbreaks at same time by two or more generations of transient-to-gregarious breeding (Symmons & Cressman, 2001). This period of one or more years in which heavy infestation and widespread takes place is called a plague and a major plague can be formed when two or more plague occur at the same time (Cressman, 2016). Locusts in plague widespread and infest greater area which can be beyond recession area and such area can be called as invasive area (Van Huis, 1992) which extends to about 32 million km² area equivalent to 20% of earth's land surface (Cressman, 2016). Finally, the plagues start to decline due to natural factors such as no rainfall for locust breeding and human activities such as using different control methods (Symmons & Cressman, 2001). However, in unfavorable conditions all locust outbreaks may not change into upsurge similarly all upsurges may not change into plague (Cressman, 2016).

CONCLUSION

Desert locust has been a devastating pest in deserts of North Africa, the Middle East, and Southwest Asia. The swarm outbreak leads to food insecurity as the insect feeds on various parts of plants such as leaves, shoots, flowers, fruit, seeds, stems, and even bark. The swarm outbreak takes various forms from upsurge to even plague under favourable climatic conditions. The movement of locust is in a windward direction; it is thus compulsory to forecast wind movement after the insect swarms are seen in deserts. As these transboundary pests appear in millions of numbers all the concerned authorities should be well pre-prepared to reduce the damage. Traditional methods can be used but only when the swarms are very few in number. For controlling thousands or millions in swarms, we need to shift from traditional cultures to modern approaches. Botanical oils like Neem oil, Linseed oil and biological methods like Green muscle are safe and environment-friendly methods. However, in an emergency, chemical pesticides are the better options. More effective, low resistance and more environment-friendly pesticides are to be further developed and used. The harmful effects of pesticides on humans, animals and insects cannot be overlooked. It must be ensured that the control methods don't pollute and damage the environment. The strategies should not solely focus on chemical methods. Other available methods should also be researched and used in an integrated way. It is thus concluded, if we fail to take serious action at time of swarming, we have to face various hazards, due to desert locust swarm outbreak.

Authors' contributions

S. Shrestha, G. Thakur, J. Gautam, N. Acharya, M. Pandey and J. Shrestha wrote this review paper.

Conflict of interest

The authors declare no conflicts of interest regarding publication of this manuscript.

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