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ORIGIN, DISTRIBUTION, BIOLOGY AND INTEGRATED MANAGEMENT OF SOLENOPSIS INVICTA (HYMENOPTERA: FORMICIDAE): A COMPREHENSIVE STUDY

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ABSTRACT

The red imported fire ant (RIFA), *Solenopsis invicta* (Hymenoptera: Formicidae), is a serious, aggressive social insect pest with an original distribution centered in the southern United States. Now, its population has been established in many countries around the globe. This insect is well-known for causing a range of harmful impacts, such as damaging crops, endangering public safety, harming livestock, reducing the diversity of native flora and fauna, and disrupting ecosystems, particularly in China. Its control is a laborious, expensive, and time-consuming task. Timely implementation of integrated pest management (IPM) strategies is needed for its effective management. Strict preventive measures are needed to avoid its invasion in new areas or places. Effective quarantine measures are essential at seaports and airports to limit the movement of RIFA across countries. If the invasion has occurred, then proper implementation of IPM strategies should be used against RIFA. Considering the broad spectrum of losses caused by RIFA, this study provides proper information about the possible entry routes of invasions and provides guidelines for the implementation of IPM strategies against RIFA.

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INTRODUCTION

Origin

The red imported fire ant (RIFA), *Solenopsis invicta* (Hymenoptera: Formicidae), is believed as a native insect pest of South America (Pitts, 2002). Their mounds can commonly observed in patches with variable densities, even 600 mounds per hectare have been observed (Vogt et al., 2003). This insect is considered a “super pest” due to the significant and often highly destructive impacts on various aspects of human life, including the economy, public health, ecosystems, and lifestyle (Wylie and Janssen May, 2017).

Biology

Colonies of *S. invicta* may be monogyne or polygyne.

Monogyne colonies have single queen while polygyne colonies have multiple queens. Their mode of reproduction and dispersion vary according to their colonial pattern (Keller, 1991; Keller and Passera, 1989; Ross and Keller, 1995).

Monogyne colonies are established by newly mated queen, while polygyne colonies are established via procedure of budding. During the process of budding, some queens and workers leave their parental colony and build a new nest. Sometimes established colonies accept a new queen coming from another colony (Glancey and Lofgren, 1988). Newly mated polygyne queens can lay 20-30 eggs/day while a newly mated monogyne queen can lay 200 eggs/day, and a mature monogyne queen can lay 800-1000 eggs/day (Taber, 2000). Larvae hatch from eggs after 8-10 days. The larval stage takes 6-12 days, and the pupal stage usually takes 9-16 days. Queen feeds the first brood of young larvae with oils regurgitated from her crop, trophic eggs, secretions from her salivary glands and with her broken wing muscles (Vinson and Sorensen, 1986).

The first batch of workers is small sized because they are fed with low nutritious food by the queen and are called "minims". They come out of the chamber for foraging and also feed the queen and new larvae. They also start building the mound. The larger workers are produced within one month. After six months, the colony size increases and consists of all three types of workers, and the mound becomes visible in a field or lawn. A typical mature colony comprises approximately 80,000 workers, but 240000 workers have also been recorded (Vinson and Sorensen, 1986). The lives of workers depend upon their size. Minor workers live for one to two months shortly, medium-sized workers live for two to three months, and major workers live for three to maximum of six months (Hedges, 1997).

Foraging workers usually feed on dead animals like insects, earthworms, and vertebrates. They also collect honeydew and also forage for sweets, proteins and fats in homes and other relevant sites. Larvae of up to third instar are provided liquid diets and after that fed with solid diets. The queen is fed with digested proteins that have positive impacts on fecundity (Vinson and Sorensen, 1986).

Historical background

Usually colonies have invaded to Central South America in 1933-1940 (Mobley and Redding, 2005). Now, RIFAs have been reported from US states, Caribbean, Australia, New Zealand, Taiwan, Hong Kong, Macao, China, and India. Its control, medical treatment, and damage to the property cost more than $6 billion annually in the United States only. We will discuss the invasion history of *S. invicta* in Australia and some countries of Asia.

Australia

Five invasions of *S. invicta* have been reported in Australia during 2001-2014. Brisbane and Queensland faced two invasions in 2001; one invasion was observed at Yarwun, central Queensland in 2006; one invasion at the Port of Gladstone, central Queensland in 2013 and the last invasion occurred at Port Botany, New South Wales in 2014. Four invasions have been eradicated successfully, including the eradication of genetically distinct population from Port of Brisbane where invasion had occupied 8300 ha in 2012, that was the largest eradication of any ant species throughout the world (Hoffmann et al., 2016; Wylie and Janssen May, 2017).

Mainland China

More than one invasion occurred in Mainland China during the 1990s, probably from the Southern United States (Ascunce et al., 2011; Lu et al., 2008). However, the infestation was confirmed in September 2004 for the first time in Wuchuan, Guangdong. At that time, the invasion occupied approximately 2000 ha of soil, while by November 2005, the infestation spread into four provinces i.e., Guangdong, Guangxi, Fujian and Hunan and total infested area increased up to 7,120 ha (Zeng et al., 2005; Zhang et al., 2007). Ministry of Agriculture of the People's Republic of China launched an eight years *S. invicta* eradication program in 2005 (Zhang et al., 2007). Ultimately, Mainland China has been declared as *S. invicta* free region since 2013.

Taiwan

The incursion of *S. invicta* in Taiwan was confirmed in Taoyuan City in October 2003 for the first time likely to be introduced from the southern United States through/or near the Taoyuan International Airport and then in Chiayi County probably imported from California (Ascunce et al., 2011; Chen et al., 2006; Huang et al., 2004; Yang et al., 2009). The Council of Agriculture in Taiwan actively launched the quarantine measures against *S. invicta* since September 2004. To control its infestations, various measurements like the disinfection of affected areas and closed inspection of movement of plant materials, nursery stocks and construction materials were taken. For technical measures, public awareness, training courses and workshops, the

National Red Imported Fire Ant Control Centre (NRIFACC) was established (Kuo, 2008). All these efforts resulted in the complete eradication of *S. invicta* in Chiayi in July 2017 (BAPHIQ, 2017). However in other regions like Taiwan's northern region, the invasion is still expanding (Schowalter et al., 2015). *S. invicta* invasion extended to Great Kinmen Island and also to the busiest seaport of Kaohsiung. The ants of these two locations genetically resemble to those that found in china than the USA.

India

Although the presence existence of *S. invicta* in India is unquestionable, it seems very difficult to find realities about invasion history, affected areas, and population density of *S. invicta*. Researchers are in doubt about these facts because of miscellaneous problems like correct identification of *S. invicta* population (Bharti et al., 2016; Rajagopal et al., 2005; Wetterer, 2013). In January 2017, *S. invicta* population was found in container shipped from Nhava Sheva (main container port close to Mumbai) at the port of Adelaide, Australia. That *S. invicta* population closely resembled that of the southern United States, especially Louisiana or Florida. This incident revealed the reality that India has been infested with RIFA.

Japan

The first case of *S. invicta* in Japan was confirmed from Amagasaki, Hyogo, on May 26, 2017, in a shipping container arrived from Nansha port in Guangzhou, China (Igarashi, 2018; Oyama and Nozaki, 2017). After that, 42 invasions had been reported from fourteen various places until the end of July 2019. All the invasions were believed to be invaded through sea freight except one case that had been reported at Narita International Airport near Tokyo in airfreight that arrived from Texas in August 2018. However, it will be unjust to make the origin of cargo container responsible for pest invasion in Japan because it may have been picked up in another port along its voyage (Japan, 2019). After confirmation of the first case, the Ministry of Environment started careful inspection of ports and their surroundings receiving cargo containers from China (Japan, 2019). Sixty-eight suspected ports were surveyed thrice in 2017, and 65 suspected ports were surveyed twice in 2018. *S. invicta* populations were found limited to the areas of ports or near ports and warehouses, indicating that *S. invicta* has not established its colonies yet. However, seven incidents of *S. invicta* activity had been reported in crevices in the pavements and also in sand drift heaped on the cement floor in the container yards (Japan, 2019). Ecological niche modeling based on winter temperatures had predicted in the past that the ecological conditions of several areas of Japan are supportive for *S. invicta*, except the northern areas (Morrison et al., 2004).

South Korea

The first case of established population of *S. invicta* ants was confirmed in September 2017 at Busan's Gamman Port (Lee, 2017; Lyu and Lee, 2017). After that, *S. invicta* populations have been observed at container terminals in Busan, Pyeongtaek and Incheon Port (Choi and Shim, 2018; Jang and Chung, 2018; Shim, 2018). Eleven mounds with alates were observed on the concrete floor of the container yard over a distance of 40 m at the Hutchinson Busan Container Terminal (Shim, 2018). Some of the above cases are supposed to be imported from Fujian province (APQA, 2018). All the mentioned cases were observed on ports and container yards. However, in September 2018, fire ants population with the queen was found at a construction site in northern Daegu, an inland city, likely introduced from Guangzhou (Choi and Shim, 2018). As invasion has been confirmed in the country, the APQA has also started a thorough inspection of various 32 possible organic sources of *S. invicta* importation, including coconut and dry wood. After the evidence of *S. invicta* in Daegu, the APQA will likely start inspection of possible inorganic sources of *S. invicta* importation too (Choi and Shim, 2018).

Economic importance

Threats to public health

Aggressive nature of *S. invicta* is a threat for the human being living in the range of their foraging areas like parks, and farmlands. Painful stings of *S. invicta* usually cause itchiness, and white pimple also appears several hours after the stinging. More sensitive people may suffer from fever, urticaria, shock, and even death. Eighty deaths had been recorded since 2013 (Choi and Shim, 2018; Vinson, 2013; Zhao and Xu, 2015). A research conducted in 2004 in China revealed that 10% of affected people suffered from fever, few of them experienced systemic allergic reaction (Xu et al., 2012), and death (Zhao and Xu, 2015).

Impacts on agriculture

S. invicta exhibits more destructive behavior as compared to other ant species. When it invades a new geographical area, its direct and indirect losses to native crops become visible (Eubanks et al., 2002). It feeds on fresh soft growth of the number of crops like soybean, okra, citrus, cabbage, bean, cucumber, potato, eggplant, sweet potato, sorghum, peanut, sunflower, sesame seeds and corn all over the year. Besides direct feeding, losses to crops also occur when its mounds interfere with field operations. Among the mentioned crops, sesame, mungbean and soybean are badly affected by *S. invicta,* resulting in significant yield losses. Their infestations reduce the germination rate of affected sesame seeds up to 64% (Huang et al., 2010; Lofgren and Adams, 1981; Rosen et al., 1994; Wu et al., 2014).

S. invicta is responsible for population reduction of flower-visiting insects like hoverflies (*Eristalinus quinquestriatus* and *E. quinquelineatus*) and flea beetle (*Phyllotreta striolata*), affecting the reproductive capacity of crops. The seed yield of rapeseed (*Brassica napus*) was apparently reduced in the infested areas (Wu et al., 2016; Wu et al., 2015).

Losses to urban settings and public places

S. invicta can disturb the routine activities of human beings by causing painful stings, especially in parks, farmlands and green belts in cities (Zhao and Xu, 2015). They build their mounds in highly sensitive instruments like power facilities because electric fields are attractive for them (Cui et al., 2018). Their mounds have been observed in transformer boxes and other electric packages in China (Luo, 2005; Zhao et al., 2008) and can cause short circuits, problems in flow of electricity and cause serious threats to public safety. They can also develop their colonies under walkways, patio slabs, lawns, foundations of buildings and concreted driveways and cause damage to these structures (Vinson and Sorensen, 1986).

The threat to biodiversity

Researchers have found that *S. invicta* is a serious threat for several species of animals, especially for ground nesting or those which lay their eggs in the soil. In several areas of the world, several animal species apparently affected after the invasion of *S. invicta*. Their invasions have also been found responsible for the population decline of ground doves, bobwhites, Texas horned lizard, peninsular intergrade kingsnake, rails, deer, terns and southern hognose snake (Allen et al., 2004; Vinson, 2013; Zhao et al., 2008). Several distinct species of wildlife are at higher risk by *S. invicta*. For example, in Australia, populations of many distinct species like the leathery turtle, green turtle, pacific ridley, Mary River tortoise, Bell's turtle, Bellinger River Emydura, hawksbill turtle, crocodiles, frogs, lizards and ground nesting birds like black-breasted button-quail, mallee fowl, plains wanderer and several other species of birds have been declined critically after the invasions of *S. invicta* in their eco-system (Moloney and Vanderwoude, 2002).

S. invicta ants are also a threat to other ant species because they are the most effective competitor of food among the other ant species, and they have disturbed mutualism between other ant species and honeydew-producing hemipterans. This hard competition for food compels other ant species to leave their habitats, resulting in a reduction of species richness. This condition has been observed in China, where more than 33% reduction in the species richness of other ants has been recorded in numerous habitats (Jiang et al., 2010; Qi et al., 2015; Song et al., 2010; Tsai et al., 2009; Wu et al., 2010; Wu et al., 2014). Many plant species are also being disturbed by *S. invicta* because these ants feed on their seedlings, interfere with pollination, seed dispersion, and germination (Australian Department of Environment).

Effects of environmental factors on RIFA

Invasive species of insects have a strong ability of population expansion and outbreak when environmental conditions are supportive for them (Pigllucci, 1996; Willmer et al., 2009). The extent of invasion risk of *S. invicta* can be guessed by comparing the environmental factors of certain geographical areas with required or tolerable environmental parameters for *S. invicta*.

Foraging activities of *S. invicta* are influenced by various environmental factors like humidity, soil moisture, and temperature etc. Among these factors, temperature is the key factor affecting foraging activities positively or negatively (Porter and Tschinkel, 1987). So, we will discuss the impacts of temperature on foraging activities of *S. invicta.*

Foraging activity of red imported fire ants is affected by ambient air temperature, soil surface temperature and the underground (up to the depth of 5 cm) temperature. The maximum foraging activity occurs at the ambient air temperature range of 25 to 33°C. The optimum soil surface temperature was ranged 27-40°C that increases foraging activities. In contrast, 28-37°C is the optimum temperature of the soil at a depth of 5 cm, which induces maximum foraging activity (Yue Lu, 2012). They adopt various tactics to minimize their exposure to peak temperatures, like at a lower temperatures (15.0°C), tunneling activities of *S. invicta* increase likely to avoid the adverse thermal exposure (Bentley et al., 2015). Populations living at high latitudes confine their activities in winter to minimize cold injuries (Anonymous, 1972; Korzukhin et al., 2001; Morrison et al., 2004; Vinson, 1997).

S. invicta can develop quick adaptation and resistance to adverse thermal conditions such as populations of *S. invicta* living at high latitudes have experience of cold exposures and have higher potential to tolerate cold temperatures without any considerable physiological cost (Lytle et al., 2020). Similarly, workers of *S. invicta* previously exposed to high temperatures (36°C for 1 hour) can survive at higher temperatures than others (Xu et al., 2009). Higher heat resistance in colonies exposed to direct sunlight as compared to shaded colonies has also been observed (Boyles et al., 2009). These observations concluded that populations of *S. invicta* established in geographical areas with peak temperatures will likely have a higher potential to tolerate adverse temperatures. Investigations have revealed that *S. invicta* are the most successful in various geographical regions as compared to other closely related species like *S. richteri. Various factors may be involved in their rapid expansion one of them is a higher ability of thermal tolerance in S. invicta (Chen et al., 2014).*

Integrated management strategies for fire ants

Various controlled measures have been developed according to regulatory policies, medical liabilities, environmental effects, and financial concerns. Complete eradication of its population in an area is very difficult due to its cryptic nature. Re-invasions are also expected in treated areas. IPM control measures are always considered judicious suggestion for the suppression of *S. invicta* invasion because these practices are eco-friendly and cost effective (Drees et al., 2013). IPM practices may vary according to intensity of invasion, available resources, economic importance of affected geographical areas and ecological hazards concerned with management practices.

Treatment threshold level

The treatment threshold level relies on the sensitivity of affected sites. In the areas associated with public activities or with organisms of ecological importance, the treatment threshold level is 1 live individual or 1 colony of *S. invicta*, while in pastures or larger treatment areas, the threshold level is 50 mounds per ha or 20 ant mounds per acre (Drees et al., 1995) or an average of 30 ants per 10 hot dog slices.

Preventive measures

Strict measures are required to prevent the entry of *S. invicta* into a new country or new areas of the country. Keeping a thorough eye on the invasion histories, following preventive measures are suggested:

(i) Appointments of experts must be made in all the expected sites to prevent or suppress the invasion.

(ii) Quarantine personnel must be well trained and provided with sufficient resources.

(iii) Expected sources that can facilitate the movement of *S. invicta* must be strictly inspected to avoid the new invasions and to overcome expansion of the rising invasions.

(iv) To secure the achieved success, coordinated succeeding efforts should be continued, otherwise, the intensity of invasion may recommence (Wylie et al., 2020).

To prevent the migration of *S. invicta* from affected neighboring countries or areas, careful inspection and surveys are required on the boarders of a country or area. Visual inspection seems a difficult operation and may not be effective as required. While various traps like food traps and pitfall traps are effective for the timely detection of migrants (Stringer et al., 2011).

Non-chemical control measures against RIFA

At present frequent and un-controlled use of synthetic insecticides is associated with problems of public health, environmental safety, resistance development infrequently exposed insect pests and safety of non-targeted organisms. So, alternatives to synthetic insecticides are becoming more popular. The following techniques can be implemented as alternatives to synthetic insecticides, or they can minimize the use of synthetic insecticides.

Cultural practices

Soil type and cultural activities affect the population abundance of red imported fire ants. These ants prefer clayey soils for the establishment of colonies. Their population can be minimized through adoption of proper cultural practices. The moisture content of the soil is directly related to the risk of ant infestation, (Ali et al., 1986).

S. invicta can affect the livestock by stinging. Younger domestic animals are more sensitive than adult ones. Most stings occur in the summer season (Barr et al., 1995; Drees et al., 1995; Drees, 1994). Proper sanitary and phytosanitary measures should be adopted to overcome their infestation on farm.

Botanicals against *S. invicta*

Many plants and plant based products have been found effective against the number of insect pests. The powder and bioactive compounds (α-asarone and β-asarone) of the Sweet flag (*Acorus calamus L.)* are highly effective against *S. invicta*. 0.33 mg/cm^2 powder caused 88% mortality of the test population, while 1 mg/cm^2 can cause 100% mortality of the test population under laboratory conditions (Kafle and Shih, 2017).

Isothiocyanates compounds (ITCs) are released by Brassicaceae family to defend themselves from invader insects. ITCs exhibit insecticidal properties, especially against insect pests of stored-products and can be used as fumigants due to their volatile nature. They are also effective against *S. invicta*. Some of them can be used as contact insecticides, and some can also be used as fumigants as well as contact toxins. (Demirel et al., 2009; Du et al., 2020; Worfel et al., 1997).

Microbial control of *S. invicta*

Several pathogens are known to infest various casts of *S. invicta* at certain stages of their life cycle that are briefly discussed.

Viral pathogens

Solenopsis invicta virus 1 (SINV-1)

SINV-1 is a positive sense single stranded RNA virus found only in ants of genus *Solenopsis*. SINV-1 can cause mortality of *S. invicta* at larval stage under laboratory conditions only. But their infestation remains asymptomatic and is unable to control *S. invicta* population under field conditions because of numerous factors including the unidentified pathogens and its inability to synthesize pure SINV-1 etc. Furthermore, this virus was found to be responsible for decreasing the effectiveness of certain insecticides when it was used in combination with those certain insecticides under laboratory conditions due to unknown reasons. However, under adverse environmental conditions, the symptoms of virus infection may appear quickly and can cause the mortality of infected individuals (Bailey, 1967; Chen and Siede, 2007; De Miranda and Genersch, 2010; Tufts et al., 2014; Valles et al., 2004).

Solenopsis invicta virus 2 (SINV-2)

The second virus discovered in *S. invicta* colonies is SINV-2 (Hashimoto and Valles, 2008a). There is no or unreliable evidence for its effectiveness against *S. invicta* either in laboratory or field conditions (Hashimoto and Valles, 2008b).

Solenopsis invicta virus 3 (SINV-3)

Picorna-like single strand RNA "SINV-3" virus infests all the casts of the colony at any stage of their life cycle. Under laboratory conditions, this virus proved very effective, causing the complete eradication of infected colonies within three months by interrupting the normal behavior of workers and by disturbing the normal feeding process to the larval brood and queen (Tufts et al., 2010; Valles et al., 2014).

SINV-3 baits can introduce the pathogens in a colony under field conditions. In an experiment, baits of sugar solution and cricket paste proved more effective. These baits resulted in the decline of eggs, broods, workers and weight of the queen (Valles et al., 2013). However, the effectiveness of this pathogen can be interrupted at a higher temperature. At a temperature of 29.3°C or higher, it fails to control *S. invicta* (Valles and Porter, 2019).

Entomopathogenic fungi against *S. invicta*

Various pathogenic fungi can effectively be used as a biological control agent against a wide variety of insect pests. *Beauveria bassiana* is one of them. Its strain ZGNKY-5 is highly effective against red imported fire ants in the laboratory as well as in field conditions. In an experiment, it caused 93.40% mortality of the test population of *S. invicta* after the total exposure of 504 hours at the dose of 1×10^8 mL^{-1} conidia (Li et al., 2016). The other two strains of *B. bassiana* (GHA and NI8) and *Metarhizium brunneum* are also effective against the *S. invicta* under laboratory conditions. *B. bassiana* (NI8) is more effective than *B. bassiana* (GHA) and *M. brunneum (Rojas et al., 2018). The effectiveness of these three fungi against S. invicta* has not been yet examined under field conditions.

Entomopathogenic nematodes

Allomermis solenopsi n. sp. (Mermithidae: Nematoda) is found as an effective biological control agent of *S. invicta* under controlled conditions (Poinar et al., 2007). More investigation is required to examine the effectiveness of the mentioned nematode species against *S. incecta* under field conditions.

Entomophagous insects against *S. invicta*

Phorid flies *(Pseudacteon spp.)* are one of the effective parasitoids against *S. invicta*. The female phorid fly lays eggs in the thorax of adult fire ant workers of any size. Besides causing mortality of affected workers, they also influence the foraging behavior and survival of *S. invicta* in the affected area (Chen and Fadamiro, 2018; Fowler, 1997; Morrison and Gilbert, 1998).

Predatory birds against *S. invicta*

Several species of birds partially or completely rely on insects for their foods. They keep the population of insects in check. Purple martin (*Progne subis*) can effectively suppress the population of *S. invicta.* It mainly feeds on the queen and the males of *S. invicta* during their nuptial flights. It is estimated that in the Southern United States, this bird feeds on several billions of the fire ants each year and suppress their population expansion (Helms IV et al., 2016). So, the population of this bird in infested areas should be encouraged.

Chemical Control

Individual mound treatments

IPM strategies against *S. invicta* also include the judicious use of synthetic insecticides at thresh hold level. In some cases, exposure of queen of *S. invicta* to sub-lethal doses of insecticides can effectively prevent colony establishment and expansion. Feeding sub-lethal dose (0.25 μg/ml) of neonicotinoids insecticide “imidacloprid” to mated queen can result in delayed hatching of eggs, and hatched larvae might not be able to transfer to pupae and adult stages (Wang et al., 2015).

Application of liquid nitrogen (LN2) is highly effective for mound treatments in the urban, agricultural, and other places of high human activities. It is not only effective for the elimination of *S. invicta* colonies but also has no hazardous impacts on non-target organisms. In a study under field conditions, after 21 days of the treatment, all the treated colonies were killed (Lin et al., 2013).

Various organophosphates (acephate, chlorpyrifos), carbamates (methomyl) and pyrethroids (lambda-cyhalothrin) have been found effective for individual treatment. Among these insecticides, methomyl is more toxic, while lambda-cyhalothrin is least toxic against *S. invicta* (Seagraves and McPherson, 2003).

Baiting of S. invicta

Effectiveness of bait against *S. invicta* mainly depends upon the distribution pattern of bait stations and attractants used in baiting stations. The number of bait stations depends upon the foraging activities of targeted species. The attraction of ants by bait varies from species to species. For *S. invicta*, various attractants have been tested, and many of them were promising. These attractants include various attractants like proteins (hotdog-baited traps), tuna, carbohydrates (sugar water solutions) etc. (Bao et al., 2011; Nyamukondiwa et al., 2014). Among carbohydrates, sucrose is preferred by most of the ant species (Blüthgen and Fiedler, 2004), so it can be used as attractant for *S. invicta*. Slow acting and non-repellent insecticides are used in baits. Among various insecticides, fipronil is most common. While boric acid also proved the best choice as a toxicant in baits against *Monomorium chinensis* and the *Anoplolepis gracilipes*. Boric acid is less hazardous to the environment (Kafle et al., 2020). The investigation is needed to find its effectiveness against *S. invicta.*

Grits treatment

It is a novel technique for the control of social insect pests. This technique uses inert food materials contaminated with non-repellent toxicants. In an experiment, corn cob grits treated with a combination of triolein and fipronil caused 90.5% mortality of the test population. This treatment was also observed effective in field conditions (Wiltz et al., 2010).

Fumigation treatment

Fumigation of toxicants is an effective technique to prevent the entry of live individuals of *S. invicta* into a new area or country. Usual fumigation techniques that make the use of volatile synthetic insecticides will likely be insecure because of their residual effects. Some naturally occurring compounds like Allyl isothiocyanate (AITC) from plants such as wasabi (*Eutrema japonicum*) have insecticidal properties with no residual effects and can be used as a fumigant. Its Fumigation can kill the live individuals of *S. invicta* being transported in the shipping containers. It is reported that encapsulated AITC in the gas-barrier bag completely killed the test population of *S. invicta* (Hashimoto et al., 2020).

CONCLUSIONS AND RECOMMENDATIONS

One of the most invasive insect pests, the red imported fire ant, arose from the southern United States and overwhelmed many countries. Despite considerable attempts for its eradication, its invasions are rising and creating serious problems with human health, biodiversity, agriculture, public places, livestock, electric devices, and eco-system. Potential resistance to adverse environmental conditions and vast adaptation to prevailing environmental conditions are considered the driving forces behind its success.

For the management of *S. invicta*, effective or strict implementation of integrated strategies are advised. For the adoption of precise strategies, the correct identification of *S. invicta* is important. Misidentification can result in devastating damage through their spread by allowing *S. invicta* to establish colonies. Appointed personnel must be able to differentiate the monogyne and polygyne colonies because their behavior, physiology, and genetics are different in many aspects.

Among IPM strategies, preventive measures are advised in infestation free countries or areas that are at risk of invasion because its eradication becomes a hard challenge after the invasion has occurred. Implementations of quarantine measures at importing sites are fundamental because these sites have been found responsible for the accidental entry of *S. invicta* individuals from different geographical regions, leading to the establishment of colonies in many countries. Swarming alates from affected neighboring countries can also enter and establish colonies, so boarders adjacent to affected countries must be monitored regularly to prevent the entry/establishment of invasion.

In the case where the invasion has established, IPM measures must be followed in addition to all the preventive measures mentioned above. Continuous implementation of IPM measures is required to eradicate or minimize the invasion. IPM measures include all biological, cultural and chemical control measures i.e. toxic botanicals, microbial application, predatory insects and birds, individual mound treatment, baiting, fumigation of suspected goods, liquids and grit treatments etc. If the invasion is detected in an area, efforts must be made to prevent the invasion expansion to other areas. Movement of goods from the affected area to other areas can cause invasion introduction to those areas, so the goods must be inspected thoroughly before being transported to other areas. As *S. invicta* are attracted to electric fields, so electric devices and cables should be observed regularly. *S. invicta* are also a great threat to wildlife, especially for endangered species of animals. Therefore, such animals should be shifted from infested areas to infestation free areas after proper sanitation treatment. If the invasion has been eradicated successfully from an area, still there will be chances that the infestation can arise again later, so it is important to continue monitoring of that area.

AUTHORS' CONTRIBUTIONS

AR, MI, and WJ designed the study, collected, formatted and curated data, arranged references as per format of the journal, wrote, reviewed and edited the manuscript, BA, MFAK, ANM, AM, and MAB collected, formatted and curated data, arranged references as per format of the journal, KS, RS, SIAS, RA, SMZ and YH formatted, edited and curated data, arranged references as per format of the journal.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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