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Biology and management of stored products' insect pest *Rhyzopertha dominica* (Fab.) (Coleoptera: Bostrichidae)

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Abstract

Food protection under storage conditions is one of the major concerns of agricultural industry. It primarily relies on a precise knowledge of biology, ecology and behavior of different pests infesting stored food products including insect pests. Stored grain insect pests reduce and deteriorate the quality and quantity of human food stocks all over the world. Lesser grain borer, *Rhyzopertha dominica*, is a major stored food insect pest of cosmopolitan nature. It is a polyphagous pest that infests almost all cereals grains and their derived products. In this paper, biological, physiological and ecological perspectives of *R. dominica* are reviewed along with some management tactics being employed to control this insect pest. Insect attractions, interactions with microorganisms, dispersion and pheromone secretion mechanisms are also discussed.

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Introduction

Human population is currently growing at an alarming rate of 1.14% per annum while agricultural resources are not progressing with such a pace (Flinn *et al.,* 2010). To meet human hunger, cereal grains such as wheat, rice, maize, sorghum and barley are the main energy sources in most of the countries that fulfill the nutritional requirements of global population. In agricultural productions, particularly of grains and other dry food, protection of the product has always been a challenging task during post-harvest period. During storage and processing of agricultural commodities, a major part of food becomes lost due to multifarious factors including insect pests. Under tropical and subtropical climatic conditions, a plenty of insect pests attack on different stored food commodities (Proctor, 1994). Most important insect pest species of stored grain products are lesser grain borer (*Rhyzopertha dominica*), red flour beetle(*Tribolium castaneum* and *Tribolium confusum*), Khapra beetle (*Trogoderma granarium*),Angoumois grain moth (*Sitotroga cerealella*), rice weevil (*Sitophilus oryzae*), granary weevil (*Sitophilus granaries*), Indian meal moth (*Plodia interpunctella*), saw-toothed grain beetle (*Oryzaephilu ssurinamensis*) and maize weevil (*Sitophilus zeamais*) (Subramanyam, 1995; Lazzari and Lazzari, 2012; Ahmed *et al.,* 2013).

Each year, millions of dollars are lost due to stored grain insect pests (Flinn *et al.,* 2003). Due to the attack of stored grain insect pests about 10–15% food grains of developing countries go astray during storage conditions each year (Subramanyam, 1995). In developed countries, food losses are less due to advanced storage techniques and infrastructure and due to effective management of insect pests as compared to developing countries like Pakistan. In Pakistan, stored grain insects cause huge quantitative and qualitative losses in grains and cereals (Ahmed *et al.,* 2013). Right from early history of Pakistan, during 1971–1973, damage due to the incidence of storage insect pests' attack in cereal crops is assessed to be about 2–10% (Nadeem *et al.,* 2011).

Among stored grain insect pests, lesser grain borer, *R. dominica*,is a destructive insect pest which infests many cereal grains at different pre- and post-harvest levels (Edde, 2012). It belongs to family Bostrichidae of order Coleoptera of insects (Potter, 1935). *R. dominica*is a worldwide insect pest, present both in field at harvesting time and in godowns, granaries and other grain storage structures (Nadeem *et al.,* 2011). Its believed to be originated from Indian Subcontinent on the dead wood, but the species has now become challenging around the globe (Potter, 1935). It is usually a polyphagous and cosmopolitan insect pest in tropical and subtropical areas, but it has also been found in the temperate regions of the world (Potter, 1935; Haines, 1995). *R. dominica* is not only a primary pest of stored grains such as of wheat and corn but also infests other stored commodities as dried fruits, peanuts, spices, tobacco, nuts, beans, bird seed, biscuits, cassava, cocoa beans (Potter, 1935; Edde, 2012). It has adapted to feed on the germ and endosperm of different cereal commodities (Campbell and Sinha, 1978). Both larvae and adults have very stout mandibles and are voracious and disparaging feeders of grains. Even this insect pest can chew and damage very hard grains (Nguyen, 2006). All these features reveal that the original food of *R. dominica* was wood (Mahroof and Phillips, 2006; Nguyen, 2006). *R. dominica* along with other stored product insect pests can cause huge economic losses to agricultural commodities in the form of weight loss of product by damaging grains, producing frass, fecal matter and a particular unpleasant odor in them and by depleting grain nutrients, rendering them unfit for human consumption and lowering their digestibility (Campbell and Sinha, 1978; Jood *et al.,* 1996; Arthur *et al.,* 2012). Certain public health issues have also been observed as jeopardy from contamination of food by insect-induced allergens such as uric acid (Sanchew-Marinez *et al.,* 1997; Park *et al.,* 2008). The basic aim of this review is to describe comprehensively the biology of this major stored food insect pest and its appropriate management tactics.

Reasons of success

Plenty of features make this insect pest most successful among the others. Its body is 2–3 mm long with head capsule concealed or hidden under thorax. It can survive under a wide range of temperature (usually 12–40°C) and exhibits a high fecundity rate. It feeds usually deep inside grain heaps. Most peculiar thing is that its larva habitually feeds while residing inside the host grain until its emergence as adult. It can be active under a wide range of humidity and can feed on grains with less than 9% moisture contents, under which other stored grain insect pests usually do not survive or at least stop feeding (Birch, 1945; Haines, 1995; Edde, 2012). Due to high dispersion ability, its infestation has also been recorded in host crops at field level (Potter, 1935; Mahroof *et al.,* 2010).

Description and biology of R. dominica

Egg

R. dominica females lay eggs singly or in clusters, the numbers of which vary along with prevailing conditions (Potter, 1935). Under optimal environmental conditions (28–32 °C and 70–80% relative humidity; Astuti *et al.,* 2013) female borers can lay up to 500 eggs during their entire life span (Table 1).

Table 1. Population growth rates of lesser grain borer (*R. dominica*) at different thermal thresholds in wheat kernels maintained with different moisture contents (Birch, 1945; Birch, 1953; Birch and Snowball, 1945).

Temperature (°C)	Moisture content of wheat (%)	Mortality of immature stages (%)	Total no. of eggs per female	Duration of development from egg to adult (weeks)	Mean generation time (T) (weeks)
38.6	14	100	-	-	-
34.0	14	22	415	3.5	6.5
32.3	14	21	573	4.0	7.0
29.0	14	26	288	4.6	7.6
18.0	14	100	38	-	-
38.2	10	100	52	6.6	-
34.0	10	77	296	5.0	8.9
26.0	10	85	256	5.1	12.0
22.0	10	100	132	13.4	-
36.0	9	100	160	5.6	-
30.0	9	100	-	-	-
18–38	8	100	-	-	-

After hatching, average time period from egg to adult is about 25 days. Female can lay eggs on a variety of grains even at moisture levels of 8% or lower. For minimizing exposure to environmental extremities, female lays eggs normally on the soft portion of grains such as on pointed embryo or on previously damaged grains (Elek, 1994; Haines, 1995; Mason, 2003). A healthy egg size is about 0.59 mm with a diameter of 0.2mm with a cylindrical shape with one end rounded and the other somewhat pointed (Edde, 2012). Freshly laid eggs are creamy white and shiny and with the passage of time, they turn rosy and opaque before hatching with wrinkles on its outer surface and bears a brown color tinge at its pointed end (Potter, 1935).

Larva

The larva of *R. dominica* is usually C-shaped with setae (tiny hairs) present on its dorsal body surface, and is creamy white in color. It has three pairs of thoracic legs and passes its entire life inside the host grains until emergence as adult. Mobility of the young ones of *R. dominica* significantly varies along with the larval instars. First and second larval stages are mostly mobile but later instars become immobile. Fully grown larva turns into pre-pupa which does not have ocelli (simple eyes) and is less mobile and with somewhat straightened body (Potter, 1935; Guedes *et al.,* 1996).

Newly emerged first instar larva readily finds the host grain for shelter and food. It prefers to enter and feeds on the germplasm rather than feeding on the endosperm portion of the grains (Mahroof and Phillips, 2006; Edde, 2012). This is the crucial stage of its life cycle, more vulnerable to environmental stress as compared to other larval instars. Female borers lay eggs normally in or on partially damaged or soft portions of the grains such as on embryo and/or on ruptured or broken grains. *R. dominica* has four larval instars. Generally 3rdinstar larvae become capable to bore into a hard substrate. Development of this insect is observed to be variable with respect to their diet nutrients. Larval growth is quicker on whole grains rather than on derived products of grains, such as cake, flour, frass, and normally takes about 30–46days and 27–31 at 25°C and 28°C, respectively, as given in Table 1. The developing larvae feed inside of the grain kernel, ultimately cause damage to germplasm and endosperm and grain weight loss, while young larvae do not penetrate into the grains normally (Mason, 2003; Chanbang *et al.,* 2008).

Pupa

Last instar larva of *R. dominica* upon maturity pupates within feeding tunnel or cavity of grain and gradually assumes the form of an adult. Normal life span of pupal stage is about 8 days at 25°C and 5–6 days at 28°C. A healthy pupa is about 3.9 mm long, having white to brownish white color. There are some discrete appendages on the rounded end of pupal body, depending upon its sexual differentiation. Inmale pupa, papillae are convergent and two segmented, while in females these are divergent with three segments (Potter, 1935; Guedes *et al.,* 1996; Nguyen, 2006).

Adult

After completion of pupal stage, newly emerged adult chew its way out through the outer grain layers. The size of adult beetle greatly varies depending upon larval health, which in term depends upon growth conditions as given in Table 1. Adult *R. dominica* is usually 2–3 mm long with cylindrical body shape. The color of beetle, which emerges in about 7–10 days, is yellowish brown and darkens slowly with the passage of time and becomes reddish-brown. *R. dominica* have the large pro-thorax (pro-notum) under which its head is concealed. Therefore, only antennae can be viewed from its dorsal side. Antennae are club-shaped with a total of ten segments. On the surface of the each forewing (elytron), there are longitudinal rows of punctures and little setae with sloping and rounded apex which covers the abdomen of adult.

The adult borer normally remains within grains for a few days and comes outside when its cuticle hardens. *R. dominica* normally completes its life cycle in about 25 days at 34°C and 68 ± 5% relative humidity (Birch & Snowball, 1945; Edde, 2012). As mentioned above *R. dominica*has a wide range of minimum and maximum thermal thresholds. Its optimum development and multiplication normally occurs at 32±3°C (White *et al.,* 2011; Astuti *et al.,* 2013). However, developmental process will be sluggish upon cooling or lowering down the grain temperature. Under suitable conditions such as at 32°C, female lays maximum up to 570 eggs but normally lays up to 500 eggs during its whole life span as given in Table 1. Females of *R. dominica* survive for many days after oviposition ceases (Mason, 2003).

Mode of damage

While feeding on grains, both larvae and adults of *R. dominica* produce huge number of excreta along with frass in the form of fecal pellets. The larvae push their fecal pellets out of the infested grains and these pellets have musty odor that can easily clue about *R. dominica* infestation. This insect pest species is considered as both an external and an internal grain feeder. It is a serious pest of entire kernel of stored grains, cereals and various other stored food products. Both the adults and larvae bore into grains, leaving their hollow husks behind. *R. dominica* can survive better on the grains having very low (about 9%) moisture content (Birch, 1945; Haines, 1995).

Interaction with microorganisms

All organisms have to interact with each other in their immediate niches for different environmental resources particularly for food, shelter and space. In case of stored product insects, such as *R. dominica*, thriving on food necessitates the insect to interact with many fungi, bacteria and other microflora and fauna within stored food products. Larvae and adults of *R. dominica* have a spherical-shaped mycetomes, full of various symbiotic microorganisms, on each side of their alimentary canals (Mansour, 1934). It was analyzed that antibiotics-mixed diet strongly affects the mycetomal microorganisms present in *R. dominica* (Kirst *et al.,* 1992). Microorganisms can be transmitted vertically from one generation to the next one of *R. dominica*. Results showed that microorganisms passed from the micropyle (external hole on egg chorion used for sperm entrance to ensure fertilization) of the developed eggs during their life cycle (Mansour, 1934; Edde, 2012).Symbiotic microorganisms have also been reported in other Bostrichidssuch as in powder post beetles (*Sinoxylonceratoniae* and *Bostrychopliteszickeli)*. These bacteria play an important role in the body of insects as these are considered to provide the host insect with indispensable nitrogen, vitamins and help in degradation of cellulose inside the gut (Douglas, 2000; Dillon and Dillon, 2004).

Insect dispersal

Dispersal mechanism of any pest species contributes as a major factor for its survival surety. Species fitness and success rate are usually reinforced with good dispersal behavior. Like other flying beetles, *R. dominica* adult is a strong flier (Mason, 2003). Flying activities are high in warm conditions and are often carried by air currents from infested storage to non-infested areas. Usually their adults migrate into bulks of stored grains through air vents and slowly moves through the grain mass (Vardeman *et al.,* 2007). Observations have revealed that these beetles can disperse at least one mile away from a common release place. Trap captures of *R. dominica* adults suggested that its populations may be present on nearby plants and seeds in the landscape. These different habitats are, in addition of stored grain infrastructures, for reproduction, hence, beetles can thrive during unavailability of stored grains or during long-range dispersal movements (Ching'Oma, 2006; Jia *et al.,* 2008). Trapping adult beetles with pheromone-baited traps is an effective method used to detect and estimate the relative abundance of stored grain insect pests during their dispersal phase. However, *R. dominica* responds readily to well-known commercially available aggregation pheromone (Bashir, 2000; Phillips *et al.,* 2000; Edde *et al.,* 2005). *R. dominica* adult beetles are usually crepuscular and mostly prefer to take flight at dawn and dusk time, with small flight peaks observed at dawn and larger peaks just before the sunset (Ching'Oma, 2006).

Host finding behavior of R. dominica

Host searching ability or efficient host perception is the key to successful multiplication of arthropods. Female insects make a number of tests for host judgment and fitness before oviposition. This insect–hostencounter creates some interaction categories as primary and secondary interaction on the basis of their eco-physiological and biological importance (Reddy and Guerrero, 2004).

Primary attraction

Generally, primary attraction includes wondering for host and its selection. There are two searching patterns observed in insects for their host plant selection i.e. random and directed searching (Schoonhoven *et al.,* 1998). In random searching insect literally 'bumps' into potential food sources, while directed searching involves the directed movement of insect towards food source using volatiles emitted by the plant or food source itself or in combination with other semiochemicals (Phillips, 1997). Phyophagous insects such as *R. dominica* use olfaction for host finding (Edde and Phillips, 2006). However the question that how *R. dominica* utilizes various chemical signals emitted by different plants during its host finding phase, has not been adequately answered.

R. dominica is a strong flier and can move towards field from storage structures (Cotton, 1950). In laboratory experiments, *R. dominica* showed ability to respond against host (stored commodities such as wheat, maize and barley grains) volatiles (Dowdy*et al.,* 1993; Mayhew and Phillips, 1994; Bashir, 2000).

In case of *R. dominica*, most studies showed that host plants have a role in primary attraction of pests towards wheat and maize (Dowdy *et al.,* 1993; Mayhew and Phillips, 1994) and in groundnuts as well (Schlipalius *et al.,*2008). Regarding odor-based host finding behavior of *R. dominica*, it has been clearly shown that volatiles released from bulk storage of wheat significantly contributed to the attraction of *R. dominica* (Dowdy *et al.,* 1993). In an experiment, about 13–15 thousand tons of wheat was used as a source of attractant (Potter, 1935).

Secondary attraction–Pheromones

R. dominica is an important primary and one of the most important economic insect pests of stored grains and their products throughout the world. For locating the food sources, males of *R. dominica* release aggregation pheromones that recruit both male and female sexes towards the food sources. These pheromones are the esters of unsaturated (S)-(+)-1-methylbutyl (E)-2-methyl-2-pentenoate also called as Dominicalure-1 or DL-1 and second is (S)-(+)-1-methylbutyl (E)-2,4-dimethyl-2-pentenoate known as Dominicalure-2 or DL-2 (Williams*et al.,* 1981). For *R. dominica*, different artificial pheromone lures are commercially available which are used in traps for the monitoring or detection of this pest in or near stored grains and their products (Williams *et al.,* 1981; Edde and Phillips, 2006a). Synthetic insecticides are being used as a management tool against various insects in storage industry. The ability to manipulate insect semiochemicals (pheromones) to optimize deterring or attraction responses of an insect would minimize the reliance on synthetic chemicals. Various potential uses of different semi chemicals in case of stored grain insect pest management consist of the interruption of host judgment, mass trapping, mating disturbance and monitoring. Due to lack of the knowledge about potential benefits of semi chemicals over conventional insecticides, this technology is not being extensively used in stored grain insect pest management.

Management of R. dominica

Various methods and techniques are being used to control stored grain insect pests including chemical, physical, cultural, mechanical, genetic, and biological control (Flin & Hagstrum, 1990;Phillips& Throne, 2009). Many scientists have reviewed different components of integrated pest management (IPM) against stored food insect pests. In case of *R. dominica* management, different IPM-based control measures are being extensively studied as detailed below (Fields, 1992;Reed *et al.,* 1995; Arthur &Phillips, 2003; Arthur *et al.,* 2009; Phillips & Throne, 2009).

Physical control

Physical control in case of *R. dominica*is mostly attained by drying or by cooling the grains or stored food products below 15°C for lowering down the insect activities (Vincent *et al.,* 2003). Range of temperature in most of wheat and other grain varieties during mid summer is mostly 27–34°C (Cuperus *et al.,*1990; Jian *et al.,* 2009). This temperature is very favorable for the growth, development, survival and maximum reproduction of *R. dominica* (Lord, 2005). It is most probably due to the fact that this grain borer is more sensitive to low temperature than other stored grain insect pests (Fields and Muir, 1995). Below 15°C, activities of insects become limited while they die or become dormant at a long-term exposure to 2°C (Fields, 1992).

Aeration is a mechanical ventilation of different stored grains aimed to maintain uniform and cool conditions within storage infrastructure. The recommended or normal airflow aeration rates are about 0.8 m^{3}air per cubic meter of the grains (Reed and Arthur, 2000). Although it is found that *R. dominica* cannot be controlled completely through aeration (Liu, 2005), it is an effective and feasible tool for reducing insect growth rates and is used as well to minimize the risk of fungal infection (Cuperus *et al.,* 1990; Liu, 2005; Arthur *et al.,* 2011).

Biological control

Among various control tactics, one of the promising control options is biological control of stored grains insect pests. It is contributing upto 3–20% in IPM of stored food products (Schöller *et al.,* 2006).In this method, different insect predators and parasitoids which are naturally occurring in bulk grain storage localities are used to control insect pests (Eliopoulos *et al.,* 2002; Schöller *et al.,* 2006). These predators and parasitoids are known to attack a number of insect pests of stored grain (Hagstrum and Flinn, 1992). In 1992, United States, Food and Drug Administration (FDA) exempted these beneficial insect fauna being widely used against different stored grain insect pests (Anonymous, 1992).

Natural enemies

R. dominica coexists with numerous predaceous hemipterans, mites and parasitoids. It was reported that there are about four mite species, five parasitoids and two hemipteran species which attack on *R. Dominica* during storage conditions (Edde, 2012). Studies have shown that most of these predators and parasitoids are larval and rarely pupal parasitoids, but no egg or adult stage parasitoid is known yet (Potter, 1935; Asanov, 1980; Flinn, 1998; Flinn and Hagstrum, 2001; Menon *et al.,* 2002; Xu *et al.,* 2008). Predaceous bugs usually prey on eggs and larvae of *R. dominica*, though they also have the capacity to feed upon pupal and adult stage (Asanov, 1980; Donnelly and Phillips, 2001). To escape from predation, *R. dominica* individuals have adopted to migrate deep into stored grains (Schöller *et al.,* 2006).

Lyctocoris campestris (F.) is a voracious egg predator of *R. dominica* which belongs to family Anthocoridae of the order Hemiptera of insects. *Lariophagus distinguendus* (F.) is a larval parasitoid of *R. dominica* belonging to family Pteromalidae of the order Hymenoptera of insects. These both species showed a great efficacy among various natural enemies of grain borers. Apart from these natural enemies, there are plenty of predators and parasitoids of *R. dominica*as are enlisted in Table 2 and 3.

Table 2. Some major predator species of *R. dominica* (Asanov, 1980 and Edde, 2012).

Predator name	Order	Family	Stage of host
*Acarophenaxlacunatus*Cross andKrantz	Prostigmata	Acarophenacidae	Egg
*A. assanovi*Livshits andMitrofanov	Prostigmata	Acarophenacidae	All stages
Xylocorisflavipes Reuter	Hemiptera	Anthocoridae	Egg, larvae
*Lyctocoriscampestris*Förster	Hemiptera	Anthocoridae	Egg
Pyemotesventricosus Newport	Acarina	Pediculoidae	Egg, larvae
*Cheyletuseruditus*Schrank	Acarina	Cheyletidae	Egg, larvae

Table 3. Some major parasitoid species of *R. dominica* (Menon *et al.,* 2002; Xu *et al.,* 2008; Edde, 2012).

Parasitoid name	Order	Family	Stage of host
Theocolaxelegans Westwood	Hymenoptera	Pteromalidae	Larval
*Cephalonomiarhizoperthae*Westwood	Hymenoptera	Bethylidae	Larval
*Lariophagusdistinguendus*Förster	Hymenoptera	Pteromalidae	Larval
Anisopteromaluscalandrae Howard	Hymenoptera	Pteromalidae	Larval

Theocolax elegans (Hymenoptera Pteromalidae) is a larval parasitoid of *R. dominica* which is a solitary ecto-parastoid and parasitizes the stored grain beetles inside the grains and kernels (Flinn & Hagstrum, 2001; Menon *et al.,* 2002). There is a wide list of possible hosts of this parasitoid. During oviposition, female borer enters its egg inside the kernel, placing it on the external body surface of larval host (*R. dominica*). Larva of *T. elegans* continues to grow externally to the larva of its host as both are still restricted inside the kernel. At 25°C, this parasitoid cans complete one generation in about 25 days.

Developmental time of *T. elegans* is almost one-half than that of its host (*R. dominica*) (Flinn *et al.,* 1996). After emergence, adult parasitoid bores out of the kernel. Few experiments have been conducted regarding augmentation of *T. elegans* for the suppression of *R. dominica* populations in stored grains (Flinn *et al.,* 1996). In Southern United States, *R. dominica* is one of the most damaging pest of stored grains and *T. elegans* was successfully used against it (Cuperus *et al.,* 1990; Flinn, 1998; Adarkwah *et al.,* 2014).

Entomopathogenic microorganisms

Bacteria, fungi, protozoans and nematodes have also been observed as a source of mortality in *R. dominica*. These microorganisms attack on both adult and larval stages of the insect. Hot and dry conditions in stored grains often limit the population of these microorganisms. Usually these entomopathogenic microorganisms prefer high relative humidity to be active (Adane *et al.,* 1996; Moino *et al.,* 1998). Nevertheless, some dissimilar findings were reported that some pathogenic fungi such as *Beauveria bassiana* are active against stored grain beetles even at relative humidity as low as 43% (Lord, 2005). In another study, Adane *et al.,*(1996) showed that *B. bassiana* infects *O. surinamensis* (saw toothed beetle) at 100% relative humidity. *B. bassiana* mostly infects *O. surinamensis* rather than *T. confusum* (red flour beetle) because *O. surinamensis* have the maximum setal density on its body particularly on abdominal sternum (Mahdneshin *et al.,* 2009; Stephou *et al.,* 2012). Some entomopathogenic microorganisms are given in the Table 4.

Table 4. Some major entomopathogenic microorganisms against *R. dominica* (Lord, 2005; Mahdneshin *et al.,* 2009; Edde, 2012).

	Entomopathogenic Microorganism	Order	Family	Stage of host
Bacteria	*Bacillus thuringiensis* Berliner	Bacillales	Bacillaceae	Larva and adult
Fungi	*Mattesiaoryzaephili*	Neogregarinorida	Lipotrophidae	Larva
	*Metarhiziumanisopliae*Metsch	Deuteromicotina	Hyphomycetes	Adult
	Beauveriabassiana Balsamo	Deuteromicotina	Hyphomycetes	Adult
Nematodes	*Heterorhabditisbacteriophora*	Rhabditida	Heterorhabditidae	Larva and adult
	*Steinernemafeltiae*Filipjev	Rhabditida	Steinernematidae	Larva and adult
	Steinernemacarpocapsae Weiser	Rhabditida	Steinernematidae	Larva and adult

Chemical grain protectants

All over the world, different pesticides are applied to control stored grain insect pests including *R. dominica* (Arthur, 1996; Collins, 2006). Due to a long and persistent exposure to pesticides, *R. dominica* has been resistant to these stored grain and food protectants (Daglish & Nayak, 2010). For instance, deltamethrin is found ineffective against *R. dominica* in several parts of the Brazileven when it is used at a high dose (Lorini and Galley, 1999; Lorini and Galley, 2000a; Lorini and Galley, 2000b).

Similarly, *R. dominica* has shown resistance against different other chemicals such as malathion, pirimiphos methyl, fenitrothion, phosphine and chlorpyrifos-methyl (Guedes *et al.,* 1996; Lorini & Galley, 1999; Opit *et al.,* 2012; Song *et al.,* 2013). It also exhibited resistance to pyrethroid-based grain protectants (Collins, 2006; Lorini &Galley, 1999). Nevertheless, deltamethrin is still considered awell known and most effective pyrethroid-based grain protectant in Brazil, India, Pakistan and other parts of the world. However, increasing trend of resistance development in*R. dominica* against pyrethroids is of major concern in grain storage industry because of high relative toxicity of these insecticides to human health. Therefore, for ensuring stored food quality and quantity, an efficient and eco-friendly integrated pest management is need of the time.

In USA during 1980s, a formulation named methoprene (Diacon; 65.7% active ingredient) was registered for the storage application against stored grain insect pests. Diacon, an insect growth regulator (IGR), was found very effective against *R. dominica*but this chemical has some limited use due to its high cost (Arthur, 2004). In 2002, another methoprene formulation consisting of S-isomers was registered. A 100% repression of F1 adult progeny of *R. dominica* was observed by the application of both dust and EC formulations of S-methoprene (Arthur, 2004). In Australia,methoprene has been used efficiently for the control of *R. dominica* (Collins, 2006). However, resistance in *R. dominica* against methoprene has been shown (Lorini &Galley, 1999) and in Australia the phenomenon of this resistance is reported as 85% (Collins, 2006).

Recently, Spinosad, a biopesticide having Spinosyn A and Spinosyn D as active ingredients, is introduced as grain protectant against stored grain insect pests. It is derived from a naturally occurring soil actinomycete bacterium *Saccharopolyspora spinosa* (Kirst *et al.,* 1992). This insecticide has both a systemic and contact effects on the target insect nervous system, which is further responsible of muscle distortion and finally paralysis (Hertlein *et al.,* 2011) in the stored grain insect pests as *R. dominica* (Flinn *et al.,* 2004; Getchell and Subramanyam, 2008; Hertlein *et al.,* 2011). Spinosad is not only registered in USA but also in several others countries of the world (Hertlein *et al.,* 2011).

Diatomaceous earth (DE)

Diatomaceous earth is used as top-dress on the grains and grains are stored immediately after DE treatment (Shah and Khan, 2014). This method can give a protective barrier against different migrating storage insect pests which may enter into the grain storage infrastructures such as bins, shells, silos etc. (Korunic *et al.,* 1998). Studies revealed that *R. dominica* has the ability to move deeper into the grains as compared to other grain beetles (Flinn *et al.,* 2010). It has been found penetrating the DE-treated grain layers, where it oviposits in the lower portion of untreated grain bulk (Vardeman *et al.,* 2007). This technique is less effective in case of empty storage structures before grain stockage. DE is also less effective whenever the aeration ducts are present within the storage structure and its bulk treatment may require high quantities of DE which further adversely affects grain physical parameters such as bulk density (Korunic *et al.,* 1998; Vardeman *et al.,* 2007).

Sanitation measures

In case of cultural practices during storage conditions, different strategies should be adopted e.g. proper sanitation of grain storage structures (such as silos, bins, godowns, shells etc.), their proper clearance from infested grain residues and other debris, careful monitoring and control of grain spillage etc. Moreover, regular inspection of the insect population in stored grains plays an important role to prevent and minimize the insect pest infestation of stored grains (Proctor, 1994; Phillips and Throne, 2009).

Phosphine fumigation

To control insect pests of the stored products, particularly for *R. dominica*, different chemicals are being used as fumigants such as phosphine, carbon tetrachloride, ethyl-formate and ethyl-bromide. Phosphine is the most important and widely used fumigant. It is normally applied at rate of 3 tablets of aluminum phosphide 100 cm^{-3}, against stored grain insect pests (Collins, 2006; Daglish and Nayak, 2010). Fumigation by phosphine controls all different life stages of insect pests and its application is also easy and economical. Moreover, it is residual free treatment. It was seen that there is no any practical alternatives of phosphine fumigation (Collins, 2006). However, phosphine resistance in *R. dominica* has also been studied in detail (Herron, 1990) and it is found that there are two major genes in insects are responsible for resistance against phosphine (Collins *et al.,* 2002; Schlipalius *et al.,* 2008). In case of *R. dominica*, both genes act as synergists in response to phosphine gas (Schlipalius *et al.,* 2008). Nevertheless, resistance problem is developing either due to over or under dosing of fumigants and due to poor fumigation practices. To solve resistance problem in insect pests including *R. dominica*, all IPM tactics are to be applied in an integrated manner.

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