Entomology

Pest status and management strategies for *Sitotroga cerealella* (Olivier) (Lepidoptera: Gelechiidae)

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Abstract
Sitotroga cerealella (Olivier) (Lepidoptera: Gelechiidae), commonly known as Angoumois grain moth or paddy moth, is a serious primary feeder and a cosmopolitan pest of all kinds of cereals. The infestation starts in standing field crop and additional damage to the grain can then occur through the attack of secondary insect pests. Given the pest status of this insect, proper management tactics must be developed to control *S. cerealella*. However, management of *S. cerealella* is still much dependent on the use of toxic chemicals that can trigger adverse effects on environment and human health. Thus, there is a dire need to explore newer alternatives that would serve the purpose of grain protection without devastating the environment. It is thereby helpful to review the literature and provide a comprehensive overview on *S. cerealella*. The paper focuses on distribution, biology, development and modes of management for the pest, as well as identifies key gaps in literature for the advancement of future research towards ecofriendly and sustainable management of this pest in the near future.

Keywords: *Sitotroga cerealella*, secondary insect pest, pest management, sustainable management

Introduction

The explosion of human population in developing countries is creating an unprecedented demand for greater production of food grains (Akunne and Ononye, 2015; Sen *et al*., 2016) [2, 73]. There are nearly one billion hungry in today's world, while more than five hundred million tons of grains are annually destroyed due to pests and plant diseases. In India, postharvest losses caused by unscientific storage, insects, rodents, micro-organisms, etc., account for about 10% of the total food grains produced (Dubey *et al*., 2008; Roy, 2020b) [22, 68]. According to the World Bank, India's annual postharvest losses equal 12 to 16 million metric tons of food grains, which is enough to feed one-third of the country's impoverished (De and Dey, 2022) [18]. Wheat, *Triticum aestivum* (L.), provides over 40% of the per capita dietary supply of calories and proteins in many developing countries (Shahsavan *et al*., 2022) [77]. Paddy, *Oryza sativa* (L.) is an important staple food crop for more than 60% of the world's population. India has the largest area under paddy in the world and ranks second in the production after China (Basavanjali *et al*., 2020) [8]. Maize (*Zea mays* L.) is the third most important cereal and cash crop of India (Demissie *et al*., 2015) [20]. Barley (*Hordeum vulgare*) is the fourth most important crop among cereals, after wheat, rice and maize, all over the world (Bushra *et al*., 2013) [12]. In response to climate change and increasing climate variability, farmers have scaled-up their production of small grains, particularly sorghum and millets (Mubayiwa *et al*., 2021) [54].

Sitotroga cerealella (Olivier) (Lepidoptera: Gelechiidae), commonly known as Angoumois grain moth or paddy moth, is a serious primary feeder and a cosmopolitan pest of all these cereals (Soomro *et al*., 2017) [80]. The most economically important SGPs have stages that feed and develop concealed within kernels, i.e. eggs, larvae and pupae of the weevils, *Sitophilus granarius*, *S. oryzae* and *S. zeamais* (Coleoptera: Curculionidae) and older larvae and pupae of *Rhyzopertha dominica* (Coleoptera: Bostrychidae) (Hansen *et al*., 2012) [31]. Infestations of *S. cerealella* occur during storage, in preharvest or postharvest and the damage caused is crucial in temperate and tropical regions (Trematerra, 2015) [83]. But the major economic losses caused by SGPs is not only the actual material they consume, but also the amount contaminated by them and their excreta that make the food commodity unfit for human consumption (Dubey *et al*., 2008) [22]. However, management of this pest is still much dependent on the use of toxic chemicals (De and Dey, 2022) [18] that can trigger adverse effects on environment and human health.

Many biotic and abiotic factors affect the population dynamics of stored product insects. Crucial among them are temperature, moisture content, air RH, intergranular gaseous compounds, dockage (Anukiruthika *et al*., 2021) [4], host grain availability, phytochemicals present in different grain cultivars and even the physical characteristics of the grains (Roy, 2022) [69]. Hence, pest populations can be effectively managed by manipulating the storage conditions and integrating the suitable physical, chemical, botanical, and traditional control measures along with natural predators. Various ecological tools like life tables, feeding dynamics and adaptations in reference to the current climatic conditions can aid in the prediction of pest emergence too. Phosphine, and not contact insecticides, is efficacious for controlling internal stages. But it has been forsaken for its acute toxicity and resistance development (Hansen *et al*., 2012) [31]. Multiple applications of the same chemistry group may have hastened the onset of resistance by insects (Brunner *et al*. 2005) [11]. Application and overuse of insecticides after infestation are also discouraged (Prakash *et al*., 2008) [60]. Methyl bromide fumigation depletes the ozone and under the Montreal Protocol, use of this fumigant has been eliminated for most postharvest applications. Efforts have since been put to develop replacements, including sulfuryl fluoride and ethyl formate, but only sulfuryl fluoride has seen wide adoption to date and the alternative fumigants come with their drawbacks (Morrison *et al*., 2021) [53]. Thus, there is a dire need to explore newer alternatives that would serve the purpose of grain protection without devastating the environment. Integrated pest management (IPM) and climate smart pest management (CSPM) are based on such understandings. Meanwhile, there has been an increase in demand by consumers for commodities that are insecticide-free or have reduced residues. Consumers are even willing to spend more for such postharvest commodities, including cereals, flour, and others. These trends track with the exponentially growing organic industry, which has reached a value of $90 billion over two decades (Morrison *et al*., 2021) [53]. Thus, it is helpful to review the literature and provide a comprehensive overview on *S. cerealella*. The paper focuses on distribution, biology, development and modes of control, as well as identifies key gaps in literature for the advancement of future research towards ecofriendly and sustainable management of the pest.

Bioecology of *S. cerealella*

Majority of SGPs belong to the orders of Coleoptera (beetles, weevils, and borers), Lepidoptera (moths) and Psocoptera (psocids) (Anukiruthika *et al*., 2021) [4]. *S. cerealella*, a lepidopteran pest of the twirler moth family Gelechiidae, is one such notorious pest. It was first reported in 1736 from the Angoumois Province of France (Bushra *et al*., 2013) [12]. Although originally described in genus *Alucita* by Olivier in 1789, this species was allocated to genus *Sitotroga* by Heinemann in 1870, as the type species of this new genus (CABI, 2021) [14]. Table 1 enlists all the recorded names and taxonomy of this insect. *S. cerealella* is a serious pest in the temperate and tropical regions of the Americas and Africa, although it occurs worldwide (Fouad *et al*., 2014) [26], like in India (Demissie *et al*., 2014) [19], Bangladesh (Hossein *et al*., 2018) [33], China (Ma *et al*., 2016) [45], Pakistan (Khan *et al*., 2010) [40], Iran (Naseri *et al*., 2017) [56], France and Spain (Butrón *et al*., 2008) [13].

Table 1: Recorded names and taxonomy of *S. cerealella* (Olivier) (CABI, 2021) [14]

Scientific name- *Sitotroga cerealella* (Olivier) **Common names**- Angoumois grain moth, rice grain moth **Other scientific names**- Alucita cerealella (Olivier), Anacampsis cerealella (Olivier), Gelechia cerealella (Olivier), Gelechia pyrophagellas **Other common names**- Rice grain moth, rice moth	**Taxonomy:** Domain: Eukaryota Kingdom: Metazoa Phylum: Arthropoda Subphylum: Uniramia Class: Insecta Order: Lepidoptera Superfamily: Gelechioidea Family: Gelechiidae Genus: Sitotroga Species: *S. cerealella*

A female lays eggs either singly or in groups of 2- 60 (El-Sherif *et al*., 2008) [25]. The eggs are white but quickly change to a reddish colour with oval shape, anterior truncate and longitudinal ridges. Whereas, the newly hatched larvae are yellowish white in colour with light brown head of all the instars (Sachin *et al*., 2022) [70]. The five larval instars are identified by the presence of head capsule or cast skin as indicator. The pupa is brown in colour and develops inside the silken cocoon (Basavanjali *et al*., 2020) [8]. The adult moth is small, with a slender 5-7 mm long body when wings are folded and 10-16 mm wingspan (Sachin *et al*., 2022) [70]. The apices of hind wings are fringed with hair, point sharply towards the tips and are widely separated, allowing the abdomen to be partially visible. Males are comparatively shorter than females and the male abdomen is thinner, pointed and blackish when viewed from the ventral side whereas in females, the abdomen is bulky, longer without any blackish coloration and larger in size. The lengths of male and female moths of *S. cerealella* are 10.1± 0.29 and 11.2 ± 0.33 mm respectively (Basavanjali *et al*., 2020) [8]. Data on bionomics and morphometry are presented in table 2. Newly emerged females are two-fold heavier than males, and temperature and relative humidity (RH) do not affect weight (Perez-Mendoza *et al*., 2004) [59].

Table 2: Bionomics and morphometry of different life stages of *S. cerealella* on paddy by Basavanjali *et al*. (2020) [8], and on maize by El-Sherif *et al*. (2008) [25]

Life stages	Duration (days)		Length (mm)	Breadth (mm)
Egg	3.9-4.2 (incubation period)		0.50-0.70	0.29-0.33
1st instar larva	2.4- 2.6		1-1.4	0.157-0.196 (head- capsule)
2nd instar larva	3.4-3.6		2.1-2.8	0.323-0.392 (head- capsule)
3rd Instar larva	9.0-11.0		2.9-3.2	0.588-0.686 (head- capsule)
4th instar larva	3.9-4.2		5.5-6	0.764-1.000 (head- capsule)
5th instar larva (or prepupa)	4.7-5.1		7-8	0.882-1.147 (head- capsule)
Pupa	6.1-6.5		5-5.5	0.78-0.88
Adult Female	5.0-7.0 (without food)	8.0-10.0 (with food)	5-6	15.5 (wing expanse)
Adult Male	4.0-5.5 (without food)	5.0-7.0 (with food)	4.5-5	14.0 (wing expanse)

*N= Average of 10 insects

Eggs are deposited by the adult on or near the grain, and neonate larvae burrow into the kernel or enter through cracks in the pericarp. Pupation occurs in a silk-lined chamber in the burrow (Perez-Mendoza *et al*., 2004) [59]. The young larvae bore into grains and feed on the inside contents (Demissie *et al*., 2015) [20]. Larval-pupal development take place within the kernel; moths leave the kernel through channels to the outside, cut by the larvae just before pupation and covered by weakly fastened flaps of pericarp (commonly called windows) (Butrón *et al*., 2008) [13]. Basavanjali *et al*. (2020) [8] studied the life cycle of the moth on paddy and observed that the oviposition and incubation period range between 2.4-2.6 days and 3.9-4.2 days, respectively. Larval and pupal period are 23.4-27.5 days and 6.1-6.5 days, respectively. Adult longevity of male without food is between 4-5.5 days, and with food it is 5.0-7.0 days. While for female, the longevities without and with food are 5.0-7.0 days and 8.0-10.0 days respectively. Life span can be about 35-45 days and the female moth lays 70 to 180 eggs. Figure 1 depicts the life cycle of *S. cerealella*. Soomro *et al*. (2017) [80] concluded that grain preference by *S. cerealella* is in the order of wheat followed by millet, corn and rice. Conversely, Mahmoud *et al*. (2020) [48] inferred that rearing of *S. cerealella* yields significantly larger number of eggs on sorghum than on wheat and corn. According to Perez-Mendoza *et al*. (2004) [59], the optimum conditions for development of Angoumois grain moth on corn (hybrid variety Pioneer 3320) are 30°C and 75% RH. Temperature is the main factor affecting developmental periods and adult survivorship of *S. cerealella*, and relative humidity has no apparent effect on the duration of larval-pupal development of *S. cerealella* but 70-85% is optimal for hatching (Demissie *et al*., 2014) [19]. Hansen *et al*. (2004) [32] noticed that developmental time of the females is significantly shorter than that of males. On maize (variety Gbogbe) at 30°C and 44% RH, they recorded survival of immature stages as 33%, r_m 0.051 day^{-1}, mean length of generation (G) 51.0 days and the net reproductive rate (R_0) to be 12.5, and that the growth rate declines dramatically at 35℃. They also observed that the greatest fecundity (124 eggs per female) occurs at 20℃, 80% RH. While according to Demissie *et al*. (2014) [19], the highest number of eggs is laid at 30℃ (172.50/female). Rai *et al*. (2011) [62] inferred that the favourable season for the development of *S. cerealella* is the post-monsoon months when it takes only 34.59 days to complete one generation, and the optimum climatic conditions are 26.68-29.23℃ and 66.16% RH. Sex ratio of *S. cerealella* is close to 1:1, irrespective of temperature and humidity (Hansen *et al*., 2004; Perez-Mendoza *et al*., 2004) [32,59].

The pest is so destructive that one gravid female can completely destroy 50 gm of paddy in storage within three subsequent generations (Hossein *et al*., 2018) [33]. The potential for damage is overwhelming because the insect can infest grains both before and after harvest. The larval feeding damage exposes seed tissues to infestation by secondary insect colonizers and fungi (Weston and Rattlingourd, 2000) [86], and the grains are left with deficiencies that include weight loss, reduction in nutritional value, contamination or tanning. The loss of maize due to this pest has been estimated to be about 15 to 21% in storage, but up to 50 to 60% has been reported in the untreated kernel and in tropical countries where summer is hot and storage facilities are improper and inadequate (Ahmad and Ahmad, 2002) [1]. In developing countries like India, maize is often stored in bags made of hessian and jute fiber, which harbor conditions conducive to infestation by grain moth (Demissie *et al*., 2015) [20]. The infestation may penetrate quite deeply into bag stacks, but these pests are usually localized on the top 10-20 cm in bulk storage (Basavanjali *et al*., 2020) [8]. Ultimately, the contaminated commodity is bought at lower prices or even refused by the buyers. When there is a high level of *S. cerealella* detritus in the food commodity, aflatoxins are produced which are the causative agents of serious diseases in humans, like cirrhosis of liver and cancer (Bushra *et al*., 2013) [12].

S. cerealella is considered to be a member of a pest complex along with *S. zeamais* (Motschulsky), *Prostephanus truncatus* (Horn) and *R. dominica* (F.) (Hansen *et al*., 2004) [32]. *S. zeamais* and *S. cerealella*, both primary feeders, compete intensively on maize. *S. cerealella* is always eliminated by *S. zeamais* under optimal conditions in a homogeneous environment but may coexist in the field, which might be explained by the interspecific trade-off hypothesis (Larsen *et al*., 2005) [43]. According to Weston and Rattlingourd (2000) [86], progeny of both the secondary pest species, *Tribolium castaneum* (Herbst) and *Oryzaephilus surinamensis* (L.), reach highest numbers on maize kernels of 'DeKalb 689' infested for 6 months by *S. cerealella*. 7Z, 11E-hexadecadien-1-ol acetate (HDA) is a sex pheromone of *S. cerealella* that provides olfactory cues (DATS) (Ma *et al*., 2016) [45]. Using HDA as the bait for pheromone traps, Trematerra (2015) [83] confirmed that infestations of rice grain moth occur both during both preharvest plantation and postharvest storage, suggesting that adults disperse up to 600 meters from the warehouse to field-plots during the spring-summer season. Nonetheless, there is a dearth of knowledge about inter and intra specific interactions (both positive and negative) of this pest, which could rather enhance our understanding of its dispersal and immigration processes in the landscape and food facilities. Table 3 presents an overview of the bioecology of *S. cerealella.*

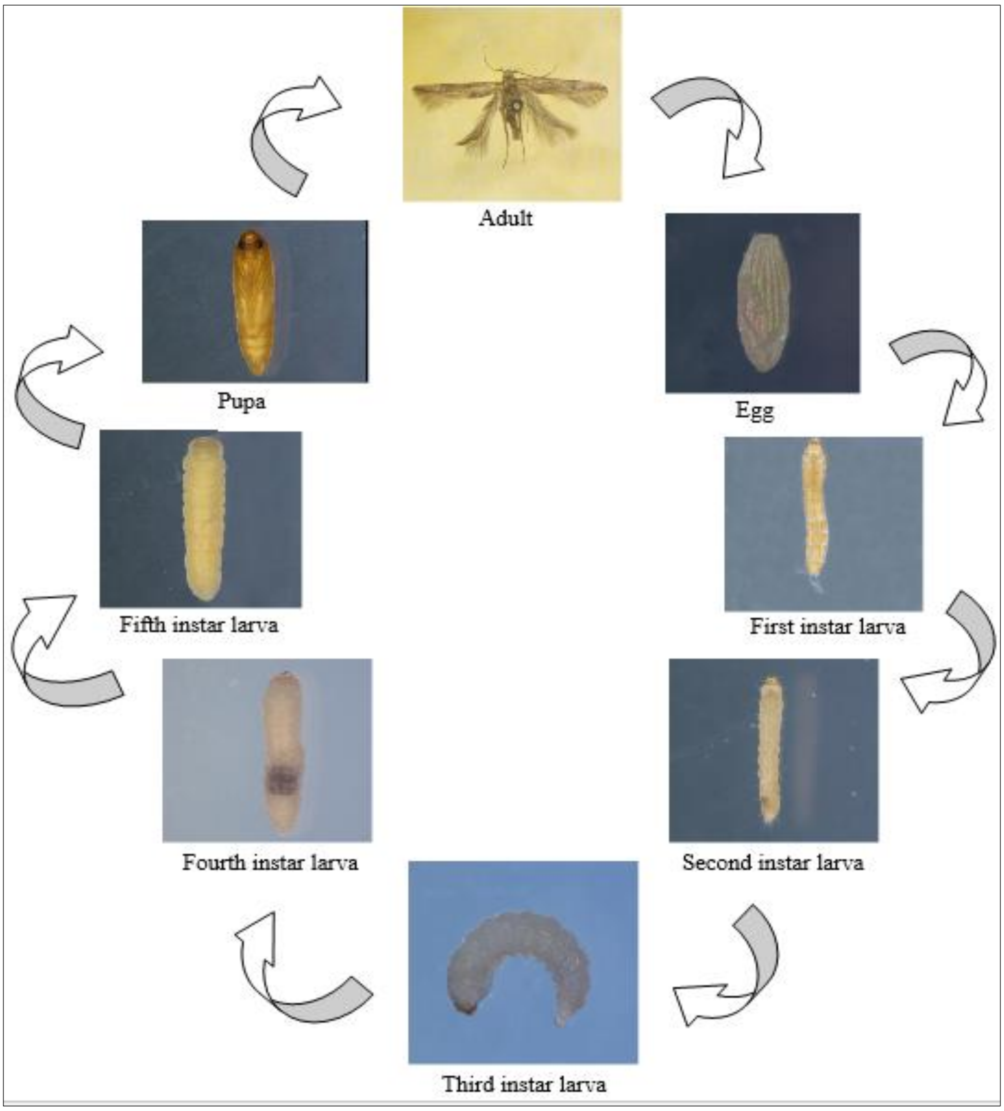

Fig 1: Life cycle of *S. cerealella*- adult, egg, larva through five instars and pupa (Basavanjali *et al*., 2020) [8]

Table 3: Overview of the bioecology of *S. cerealella*

Description				References
Pest status and Distribution	A major stored grain pest (SGP) and a primary feeder, distributed worldwide			Larsen *et al*., 2005 [43]; Rai *et al*., 2011 [62]
Host	Rice, maize, wheat, sorghum, barley			Basavanjali *et al*., 2020 [8]; Mahmoud *et al*., 2020 [48]; Sachin *et al*., 2022 [70]
Nature of damage	Young larvae bore and feed on grains, leading to weight loss, reduction in nutritional value, contamination or tanning and expose seed tissues to infestation by secondary insect colonizers and fungi. Adult moths leave the kernel through channels cut by the larvae.			Weston and Rattlingourd, 2000 [86]; Butrón *et al*., 2008 [13]; Demissie *et al*., 2015 [20]
Population growth	Developmental stages- Egg→larva→pupa→ adult; larval instars- 5	On paddy, oviposition period-2.4-2.60 days; incubation period- 3.9-4.2 days; larval period- 23.4-27.5 days; pupal period- 6.1-6.5 days; adult longevity- male: without food- 4-5.5 days, with food- 5.0-7.0 days Female: without food- 5.0-7.0, with food- 8.0-10.0; life span- 35-45 days; fecundity- 70-180	Optimum conditions for development on corn (hybrid variety Pioneer 3320)- 30°C and 75% RH On maize (variety Gbogbe) at 30°C and 44% RH, survival of immature stages- 33%, r_m- 0.051 day^{-1}, G- 51.0 days, R_0- 12.5	Perez-Mendoza *et al*., 2004 [59]; Hansen *et al*., 2004 [32]; Basavanjali *et al*., 2020 [8]
Interspecific relationships	Forms pest complex along with Sitophilus zeamais, Prostephanus truncatus and Rhyzopertha dominica. With S. zeamais, it may coexist or be eliminated. Facilitates growth of secondary pest populations of Tribolium castaneum and Oryzaephilus surinamensis.			Weston and Rattlingourd (2000) [86]; Hansen *et al*., 2004 [32]; Larsen *et al*., 2005 [43]

Climate change and pest emergence

Agriculture, “an open-air factory”, is an economic activity that depends heavily on climate and certain weather conditions to sustain human needs. The growing human population has rising demands for food production and by 2050, global agricultural productions will possibly need to be doubled to meet the demands. Numerous studies have recommended enhancing crop yield over clearing more land surface for crop production. Modern scientific research and agronomy are focused on climate change and its effects- heat waves, flooding, intense storms, droughts and other extreme weather events. Changes in precipitation patterns may have higher impacts on crop production than temperature rise, especially in areas where dry seasons present a limiting factor for agricultural production (Skendži´c *et al*., 2021) [79]. As mentioned in the previous section, temperature is among the factors of utmost importance for the population dynamics of *S. cerealella,* as well as the relationships between pests, environment, and natural enemies. Machekano *et al*. (2018) [46] noticed that to survive desiccating storage environments, *S. cerealella* relies more on high body water content compared to lipid reserves. Similarly, *S. cerealella* exhibits high basal heat tolerance, but basal cold tolerance is relatively compromised. The low water loss rates might be an evolutionary resistance mechanism for desiccation tolerance, which may explain its distribution and survival under global change. More researches need to be conducted to reveal the origin, distribution and current range of this pest. Because modelling and documenting the effects of climate change on shifts in the distribution of the pest population will become increasingly important, as they may result in a radically shifted range and increased grain damage (Quellhorst *et al*., 2021) [61]. Lehmann *et al*. (2020) [44] observed mixed responses to climate warming in different insect pest species. The results indicated that temperature rise may lead to increased pest severity in most of their case studies, but 59% of all species analysed showed responses that could reduce their harmful impact, mostly via reduced physiological performance and range contraction. Another study of about 1100 insect species found that climate change due to global warming will drive about 15–37% of these species to extinction by 2050 (Skendži´c *et al*., 2021) [79].

Management strategies

S. cerealella poses serious threat to the world's food supply at a time when about a billion people starve globally. Therefore, it is necessary that we fully use as many tools in the IPM toolkit as possible. Here we present an account of the strategies that have been implemented to control this devastating pest.

Physical management strategy

Continuous monitoring must be conducted to maintain safe storage conditions for the commodities throughout the storage period because even when food grains are initially stored at the recommended safe storage conditions, the factors may change with time. Temperature and moisture content define the extent of infestation as well as the shelf life of stored grains (Anukiruthika *et al*., 2021) [4]. Perez-Mendoza *et al*. (2004) [59] observed that at 10 and 40°C, none of the stages of *S. cerealella* survives at any relative humidity. They also suggested that decreasing the temperatures (to 15°C for stored corn) can be effective for Angoumois grain moth control because that greatly increases immature developmental times. Rai *et al*. (2011) [62] also found that the insect fails to develop completely in most of the rice varieties during winter. A study conducted by Mubayiwa *et al*. (2021) [54] showed high positive correlation between grain moisture content and the insect pests *R. dominica*, *T. castaneum* and *S. cerealella*. Thereby, hermetic technologies like Purdue Improved Crop Storage (PICS) bags, GrainPro Super Grainbags and metal silos may be used against *S. cerealella* for the storage of sorghum. Ziaee *et al*. (2022) [87] suggested that an Iranian diatomaceous earth formulation, Dryasil, can serve as a grain protectant that does not adversely affect the properties of different rice varieties, to control *S. cerealella.* Among the containers, plastic container provides the highest protection of wheat against infestation by this insect, followed by tin kouta (Ali *et al*., 2009) [3]. Attention must be paid to maintain cleanliness of the storage area, otherwise infestation by a primary feeder may lead to secondary pest population build-ups (Shah *et al*., 2021b) [75]. According to Hallman and Phillips (2008) [30], ionizing irradiation prevents F1 egg hatch of adult Angoumois grain moths, irradiated in ambient and hypoxic atmospheres. A generic dose of 600 Gy in ambient atmospheres might be efficacious for all insects, but many fresh commodities might not tolerate it when applied on a commercial scale. Gaseous ozone (O_3) treatment can bring about mortality at all stages of the pest. A dosage of 21 ppm for 5 days results in 100% mortality of the *S. cerealella* adults (Hansen *et al*., 2012) [31].

Chemical management strategies

The biological effect of an insecticide primarily depends on the function of the active substance (toxicity, hormonal or behavioural disruption, etc.) against the target. To ensure good field efficacy of the insecticide, the active substance must be properly formulated both physically and chemically and then delivered in appropriate quantity to the physiologically sensitive target site of the arthropod (Stejskal *et al*., 2021) [82]. Additional bioassays might confirm the emergence of a "sweet spot" or hormesis. Sweet spot is the decrease of mortality of the insects with the increase of insecticide concentration (Lampiri *et al*., 2021) [42] and hormesis is a biphasic dose-response of a given chemical compound that is stimulatory at low doses and toxic at high doses (Mallqui *et al*., 2014) [49]. Synthetic pyrethroids, cypermethrin, deltamethrin and fenpropathrin significantly reduce adult emergence of the grain moth at a concentration of 5 ppm, and are superior to the organophosphates, viz., malathion and karphos. At 20 ppm, JHA, fenoxycarb and MV 678 bring down adult emergence by 100 and 99.2% respectively. IGRs, XRD 437 and chlorfuazuron also greatly reduce the adult emergence at 20 ppm concentration (Eisa, 1992) [24]. Naphthalene and camphor prove to be efficacious in rice grain moth prevention as well (Ali *et al*., 2009) [3]. A new emulsifiable concentrate (EC) formulation of deltamethrin reduces progeny production of *R. dominica* and *S. cerealella*, and hence can be used for protection of brown rice (Arthur, 2019) [5].

Biorational management strategies

Chemical pesticides had revolutionized agriculture, but they also wreak havoc to the environment and impair farmer's health, which call for the development of biopesticides or eco-friendly tools for pest management. Shaaya *et al*. (1997) [74] reported that at a dosage of 10-15 g/kg seeds, crude rice bran oil gave full protection from *S. cerealella* infestation of paddy for 9 months. With refined rice bran oil and crude cotton oil, some infestation was observed nonetheless. However, all oils tested at this rate had severe detrimental effects on seed germination 2 months after the treatment. Extracts of Mexican sunflower (*Tithonia diversifolia*), *Psychotria prunifolia* leaves and astilbin from Fava d'anta (*Dimorphandra mollis*) flowers have the potential to protect wheat grains against *S. cerealella* (Fouad *et al*., 2014) [26]. Essential oils of cheese wood (*Alstonia boonei* de wild), bitter kola (*Garcinia kola* Heckel), ebolo (*Crassocephalum crepidoides*) also bring about moth mortality (Gbaye *et al*., 2016) [27]. Interfering with olfactory pathways to disrupt male–female communication with sex pheromones is another practice in pest control (Anukiruthika *et al*., 2021) [4]. Ma *et al*. (2016) [45] and Shah *et al*. (2021a) [76] achieved such mating suppressions by using plant volatiles of garlic (*Allium sativum*) or its active substance, diallyl trisulphide (DATS). Naseri *et al*. (2017) [56] investigated the fumigant and sublethal effects of essential oil of *Artemisia khorassanica* and *Artemisia sieberi*, and found them to be significantly effective. Hossein *et al*. (2018) [33] conducted a study in which they found that dried neem (*Azadirachta indica*) leaf powder reduces rice grain infestation by number and weight. A high percentage of germination over control and a high benefit cost ratio (BCR) can also be achieved from the treatment. According to Huang *et al*. (2007) [34], spinosad reduces egg-to-adult emergence of *Plodia interpunctella* and *S. cerealella* on hard, white winter wheat. Gemu *et al*. (2013) [28] amassed that locally available agricultural wastes like coffee husk and wood ash at all dosages, and sawdust at certain rates are effective in controlling *S. zeamais* and *S. cerealella*.

Biological management strategies

The moth can also be controlled by using natural predators. Wen and Brower (1994) [85] showed that the abundance of *S. cerealella* progeny was significantly reduced by releasing the parasitoid *Pteromalus cerealellae*. Endosymbiotic bacteria belonging to the genus *Wolbachia* have critical effects on insect reproduction, and hence may be considered for future pest control strategies if the strains are detected and characterized carefully (Kageyama *et al*., 2010) [36]. *Trichogramma brassicae* wasps, held under continuous laboratory rearing, can be used in biological control of *S. cerealella* until the 15th generation (Ghaemmaghami *et al*., 2021) [29].

Biotechnological management strategy

Sedlacek *et al*. (2001) [72] observed that emergence of *S. cerealella* was significantly lower for individuals reared on P33V08 and N6800Bt, MON 810 and Bt-11 transformed corn hybrids containing CrylAbBt delta-endotoxin, than on their non-Bt transformed isolines. Nanotechnology is an emerging arena in agriculture and crop protection for effective delivery of fertilizers and crop protection chemicals. Batool *et al*. (2021) [9] developed a nanoencapsulated cysteine protease of 25 kDa, isolated from White siris (*Albizia procera*) (ApCP). At 7.0 and 3.5 mg/g concentrations, the graphene quantum dots (GQDs) encapsulated biopesticide completely prevented population build-up of this pest.

Ecological management strategy

Demography serves as another fundamental tool in ecology to quantify insect development, survival and reproduction (Carey, 1993, 2001) [15,16]. Life table study is a central theme in demographic analysis to understand the temporal and spatial patterns in population dynamics (Southwood, 1978; Carey, 2001; Roy, 2017) [81,16,65], which was first applied to insect population by Morris and Miller (Morris and Miller, 1954) [52]. It gives a comprehensive description of fecundity, duration and survival at each life stage, life expectancy, mortality, and allows the prediction of population size and age structure of a pest insect at a given time (Carey, 1993; Roy, 2017) [15,65]. Hansen *et al*. (2004) [32] conducted life table studies of *S. cerealella* on maize and stated that if those are compared with other life table studies on this species on maize in India and North America, variations among the strains become evident. Murad and Batool (2017) [55], from their life table analysis, revealed that adult survival rate (Lx) and death rate (Dx) of *S. cerealella* are similar at both highly susceptible and least susceptible varieties, i.e., Pirsabak-2005 and Sirin, respectively. Karimi-Pormehr *et al*. (2018) [39] constructed two-sex life table of *S. cerealella*. Based on the parameters, they confirmed the degree of resistance or susceptibility of 10 barley cultivars. From such knowledge, time-based application of proper pest management measures can be devised, as done by Roy (2022) [69] on sesame (*Sesamum indicum* L.). Rizvi *et al*. (2009) [63] prepared both age-specific (horizontal) and stage-specific (vertical) life-table of cabbage butterfly, *Pieris brassicae* on various cole crops. The age-stage and two-sex life tables are equally significant and eliminate many of the inherent errors of traditional life table due to sexual biasness (Chen *et al*., 2017; Roy, 2022) [17,65,69].

Varietal resistance and susceptibility

One important aspect of IPM is determination of host plant resistance and susceptibility. This tactic may reduce or completely eliminate the need for insecticides, while protecting the environment and human health, and minimizing non-target effects (Quellhorst *et al*., 2021) [61]. Karimi-Pormehr *et al*. (2018) [39] suggested that nutritional quality, especially seed hardness, may be the major factor affecting the susceptibility of barley cultivars to *S. cerealella*. Khan *et al*. (2010) [40] found that IBW-97103 is the wheat genotype with high resistance and genotype WS-94194 is least resistant. Borzoui and Naseri (2016) [10] stated that out of 6 cultivars, wheat variety Bam is highly susceptible and Sepahan is the most resistant. Wheat variety Sirin is least susceptible and Pirsbak-2005 is highly susceptible to *S. cerealella* (Murad and Batool, 2017) [55]. The wheat cultivar Uqab is susceptible, followed by Saleem 2000 and Ghaznawi, and Fakhre-Sarhad is tolerant (Nisar *et al*., 2018) [57]. Mathew *et al*. (2019) [50] recorded wheat genotypes RMLT-108 and RMLT-505 as resistant, RMLT-104 as a moderately resistant genotype and the least resistant genotype to be CB-16 116. Ashamo (2010) [6] concluded that the paddy variety Taichung Native-1 is the most resistant to *S. cerealella* and Pusa 44 is the least resistant variety. Rai *et al*. (2011) [62] noticed that the development period and hence favorability for the growth of *S. cerealella* on different rice cultivars vary according to seasonality. Santos *et al*. (2015) [71] deduced that *Oryza glaberrima* varieties TOG 5681 and CG 14 are the most resistant to *S. oryzae* (L.) and *S. cerealella*. Whereas, the resistance of NERICA and Sativa varieties differs from tolerant to susceptible. Kumar *et al*. (2018) [41] observed that NDR-80 is the most tolerant rice cultivar. While, at 180 days, Lalmati is greatly susceptible. Some rice varieties of West Bengal, viz., Champakushi, Malabati and Valki, are indigenous and highly tolerant to *S. cerealella* infestation irrespective of the moisture content in storage conditions (De and Dey, 2022) [18]. Demissie *et al*. (2015) [20] reported Pratap makka-5 to be the most resistant maize variety and the most susceptible varieties are PMH-1, Navjot, KH-101 and HQPM-1. Bushra *et al*. (2013) [12] found that the barley cultivar Soorab underwent maximum damage and weight loss, while these were minimum in the cultivar Sanober-96, but none of cultivars proved itself completely resistant or susceptible. Karimi-Pormehr *et al*. (2018) [39] observed that barley cultivar 19A1 is the most propitious for the growth of *S. cerealella* and cultivar Fajr30 is the most unsuitable. Table 4 gives an account of the strategies adopted for management of *S. cerealella*.

Table 4: Management strategies for *S. cerealella*

Management strategies	References
Chemical treatments: Synthetic pyrethroids (cypermethrin, deltamethrin and fenpropathrin), JHA (fenoxycarb and MV 678) and IGRs (XRD 437 and chlorfuazuron); Naphthalene and camphor; Deltamethrin emulsifiable concentrate	Eisa, 1992 [24]; Ali *et al*., 2009; Arthur, 2019
Physical control: Low temperature; Ozone treatment; Ionizing irradiation; Iranian diatomaceous earth formulation, Dryasil; Hermetic treatments (Purdue Improved Crop Storage bags, GrainPro Super Grainbags, metal silos) for grain storage; Plastic containers and tin kouta	Perez-Mendoza *et al*., 2004; Hallman and Phillips, 2008; Ali *et al*., 2009 [3]; Hansen *et al*., 2012 [31]; Mubayiwa *et al*., 2021 [54]; Ziaee *et al*., 2022 [87]
Biorational control: Extracts of Mexican sunflower (Tithonia diversifolia), Psychotria prunifolia and Fava d'anta (Dimorphandra mollis); Dried neem (Azadirachta indica) leaf powder; Diallyl trisulfide (DAT) from garlic (Allium sativum) essential oil; EO of Artemisia khorassanica and Artemisia sieberi; Extracts of cheese wood (Alstonia boonei), bitter kola (Garcinia kola) and ebolo (Crassocephalum crepidoides); Spinosad; Nanoencaspsulated cysteine protease; coffee husk, wood ash and sawdust	Huang *et al*., 2007 [34]; Gemu *et al*., 2013 [28]; Fouad *et al*., 2014 [26]; Ma *et al*., 2016 [45]; Gbaye *et al*., 2016 [27]; Naseri *et al*., 2017 [56]; Hossein *et al*., 2018 [33]; Shah *et al*., 2021a [76]
Biological control agents: Pteromalus cerealellae (Hymenoptera: Pteromalidae); Wolbachia sp. (Rickettsiales: Anaplasmataceae); Trichogramma brassicae (Hymenoptera: Trichogrammatidae)	Wen and Brower, 1994 [85]; Kageyama *et al*., 2010 [36]; Ghaemmaghami *et al*., 2021 [29]
Biotechnological management: P33V08 and N6800Bt, MON 810 and Bt-11 transformed corn hybrids containing CrylAbBt delta-endotoxin; nanoencapsulated cysteine protease from White siris (Albizia procera) (ApCP)	Sedlacek *et al*., 2001 [72]; Batool *et al*., 2021 [9]
Ecological tools: Life table construction and management	Hansen *et al*., 2004 [32]; Murad and Batool, 2017 [55]; Karimi-Pormehr *et al*., 2018 [39]
Resistant cultivars: wheat genotye IBW-97103; wheat cultivar Sepahan; wheat variety Sirin; wheat cultivar Fakhre-Sarhad; wheat genotypes RMLT-108 and RMLT-505; paddy variety Taichung Native-1; Oryza glaberrima varieties (TOG 5681 and CG 14); rice genotype NDR-80; rice varieties Champakushi, Malabati and Valki; Pratap makka-5 maize variety; barley cultivar Sanober-96; barley cultivar Fajr30 **Susceptible cultivars:** wheat genotye WS-94194; wheat cultivar Bam; wheat variety Pirsbak-2005; wheat cultivar Uqab; Pusa 44 paddy variety; wheat genotype CB-16 116; Oryza glaberrima varieties NERICA and Sativa; rice genotype Lalmati; PMH-1, Navjot, KH-101 and HQPM-1 maize varieties; barley cultivar Soorab; barley cultivar 19A1	Khan *et al*., 2010 [40]; Ashamo, 2010 [6]; Bushra *et al*., 2013 [12]; Santos *et al*., 2015 [71]; Demissie *et al*., 2015 [20]; Borzoui and Naseri, 2016 [10]; Murad and Batool, 2017 [55]; Nisar *et al*., 2018 [57]; Karimi-Pormehr *et al*., 2018 [39]; Kumar *et al*., 2018 [41]; Mathew *et al*., 2019 [50]; De and Dey, 2022 [18]

Discussion

Grain stores are a perfect habitat for insects that live on dry seeds because the insects are protected from weather extremes, have access to an unlimited food resource and are undisturbed for long periods (Hansen *et al*., 2012) [31]. Basavanjali *et al*. (2020) [8] and Sachin *et al*. (2022) [70] elaborated the life cycle of *S. cerealella*. Temperature is the most critical abiotic factor influencing the population dynamics, and even a slight alteration in temperature can bring the spatial and temporal changes in phenology of insects. Thus, precise models based on the information of temperature-dependent development and distribution are essential for forecasting pest emergence (Maharjan *et al*., 2017) [47]. Host grain availability and quality in terms of their phytochemicals also play a vital role on development and ecology of the pest (Awmack and Leather, 2002; Roy, 2014) [7,64]. The primary metabolites are responsible for their general growth and reproduction like other animals. Whereas, consumption of secondary metabolites reduces the adult longevity and fecundity, and retards larval growth (Roy, 2017, 2019) [65,66] due to higher metabolic costs (War *et al*., 2012) [84]. The complex mixture of other secondary metabolites in many plants may provide defense against a range of pests (Dicke, 2000) [21]. Demissie *et al*. (2015) [20] postulated that it is important to breed maize variety considered on the low ash, low amylose and high phenolic content besides other morphological and physical characteristics, in order to get maize variety which is resistant to Angoumois grain moth. The mean developmental period of the insect is inversely correlated with resistance (Mathew *et al*., 2019) [50]. Quellhorst *et al*. (2021) [61] stated that with the innumerable varieties of hybrids and genetic lines of maize, future work should address maize hybrid groups that are most commonly used in areas where *P. truncatus* is not present, in order to forestall the further spread of this species and for a genetics-oriented control strategy. The same can be concluded about *S. cerealella*. But other than studies on varietal resistance or susceptibility, researches concerning development of other management strategies against *S. cerealella* are lacking at the national level in India.

Farmers and commercial grain elevator managers use a range of pest management options including cultural practices that minimize pest build-ups or migration into storage structures, such as cleaning of bins and equipment before harvest, sealing structures, cleaning up grain spills on the grounds, spraying of bins and storage structures, grain drying and cooling (Edde,

2012) [23]. Hermetic technologies that work on the principle of creating a modified environment within the storage container, are constructed of materials with very low oxygen permeability and are becoming popular in grain storage (Mubayiwa *et al*., 2021) [54]. Ionizing irradiation has many uses including sterilizing insects for population management, in eradication programs, as a phytosanitary treatment, and for general disinfestation of commodities (Hallman and Phillips, 2008) [30]. Gaseous ozone (O_3) is highly oxidative and unstable and decomposes rapidly to oxygen without leaving residues. It is a powerful disinfectant and has recently received increasing interest for the control of insect pests, even those that are resistant to phosphine (Hansen *et al*., 2012) [31]. Ziaee *et al*. (2022) [87] suggested that Dryasil (IGA-NT Co., Iran), a marine diatomaceous earth (DE) enhanced with 10% silica aerogel, can be considered a grain protectant to control *S. cerealella*. DE is a promising substitute for chemical pesticides in controlling stored product insects, whose particles absorb the waxy layer of insect cuticle, resulting in water loss and death. From the current research trends, it can be concluded that nanotechnologies, hermetic technologies for storage, various botanical and even biological controls are gaining ground in combating stored grain pests.

Unfortunately, farmers still use broad-spectrum synthetic pesticides injudiciously for the management of even a single pest, without the knowledge of economic threshold level or pest population growth rate (Roy, 2022) [69]. These result into secondary pest outbreak, pest resurgence, development of pesticide resistance and emergence of new pest biotypes, which ultimately lead to regulatory complications in the agroecosystem (Kang, 2019; Roy, 2022) [38,69]. To face the ecosystem crisis, population dynamics, nutritional ecology and economic threshold-based time specific sustainable management are indispensable (Carey, 1993; Chen *et al*., 2017; Southwood, 1978; Roy, 2022) [15,17,81,69]. Pest nutritional ecology, demographic parameters and their yield reduction efficiency inform about the time-based infestation capability and density of the pest in the crop ecosystem (Kakde *et al*., 2014; Roy, 2017) [37,65]. The economic injury level and economic threshold level are calculated based on yield loss, degree of pest infestation, cost of protection and market price of the stored product (Pedigo and Higley, 1992) [58]. Finally, we are in the middle of a serious climate emergency. Climate models predict that the average temperature of the globe will increase by 1.8–4℃ by the end of the current century. The effects of climate change on insects are complex. Given the enormous heterogeneity of insect species and their host plants, and global climate variability, mixed responses of insect species to global warming are expected in different parts of the world (Skendži´c *et al*., 2021) [79]. Therefore, a proactive and scientific approach is required to deal with this problem.

Conclusion

Economical and effective control measures for *S. cerealella* requires detailed and accurate knowledge of its bio-ecology along with the possible prediction of population levels and various mortality factors affecting its abundance. Effective management program requires the use of all available control tactics to obtain the highest level of grain protection at the lowest cost, with considerations for safety of the farm workers and environmental stewardship. Indiscriminate use of chemical pesticides had already toppled the ecological balance when climate crisis began to impinge, with its highly variable precipitation patterns presenting newer problems through altered pest physiology, spectrum, behaviour and pesticide efficacy. Also, since *S. cerealella* co-occurs with other stored grain pests, management programmes must target multiple pests simultaneously. We must analyse all these factors critically during the management of this pest species in household and commercial units. Therefore, ETs-based time series for judicious application of any sustainable control measures will reduce ecological imbalance and promote IPM as well as CSPM in near future.

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