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Effect of Pakistani Wheat Cultivars and Population Density on the Biological Parameters of Wheat Weevil, *Sitophilus granarius* (L.) and their Management through Gamma Irradiation

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AA, UK and AA performed the experiment and sample collection. UK, MZ, SJAS and AA provided resources and supervised the project. AA and UK designed experiments, analyzed and interpreted data. AA, UK, NF, AS and AA performed statistical analysis, writing and reviewing the manuscript. AUH, SK, IM, NF, MZ and SJAS processed data, investigation and manuscript reviewing. All authors agreed to the final version of manuscript.

Key words
Wheat cultivar, Initial population density, *Sitophilus granarius,* Irradiation, Control, Percentage Seed germination

ABSTRACT

The wheat weevil, *Sitophilus granarius*, is a significant pest of stored grains that has an impact on the quantity and quality of wheat. The current study was carried out in laboratory setting to assess the impact of wheat cultivars (Fakhr-e-Sarhad, Bakhtawar-92, Bathoor, Lalma, and Insaf) and initial population densities (10, 20, and 30 adults) on the biological parameters of *S. granarius*. Among all wheat cultivars, Lalma required the shortest time (23.3-24.7 days) for the first adults of *S. granarius* to emerge, whereas Bakhtawar-92 took the longest (27.0-36.0 days). Considering all initial population densities, the average number of progeny was highest in the Lalma (163.8-305.3 adults) and Bathoor (108.0-205.3 adults), and lowest in Fakhr-e-Sarhad (18.0-46.7 adults), with the exception being Bakhtawar-92, where very few or no adults emerged. Among all population densities, the highest body weight was found in Insaf (7.6-8.5 mg) and the lowest weight (6.3-8.3 mg) in Bathoor. When comparing all initial population densities, the Lalma and Bathoor wheat cultivars showed the highest adult longevity, ranging from 5.7-8.0 days and 6.3-8.0 days, respectively. For managing *S. granarius* through gamma irradiation, the Lalma wheat cultivar was used as a food substrate. The estimated lethal doses, LD_{50} and LD_{90} values i.e., 217.69 and 670.31 Gy, respectively, were found to be significantly higher at shorter PEI (7 days), while the lethal times were found to be shorter at higher irradiation doses i.e., for 350 Gy, the LT_{50}=4.94 days and LT_{90}=9.07 days.

INTRODUCTION

Wheat (*Triticum aestivum*) is the major source of nutrients for about 40% of the world's population (Giraldo *et al*., 2019). Similar to many other seasonal crops, wheat is stored during the off-season to ensure a steady supply. Unfortunately, pest infestations often plague this storage period, leading to substantial economic losses due to reduce grain quality and quantity (Keskin and Ozkaya, 2015; Ahmad *et al*., 2021). The attack of stored grain insect pests worldwide results in the loss of approximately 20-37% of stored grain products, valued at around $70 billion annually (Qayyum *et al*., 2021). Several types of insects, including khapra beetle (*Trogoderma granarium*), lesser grain borer (*Rhyzopertha dominica*), bruchid beetles (*Callosobruchus maculatus*), angoumois grain moth (*Sitotroga cerealella*), and *Sitophilus* species (Holscher, 2000; Khalique *et al*., 2018, 2024), attack and damage stored grains. Species of the *Sitophilus* genus are considered notorious pests of stored grains and are widely known for their four major types of species i.e., granary weevil, *Sitophilus granarius*; maize weevil, *Sitophilus zeamais*; rice weevil, *Sitophilus oryzae*, and tamarind

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weevil, *Sitophilus linearis*. The maize and rice weevils are particularly significant in warmer climates due to their strong physical and ecological similarities. Distinguishing between these two species can be challenging because of these resemblances. In contrast, the wheat weevil sets itself apart by its inability to fly (Egbon and Ayertey, 2009; Corrêa et al., 2013). The wheat weevil, scientifically known as *Sitophilus granarius* (Coleoptera: Curculionidae), is one of the most detrimental pests to grain worldwide. Its impact affects both grain quantity and quality, making it a significant threat to grain storage and agricultural productivity (Kljajić and Perić, 2006; Golnaz et al., 2011; Kaske et al., 2019).

S. granarius is the internal feeder, causing damage inside the grains. External damage does not become visible until the entire grain sustains damage. It has been reported that *S. granarius* causes 60% weight loss in wheat grains during its development from larvae to adulthood, which is hidden inside the grain (Keskin and Ozkaya, 2013). Chemical control methods, such as fumigation of stored commodities with carbon disulfide, phosphine, or dusting with malathion, carbaryl, pirimiphos-methyl or permethrin, adequately manage the destructive activities of storage pests, but they cause ecological disruptions and raise public health concerns (Adedire et al., 2011).

To mitigate ecological disruptions and public health concerns stemming from the indiscriminate use of pesticides, it's imperative to explore alternative, eco-friendly techniques for pest management within an ecologically sound integrated pest management system. To tackle this problem, researchers are actively exploring inventive approaches, such as investigating insect food preferences and utilizing irradiation techniques. Various studies have shown that stored grain pests exhibit preferences and aversions for different types of grains. Their resistance mechanism is complex and depends on the biochemical and physical adaptations within the storage environment. Therefore, host plant resistance emerges as a crucial factor in the management of stored grain insects (Mahmoud et al., 2011; Lemic et al., 2020). The development of insect-resistant wheat varieties serves as an early demonstration of host plant resistance. The advancement of host plant resistance in wheat has employed various breeding approaches, from traditional evaluation and selection to the utilization of marker-assisted selection (Kordan et al., 2019).

It is essential to identify the resistance levels of different insect species that infest grain during storage. This knowledge can serve as one of the alternatives in storage pest management strategies (Saad et al., 2018; Mehta and Kumar, 2021). Physical characteristics such as testa thickness and hardness, along with their chemical composition of proteins, fats, and starch, primarily influence the susceptibility of different grain varieties to storage pests (Kordan et al., 2023). In addition, agriculture undoubtedly employs irradiation as a pest control method. Pests, such as insects, are exposed to controlled doses of ionizing radiation. The radiation harms the pests' DNA and other cellular structures, preventing them from reproducing and causing damage to grain commodities. For nineteen centuries, people have used radiation to preserve food and drugs. Recently, this technique has expanded its applications to include the sterilization of mass-reared insects for the sterile insect technique (SIT). Pests like the grain weevil, Mediterranean mealworm, Indian mealworm, cigarette beetle, mad fly, onion fly, fall armyworm, tobacco budworm, and African cotton leafhopper can be killed by irradiation doses ranging from 25 Gy to 1200 Gy (Timbadiya et al., 2018). Notably, this control method demonstrates its environmental friendliness by achieving suppression without causing radiation stimulation or leaving any residual effects. Researchers have also found that gamma radiation effectively controls stored insect pests. Isotopic sources emit gamma rays in all directions, enabling surrounding insects to achieve high energy utilization efficiency and simultaneously apply it to multiple containers (Ayvaz and Yilmaz, 2015).

The current study was focused on evaluating the impact of initial population densities and various wheat cultivars on key biological parameters of *S. granarius*. Additionally, study assessed the efficacy of gamma irradiation as a management strategy by determining its effect on *S. granarius* mortality in the most susceptible wheat variety.

MATERIALS AND METHODS

Sitophilus granarius *population*

Adults of *S. granarius* were collected from market-purchased infested wheat from Peshawar (34.00991° N, 71.5883° E). The population was reared on infestation free wheat grains in 2.5 L plastic jars covered with muslin cloth for ventilation. A laboratory population was maintained at a controlled temperature of 27±2°C, a relative humidity of 65±5%, and a photoperiod (light:dark) of 08:14 h.

Wheat cultivars

Five different wheat cultivars i.e., Fakhar-e-Sarhad, Bakhtawar-92, Insaf, Lalma, and Bathoor were obtained from Plant Breeding and Genetics Division, NIFA, Peshawar and exposed to 4 °C for at least seven days to kill potential insect infestation. After this, all cultivars were kept under controlled laboratory conditions at 27±2°C temperature for 24 h prior to the experiment.

Effect of wheat cultivars on the life parameters of S. granarius

For each of the three population densities of *S. granarius* i.e., 10, 20, and 30 adults, 50 g of each type of cultivar were placed into 175 mL glass jars separately. In three replicates, unsexed adults aged one to two weeks were added to each cultivar/population density combination. The mouth of the jars were covered with white cotton cloth and tied with rubber bands. The released adults were allowed to oviposit and feed on the grains, and after seven days, the weevils were gently removed by a sieve, causing the least disruption to the developing offspring.

The moment for *S. granarius* first adult emergence in each cultivar/population density combination was determined by following the modified method described by Đukić *et al*. (2016). In brief, the jars were checked daily and the day when first adult was observed was recorded and marked that moment as day 1. Following the development of the first adult, newly emerged adults were counted daily and removed until the last adult emerged in each jar. By counting the total number of emerged adults in each cultivar/population density combination, the total number of progenies were determined. For adult longevity, 15 adults from each treatment were randomly selected and shifted into 2 mL glass vials in two sets: One with food and one without food, and were examined daily until death. The time period between adult emergence and adult mortality was considered as longevity.

Prior to the experiment, the initial weight of each wheat cultivar was calculated to determine the amount of food consumed by *S. granarius* larval stages and the grain's final weight was also determined after the last adult emerged.

A random selection of new adults was put in 175 mL glass jars during the count checks. An analytical scale (Sartorius Balance LS 300, USA) was used to assess the average adult body weight of *S. granarius*. The total body weight of 15 newly emerged adults from each cultivar/population density combination was determined and the average body weight was calculated using the following formula:

$$\text{Average body weight} = \frac{Total\ weight}{no\ of\ adults}$$

Effect of gamma irradiation doses against the mortality of S. granarius

In order to assess the impact of gamma irradiation doses on *S. granarius*, twenty unsexed adults were individually inserted, aged one to two weeks, into each glass petri plate which contained 20 g wheat grains (*Lalma cultivar*) as adult diet. Petri plates were exposed to different irradiation doses i.e., 50, 100, 150, 200, 250, 300 and 350 Gy in a cobalt-60 irradiation source. The un-irradiated sample was considered as control treatment. After exposure, the petri plates were kept under controlled conditions at 27±2°C, relative humidity 65±5% and photoperiod (light: dark) 08:14 h. The experiment was repeated three times, adhering to the complete randomized design. The mortality data of adults were recorded on daily basis in order to observe the lethal doses (LD_{50} and LD_{90}) and lethal time (LT_{50} and LT_{90}).

Effect of gamma irradiation doses on the percentage seed germination

To determine the residual effect of gamma irradiation doses on the wheat grains, the seed germination test was conducted. Ten sound wheat grains of Lalma wheat cultivar were introduced separately into each glass petri plates. In a cobalt-60 irradiation source, petri plates were exposed to different irradiation doses i.e., 50, 100, 150, 200, 250, 300 and 350 Gy, and un-irradiated grains were considered as a control treatment. After being exposed, the irradiated and un-irradiated seeds were carefully placed between layers of wet filter paper in separate petri plates and kept in a controlled environment with a temperature of 27±2°C, a relative humidity of 65±5%, and a light-dark cycle of 08:14 h. Complete randomized design was followed with three replications of each treatment. Germination percentages were determined by using the following formula:

$$\text{Seed germination (\%)} = \frac{\text{Germinated seed}}{\text{Total seed}} \times 100$$

Data analysis

A two-way analysis of variance (ANOVA) was performed to analyze first adult emergence (FAE), Number of progeny (NoP), adult longevity, their body weight, and food consumption while one-way analysis of variance was employed to analyze the germination percentage of irradiated seeds by using Statistix version 8.1 (Analytical Software, 2005). The Tuckey HSD test was used to compare the means of all parameters at $\alpha = 0.05$ (Đukić *et al*., 2016). To calculate the lethal doses and lethal time to kill 50% and 90% of the *S. granarius* population, mortality data were subjected to probit analysis by using SPSS version 16.

RESULTS AND DISCUSSION

First adult emergence

The initial population density, wheat cultivars, and their interaction had significant effects on the first adult emergence of *S. granarius* (wheat cultivar: $F = 19.05$; $P < 0.05$; population density: $F = 6.21$; $P < 0.05$; wheat cultivar x population density: $F = 3.45$; $P < 0.05$). The first adult emergence (the average days between parent removal and first day of *S. granarius* emergence) was found to be significantly different among different wheat cultivars and initial adult population densities (Table I). The impact of wheat cultivar/ population density combination was most evident on the first day of adult emergence for Bakhtawar-92 and Lalma wheat cultivars at an initial population density of 10 adults/50 g i.e., adults emerged significantly after 36.0 and 24.7 days, respectively, while the earliest adult emergence, i.e., after 27.0 and 23.3 days, was recorded at a density of 30 adults. In Insaf and Bathoor wheat cultivars, the first adult emergence of *S. granarius* took a shorter time period (25.3 and 24.7 days) at the initial population density of 20 adults, while at the lowest initial population density, the duration was significantly longer, i.e., 27.0 and 26.0 days, respectively. Conversely, the longest time interval (28.3 days) for first adult emergence was found in the Fakhr-e-Sarhad wheat cultivar at an initial density of 20 adults, while at the highest population density (30 adults/50 g), the duration was significantly shortest, i.e., 27.3 days. Comparing all population densities and wheat cultivars, *S. granarius* required the shortest time period for first adult emergence in the Lalma wheat cultivar (23.3-24.7 days) and Bathoor wheat cultivar (24.7-26.0 days), while longer in the Fakhr-e-Sarhad wheat cultivar (27.3-28.3 days), and the longest in Bakhtawar-92 (27.0-36.0 days).

Table I. First adult emergence average number of progeny, average body weight and food consumption by *S. granarius* in wheat cultivars at different population densities.

Wheat cultivars	Population density		
	10	20	30
First adult emergence (day, Mean±SEM)			
Fakhr-e-Sarhad	27.7 ± 0.33 ^{bc}	28.3 ± 0.33 ^{bc}	27.3 ± 0.88 ^{bc}
Bakhtawar-92	36.0 ± 0.33 ^{a}	30.0 ± 2.51 ^{a}	27.0 ± 0.88 ^{bc}
Insaf	27.0 ± 0.88 ^{bc}	25.3 ± 0.33 ^{bc}	26.7 ± 0.88 ^{bc}
Lalma	24.7 ± 1.66 ^{bc}	23.3 ± 0.33 ^{bc}	23.3 ± 0.33 ^{bc}
Bathoor	26.0 ± 1.15 ^{bc}	24.7 ± 0.88 ^{c}	26.0 ± 0.00 ^{bc}
Average total progeny (number Mean±SEM)			
Fakhr-e-Sarhad	18.0 ± 3.78 ^{e}	46.7 ± 15.3 ^{de}	43.3 ± 1.70 ^{de}
Bakhtawar-92	1.0 ± 1.00 ^{e}	0.0 ± 0.00 ^{e}	0.7 ± 0.66 ^{e}
Insaf	92.0 ± 8.50 ^{cde}	129±25.40^{bcde}	170.7±31.80^{abcd}
Lalma	163.8±32.60^{bcd}	249 ± 60.60 ^{ab}	305.3 ± 42.60 ^{a}
Bathoor	108.0±9.53^{cde}	168±12.30^{abcd}	205.3±33.60^{abc}
Average body weight (mg, Mean±SEM)			
Fakhr-e-Sarhad	7.5 ± 0.33 ^{c}	7.5 ± 0.17 ^{c}	8.5 ± 0.17 ^{a}
Insaf	7.6 ± 0.08 ^{bc}	8.5 ± 0.21 ^{a}	7.6 ± 0.40 ^{bc}
Lalma	6.5 ± 0.20 ^{d}	8.4 ± 0.37 ^{a}	7.1 ± 0.088 ^{cd}
Bathoor	6.3 ± 0.17 ^{d}	6.4 ± 0.17 ^{d}	8.3 ± 0.17 ^{ab}
Average food consumption (g, Mean±SEM)			
Fakhr-e-Sarhad	2.2 ± 0.11 ^{de}	3.0 ± 0.41 ^{de}	2.2 ± 0.40 ^{de}
Bakhtawar-92	1.9 ± 0.24 ^{e}	2.0 ± 0.11 ^{e}	3.5 ± 1.66 ^{cde}
Insaf	3.8 ± 0.56^{bcde}	4.9±0.56^{abcde}	5.3 ± 0.81 ^{abcd}
Lalma	6.1 ± 0.58^{abcde}	7.7±0.33^{abc}	8.5 ± 0.56 ^{a}
Bathoor	4.9 ± 0.59^{abcde}	6.3±1.04^{abcd}	7.9 ± 1.18 ^{ab}

The means in the column and rows with different lowercase letters revealed statistically significant differences at 0.05% of probability (Statistix v8.1).

Only the Bakhtawar-92 wheat cultivar showed a significant impact on the first day of adult emergence, emerging almost 11.3 days later than the Lalma wheat cultivar at an initial population of 10 adults. Comparing all wheat cultivars, our results revealed the influence of population densities on the emergence times of *S. granarius*, with significant variations observed among different wheat cultivars. Specifically, for the Fakhr-e-Sarhad cultivar, the longest duration for emergence occurred at population density 20, with an average of 28.3 days. In contrast, among the other four cultivars, the longest emergence times were observed at a population density level of 10. Conversely, the lowest mean emergence times were recorded at a density level of 30 for all wheat cultivars. Alabi *et al.* (2008) made a similar report that larval cannibalism has potential benefits for reaching the adult stage earlier, with increasing chances of survival, a greater body weight and a shorter life cycle. The findings of current study are align with those of Đukić *et al.* (2016) who reported that the initial population densities have significant impact on the first day emergence of *Tribolium castaneum* when feeds on different diets.

Number of progeny

The initial population density and wheat cultivar significantly affected the number of *S. granarius* progeny, while their interaction effect was non-significant (wheat cultivar: $F = 38.82$; $P < 0.05$; population density: $F = 8.33$; $P < 0.05$; wheat cultivar x population density: $F = 1.16$; $P > 0.05$). The total number of *S. granarius* progeny varied significantly among different wheat cultivars and initial population density (Table I). Within wheat cultivars, the average total number of progeny increased significantly with the increase in initial population density, an exception being the Fakhr-e-Sarhad wheat cultivar, where the highest progeny was recorded from the initial density of 20 adults (46.7 adults) compared to the initial population density of 10 and 30 adults, i.e., 18.0 and 43.4 adults, respectively

(Table I). Among all the initial population densities, with the exception of Bakhtawar-92 wheat cultivar, where a few or no adult emerged from all population densities and was excluded from further experiments, the Lalma wheat cultivar was found to have the highest number of progeny (163.8-305.3 adults).

The average number of *S. granarius* progeny increases with increasing initial population density, resulting in a 2.4, 1.8, 1.8 and 1.9-fold higher average number of adults in Fakhr-e-Sarhad, Insaf, Lalma and Bathoor at the highest initial population density than the lowest population density. Đukić *et al*. (2016) found similar results that the average number of progeny of *Tribolium castaneum* increased with increasing initial population density, reaching its peak at the highest initial population density of 100 adults compared to the lowest density of 10 adults. Our findings are also similar to the investigations of Taylor (1974), who recorded higher total progeny of *Callosobruchus maculatus* (F.) at the initial population density of 40 adults than the density of 10 adults when feeding on a 100 g cowpea diet. The congruence in the findings likely stems from shared principles of population dynamics, where increased initial population densities lead to greater reproductive output, as observed across different stored grain pest species.

Longevity of adults in the presence and absence of food

The initial population density, wheat cultivars, and their interaction had significant effects on the adult longevity of *S. granarius* in the absence of food (wheat cultivar: $F = 4.58$; $P < 0.05$; population density: $F = 3.93$; $P < 0.05$; wheat cultivar x population density: $F = 7.47$; $P < 0.05$). Adult longevity of *S. granarius* in the absence of food varied significantly among different wheat cultivars and initial population density (Fig. 1A). The average adult longevity of *S. granarius* increased significantly within wheat cultivars as the initial population density decreased, with the exception of Insaf wheat cultivar, which recorded the longest adult longevity at an initial population density of 20 adults (6.7 days) compared to the initial population density of 10, i.e., 5.0 days (Fig. 1A). When comparing all wheat cultivars and initial population densities, Lalma and Bathoor wheat cultivars recorded the highest adult longevity at 5.7-8.0 days and 6.3-8.0 days, respectively, while Fakhr-e-Sarhad and Inasf wheat cultivars recorded the shortest at 6.3-6.7 days and 5.0-6.7 days, respectively.

Conversely, in terms of food availability, the combination of initial population density and wheat cultivars as main effects significantly affects the adult longevity of *S. granarius* (wheat cultivar: $F = 13.12$; $P < 0.05$; population density: $F = 20.16$; $P < 0.05$; wheat cultivar x population density: $F = 0.94$; $P > 0.05$). The adult longevity of *S. granarius* in availability of food varied significantly among the wheat cultivars and initial population density (Fig. 1B). Within wheat cultivars, an initial population density of 20 adults yielded the longest adult longevity, with the exception of Fakhr-e-Sarhad, which recorded the longest adult longevity at an initial population of 30 adults, resulting in 22.7 days, compared to initial population density of 20 adults (22 days). The Bathoor wheat cultivar recorded the longest adult longevity (23-41 days) among all initial population densities and wheat cultivars, while the Lalma wheat cultivar recorded the shortest, 6.3-26.3 days.

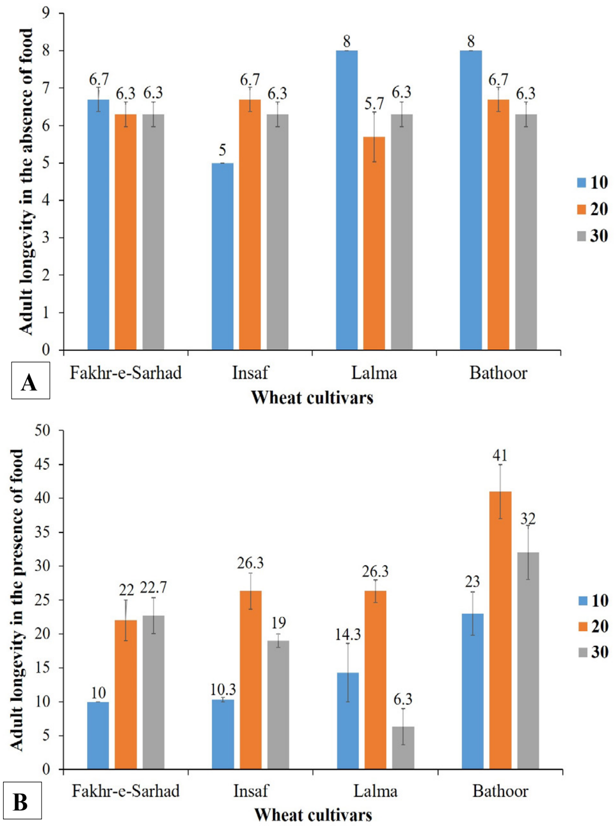

Fig. 1. Adult longevity of newly emerged *S. granarius* in the absence (A) and the presence (B) of food.

The study's current findings highlight the influence of both wheat cultivars and population densities on the longevity of *S. granarius* in the presence or absence of adult food. Okram and Hath (2019) found significant variations in the adult longevity of rice weevils reared under both the presence and absence of food, which aligns with the current results. The findings of the current study also align with the previous studies showing that the insect diet significantly influence the adult longevity of insects i.e., *Sitophilus oryzae* and *Clitostethus arcuatus* (Yazdani and Zarabi, 2011; Yadav *et al*., 2018; Jalaeian *et al*., 2021). The parallel findings may be attributed to the impact of environmental factors such as diet type and initial population density, influencing the physiological responses and survival rates of stored grain insects observed across different species.

Body weight of emerged adults

The adult body weight of newly emerged *S. granarius* varied significantly in comparison to both the wheat cultivars and initial population densities (wheat cultivar: $F = 23.24$; $P < 0.05$; population density: $F = 41.20$; $P < 0.05$; wheat cultivar x population density: $F = 28.55$; $P < 0.05$). Among all wheat cultivars, the Insaf and Lalma wheat cultivars exhibited the highest average adult body weight of *S. granarius*, measuring 8.5 and 8.4 mg, respectively, at an initial population density of 20 adults, except for Fakhr-e-Sarhad and Bathoor, which recorded the highest average adult body weight of 8.5 and 8.3 mg, respectively, at an initial population density of 30 adults (Table I). When comparing all initial population densities and wheat cultivars, the Insaf wheat cultivar recorded the highest adult body weight (7.6-8.5 mg), while Bathoor recorded the shortest (6.3-8.3 mg).

The initial population density in all wheat cultivars influence the adult body weight of *S. granarius*. The most significant difference was detected in the Fakhr-e-Sarhad, Lalma and Bathoor wheat cultivars, where adult body weight at the highest initial population density was 1.1, 1.0 and 1.3-fold higher than at the lowest population density. All wheat cultivars showed a significant difference in body weight of newly emerged adults at the initial density of 20 i.e., Insaf wheat cultivar offspring having a 1.3-fold higher body weight than Bathoor offspring. The findings of the current study are similar to the previous studies showing that the insect diet and population density significantly influence the adult body weight of stored grain insects i.e., *Plodia interpunctella*, *Candra cautella* and *Tribolium castaneum* (LeCato, 1976; Assie *et al*., 2008).

Food consumption

The initial population density and wheat cultivar significantly affected the food consumption of *S. granarius*, while their interaction effect was non-significant (wheat cultivar: $F = 21.84$; $P < 0.05$; population density: $F = 6.97$; $P < 0.05$; wheat cultivar x population density: $F = 0.36$; $P > 0.05$). The results showed that the initial population density had a bigger impact on food consumption for each type of wheat cultivar and food consumption increases with increasing initial population density in each wheat cultivars, except of Fakhr-e-Sarhad where maximum food consumption i.e., 3.0 gm occurred at initial population density of 20 adults as compared to 30 adults (2.2 g). Lalma and Bathoor wheat cultivars showed the most significant food consumption at 8.5 mg and 7.9 mg, respectively, at the highest initial population density, and 6.1 mg and 4.9 mg, respectively, at the lowest population density (Table I). Considering all wheat cultivars and initial population densities, the Lalma wheat cultivar had the significant maximum food consumption (6.1-8.5 mg), while Bakhtawar-92 had the minimum (1.9-3.5 mg).

Average food consumption by *S. granarius* increases with increasing initial population density, resulting in the average weight loss in Bakhtawar-92, Insaf, Lalma and Bathoor being 1.6, 1.5, 2.4 and 3.0-fold higher at the highest initial density than at the lowest population density. However, 0.8-fold lower weight loss was found in Fakhr-e-Sarhad wheat cultivar at the highest population density than at the lowest density of 20 adults. This may be partially due to insects having preferences for certain diet types over others (Wistrand, 1974; Boamah *et al*., 2023). Jalbani *et al*. (2017) found that the weight loss of grains was related mutually to the progeny production of rice weevils. Khan *et al*. (2014) and Mehta and Kumar (2021) conducted experiments on different wheat genotypes and found that the susceptible wheat genotypes experienced the most weight loss. Similar observations were also found by Suleiman *et al*. (2015), who found that a high number of progeny led to the highest weight loss of grains.

Mortality of S. granarius *exposed to different irradiation doses*

Irradiation doses significantly affects the mortality of *S. granarius* at seven days, fourteen days and twenty one days post exposure intervals ($P < 0.05$) (Fig. 2). Administration of irradiation doses to *S. granarius* explained 5.0 to 81.67%; 43.33 to 100.0% and 76.67 to 100.0% mortality, which was significantly higher at the higher dose (350 Gy) and lower at the lower dose (50 Gy) at 7, 14 and 21 days

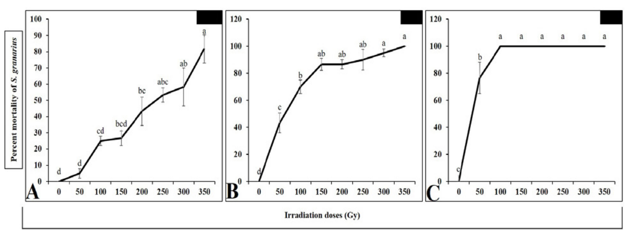

Fig. 2. Percent mortality of *S. granarius* for different irradiation doses at 7 days post exposure intervals (A), 14 days post exposure intervals (B) and 21 days post exposure intervals (C).

Table II. Toxicity of Irradiation doses against the adults of *Sitophilus granarius* for lethal doses.

Day after irradiation exposure	n†	LD_{50}* (95% CL)	LD_{90}** (95% CL)	Fit of probit line			
				Slope (SE)	X^2	Df	P
7	420	217.69 (194.04-247.18)	670.31 (522.97-976.57)	2.62 (0.29)	7.69	5	0.17
14	420	59.51 (44.69-72.65)	203.46 (172.76-252.21)	2.40 (0.28)	4.17	5	0.53
21	420	33.97 (18.13-42.56)	64.94 (55.18-84.16)	4.56 (1.23)	1.16	5	0.95

†Number of insects used in bioassay. *. LD_{50} = Lethal dose to kill 50% population. **. LD_{90} = Lethal dose to kill 90% population.

post exposure intervals, respectively (Fig. 2). These results also explain that all the tested doses demonstrated more than 50% mortality at higher dose (250-350 Gy) at 07 d PEI, (100-350 Gy) at 14 d PEI and (50-350 Gy) at 21 d PEI in *S. granarius*.

Lethal doses and lethal time values of irradiation doses against S. granarius *exposed to different post exposure intervals*

The lethal dose values of irradiations varied significantly for each exposure interval, as shown by the fact that their respective 95% confidence limits did not overlap (Table I). The estimated LD_{50} and LD_{90} values of irradiation doses, i.e., 217.69 and 670.31 Gy, respectively, were significantly higher at shorter PEI (7 days), followed by 59.51 and 203.46 Gy after 14 days PEI, and lower at longer PEI (21 days), i.e., 33.97 and 64.94 Gy, respectively (Table II). Nasr *et al.* (2022) reported that the survival rate of *S. oryzae* decreased with an increase in irradiation doses. Our findings are also similar to Paithankar *et al.* (2017), who investigated the impact of gamma radiation on Drosophila fruit fly mortality and observed 100% mortality within a 24-h at 1500 Gy irradiation dose compared to 50% mortality (LD_{50}) at 1228 Gy. The correlation probably comes from the fact that higher doses of gamma irradiation cause insect populations to die off more quickly, as shown by several studies, such as Ghosh *et al.* (2018) and Nasr *et al.* (2022).

With respect to the time taken to cause 50% (LT_{50}) and 90% (LT_{90}) mortality of the exposed *S. granarius* adults, 350 Gy had an LT_{50} of 4.94 days and LT_{90} of 9.07 days followed by 300 Gy (LT_{50} = 5.97 days; LT_{90} = 13.53 days), 250 Gy (LT_{50} = 6.44 days; LT_{90} = 15.48 days), 200 Gy (LT_{50} = 7.79 days; LT_{90} = 16.51 days), 150 Gy (LT_{50} = 9.31 days; LT_{90} = 17.43 days), and 100 Gy (LT_{50} = 10.24 days; LT_{90} = 20.13 days). Whereas, 50 Gy took the longest time i.e., 16.57 and 28.67 days to cause 50% and 90% mortality, respectively, of the exposed weevils (Fig. 3). Findings of the current study are similar to the investigation of Kumar *et al.* (2017) who reported the highest mortality of *Lasioderma serricorne* within a shorter timeframe (8 days) at 1200 Gy as compared to lower irradiation doses.

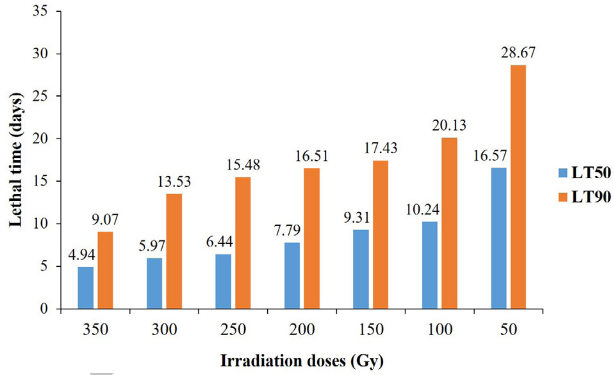

Fig. 3. Lethal time (days) of different irradiation doses to kill 50 and 90% population of the exposed *Sitophilus granarius* adults.

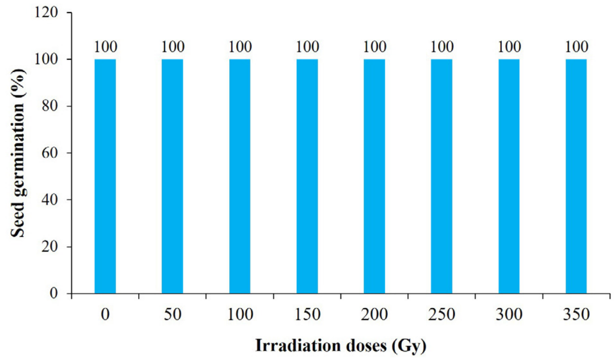

Fig. 4. Effects of gamma irradiation on wheat seed germination (%).

Seed germination percentage after irradiation treatment

The gamma irradiations had non-significant effect on the percent seed germination of wheat grains (F = 0.57; P > 0.05). As illustrated in Figure 4, irradiated wheat seeds maintained their germination capacity compared to the control. The research conducted by Borzouei *et al.* (2010) supports our current findings, as they achieved a 100% seed germination rate through radiation treatment ranging from 100 to 400 Gy. Similarly, the effectiveness of ionizing radiation in improving seed germination in tree species, demonstrated by Iglesias-Andreu *et al.* (2012), aligns with our study's results. Kovacs and Keresztes (2002) reported that gamma radiation tends to increase seed germination by breaking dormancy, enhancing enzyme activity, and promoting cellular division and growth.

The current study suggests that the selecting wheat cultivars with natural resistance, like Bakhtawar-92, can help to reduce *S. granarius* populations. Cultivars like Lalma and Bathoor, which shows higher susceptibility, should be monitored closely. Additionally, managing initial population densities through regular inspections and prompt interventions can minimize pest emergence, food consumption, and progeny production, ultimately protecting stored wheat. Gamma irradiations effectively controls *S. granarius*, with doses between 250 Gy and 350 Gy resulting in significant mortality without affecting seed germination. Higher doses lead to faster mortality, while lower doses are suitable for moderate infestations, making gamma irradiation a promising supplementary pest control method for stored wheat. The use of mixed age and sex adult populations as well as the biochemical composition of wheat grains in the current study may have influenced the biological parameters of *S. granarius*. Future studies should aim to control these factors during experimentation to enhance the precision of evaluating wheat resistance and effectiveness of control measures.

CONCLUSION

The insect population densities and different types of wheat cultivars affects the key biological parameters of *S. granarius*. Moreover, the results emphasize the dose-dependent nature of gamma irradiation's effects on *S. granarius* mortality rates. Higher doses lead to quicker mortality, while lower doses require more time for the same effect to occur. The findings of this study enrich our understanding of the biological parameters of *S. granarius*, offering valuable insights to mitigate prevailing losses and thereby fostering the safety and improving the quality of stored wheat.

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IRB approval

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Generative AI or AI-assisted technology statement

The authors declare that no Generative AI was used in the creation of this manuscript.

Statement of conflict of interest

The authors have declared no conflict of interest.

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