J. Entomol. Res. Soc., 25(3): 579-599, 2023
Doi: 10.51963/jers.v25i3.2472

Research Article
Online ISSN:2651-3579

# Studies on Effect of Gamma Radiation on Biological Parameters and Male Sterility in Parental and F1 Generation of *Spodoptera frugiperda* (J.E. Smith)

Mohammad RAFI[1a] Gonchikara Siddanaa PANDURANGA[1*]
Tamminana RAJASEKHARAM[2] Karnam V. HARI PRASAD[1b]

[1]Department of Entomology, S. V. Agricultural College, ANGRAU, Tirupati - 517 502, INDIA
[2]Department of Pathology, Citrus Research Station, YSR Horticultural University, Tirupati - 517 502, INDIA

e-mails: [1a]rafimohammad.2314@gmail.com, [1*]gs.panduranga@angrau.ac.in, [2]trajasekharam@gmail.com, [1b]kv.hariprasad@angrau.ac.in

ORCID IDs: [1]0009-0008-8260-6765, [1*]0000-0001-5713-2010, [2]0009-0007-6165-1797, [1b]0000-0002-9680-0736

## ABSTRACT

The male pupae (7 days old) of fall armyworm, *Spodoptera frugiperda* were exposed to eight different doses of gamma radiation (25, 50, 75, 100, 125, 150, 175 and 200 Gy) using Co-60 source. Among the doses tested, a radiation dose of 100 Gy had induced >80.00% of sterility with least negative effects on adult emergence (71.00%), deformation (9.00%), adult longevity (6 days) and survival under food stress (59.00%) in parental generation. In F1 generation, larval duration was 23.67 days at 100 Gy compared to 20.33 days at unirradiated control. More than 50% of pupae (51.33%) were recovered with pupal weight of 1.51 g/10 pupae at 100 Gy. Emergence of F1 adult at 100 Gy was 66.23% with least percentage of deformation (12.60%) and F1 adults lived up to 5.55 days with 52.00% of survival under food stress. Biological parameters of F1 generation were severely affected at radiation doses ranging from 125 to 200 Gy. Percentage of male sterility was increased with increase in radiation doses. A radiation dose, 100 Gy has induced male sterility of 81.89% and 86.23% in parental and F1 generation with no deleterious effects on adult emergence, longevity, survival and other quality parameters of *Spodoptera frugiperda*.

*Key words:* Fall armyworm, gamma radiation, parental generation, F1 generation, biological parameter, male sterility.

Rafi, M., Panduranga, G.S., Rajasekharam, T., & Hari Prasad, K V. (2023). Studies on Effect of Gamma Radiation on Biological Parameters and Male Sterility in Parental and F1 Generation of *Spodoptera frugiperda* (J.E. Smith). *Journal of the Entomological Research Society*, 25(3), 579-599.

*Received: May 24 2023* *Accepted: October 02, 2023*

## INTRODUCTION

Maize *(Zea mays L.)* is the third most important cereal crop next to rice and wheat sharing about 2% of world's maize production. In India, the area under cultivation of maize is 9.9 million ha with an annual production of 23.10 million tonnes (Anonymous, 2022-23) contributing nearly 10% to the national food basket. Maize is used as a basic raw material in thousands of industrial products including starch, oil, protein, food sweeteners, cosmetics and pharmaceuticals.

Insect pests *viz.,* shoot fly, *Antherigona soccata* Rondani; corn aphid, *Rhopalosiphum maidis* (Fitch); stem borer, *Chilo partellus* (Swinhoe) and corn earworm, *Helicoverpa zea* (Boddie) are the most common pests in maize ecosystem. Recently In India, Fall armyworm (FAW), *Spodoptera frugiperda* (J.E. Smith) (Lepidoptera: Noctuidae) was first reported on maize in the Shivamogga district of Karnataka during May-June, 2018 by Sharanabasappa et al (2018) and most devastating invasive pest has become a major threat to maize cultivation in India (Suby et al, 2020).

Fall armyworm (FAW) is a serious pest of maize native to tropical and subtropical regions of America. It is also known to feed on more than 350 plant species belonging to cereals, millets, cotton and vegetables (Wan et al, 2021). Later in the year 2019, FAW was reported in Andhra Pradesh, Telangana, Maharastra, Tamil Nadu, Bihar, Chhattisgarh, Gujarat, Odisha, West Bengal and Madhya Pradesh (Vishwakarma, Pragya, Patidar, Das, & Nema, 2020). Its invasiveness is due to its wide host range, high dispersal ability, no diapause and high fecundity (Montezano et al, 2018). Warm and humid growing seasons with heavy rainfall favour its survival, population build up and insects cannot develop at temperature below 10°c (Stokstad, 2017). The female moth lays more than 1000 eggs in single or multiple clusters under the surface of leaf or on the stem. The eggs of *S. frugiperda* are creamy white and egg mass covered with an anal tuft of hairs. Sometimes female adult lays egg mass without hair covers. There are six instars with duration of 15 -19 days and extends up to 30 days during winter. The presence of white inverted "Y" shaped marking on the head region of mature larvae and the presence of four black dots in a square shape on the last abdominal segment are the distinctive features of FAW (Prasanna, Huesing, Eddy, & Peschke, 2018, Sharanabasappa et al, 2018b).

Fall armyworm attacks maize plants at all phases of crop development, but it is most common during the whorl stage, which lasts up to 45 days after sowing. Early instars feed by scraping and skeletonising the upper epidermis of leaves resulting in short pin holes (window pane) on leaves. The damage by the late instars ($4^{th}$ instar onwards) results in extensive defoliation of leaves and the presence of faecal pellets in whorls. Due to this pest, maize production in India reduced by 5-10% equivalent to 0.04 to 0.075million tonnes (Suby et al, 2020).

Farmers and commercial growers depend predominately on the use of synthetic insecticides for controlling this insect pest. The use of insecticides as a sole tool in the management of insect pests has potential drawbacks such as the development of insecticide resistance, persistence of pesticide residues on crop produce, outbreak of secondary insect pests and pest resurgence (Togbe, Zannou, Gbehounou, Kossou & Van Huis, 2014). Hence, it is necessary to explore other alternative methods that are ecologically safe.

SIT (Sterile Insect Technique) is a species specific, non-polluting and environmental friendly method of insect control that relies on mass production and sterilization of target insects by radiation and systematic release of sterile males into the target environment to induce sterility in a wild population (Knipling, 1979). It is a method of pest control that uses radiation to generate mutations or chromosomal abnormalities in germ cells, resulting in reproductively sterile adult insects (Reichard, 2002).This technique is successfully used against several insect pests including Mediterranean fruit fly, *Ceratitis capitata* (Wiedemann) in Chile and Peru regions during 1995; Melon fly, *Bactrocera cucurbitae* (Coquilett) in Japan during 1993; Mexican fruit fly, *Anastrepha ludens* (Loew) in southern California and northern Mexico during 1964; Pink bollworm,*Pectinophora gossypiella* (Saunders) in south western USA and northwestern Mexico; Codling moth,*Cydia pomonella* (Linnaeus) in Columbia and Tsetse fly,*Glossina austeni* Newstead in Zanzibar during 1998 (Hendrichs,Vreysen, Enkerlin, & Cayol, 2005).

Determination of the optimum dose of gamma radiation for male sterilization without compromising the quality of adults in terms of adult emergence, adult longevity and survival of sterile males is crucial in the successful application of SIT. Because, high doses of radiation increase the sterility but decrease the mating competitiveness of sterile males. Whereas lower doses may not induce enough sterility (Calkins and Parker, 2005; Collins, Weldon, Banos, & Taylor, 2008). To induce the desired level of sterility with the least negative impacts on sexual performance of sterile insects, the radiation dose must be optimized. An optimum dose of gamma radiation should not interfere with the ability of sterile males to compete with wild males for their wild female mates in the released Environment (Dyck, Hendrichs, & Robinson, 2005). Hence the quality of sterile males must be assessed by studying the effects of gamma radiation on quality parameters *viz.,* adult emergence, adult longevity and survival under food stress which primarily reflects the male's ability to survive, interact with its environment, locate, mate and fertilize females of target wild populations (Collins, Weldon, Banos, & Taylor, 2009).

## MATERIALS AND METHODS

The studies on the effect of different doses of gamma radiation on biological parameters of Fall armyworm, *Spodoptera frugiperda* were conducted during 2021-22 at Insectary, Department of Entomology, Sri Venkateswara Agricultural College, Acharya N.G. Ranga Agricultural University, Andhra Pradesh, India.

### Maintenance of Fall armyworm culture

The initial culture of FAW was obtained by collecting egg masses and early instar larvae from farmer's fields and the College farm of S.V. Agricultural College, Tirupati, Andhra Pradesh. Hatched neonates and early instars of FAW were inoculated on artificial diet (Barreto, Loguercio, Valicente & Paiva, 1999) and accessed to feed on artificial diet up to second instar stage. The third instar larvae were reared individually in a separate plastic cell of diet tray to avoid cannibalism. Fresh diet was provided as and when required for the developing caterpillars of FAW till pupation. Pupae were collected and transferred to adult rearing cages (30×30×30 cm) for adult emergence. Male and female adult moths were collected and confined to cages (30×30×30 cm) provided with 10% honey solution (cotton swabs) as an adult diet and water-soaked cotton swabs in 100 ml conical flasks as a source of water. Potted corn plants of 4-5 leaf stage were provided as oviposition substrate for collection of egg mass. Egg masses were collected and placed on clean and disinfected corn leaves for hatching. Hatched neonates were transferred to artificial diet.

## Exposure of pupae to gamma radiation

Pupae required for irradiation were obtained by rearing the larvae on artificial diet. Male and female pupae were differentiated by observing the distance between the genital opening and anal slit (Figure 1. a, b). The distance between genital opening and anal slit is more in females. The male pupae of 7-days old were taken in plastic petri plates provided with blotting paper at the base and the inner sides were lined with non-absorbent cotton to avoid damage to the pupae. Petri plates containing male pupae (50 pupae for each replication and each treatment replicated thrice) were exposed to gamma radiation (Cobalt-60 source) at 25, 50, 75, 100, 125, 150, 175 and 200 Gy using a gamma chamber (Table 1) at IIHR, Bengaluru, Karnataka, India (Figure 1. c, d).

Table 1. Specifications of gamma chamber used for irradiation of fall armyworm (*Spodoptera frugiperda*) pupae.

| S. No. | Specifications | Capacity |
|---|---|---|
| 1 | Model | GC-5000, BRIT and AERB |
| 2 | Maximum Co-60 source capacity | 518 TBq (14000 ci) |
| 3 | Discharge rate | 9 KGy/hr |
| 4 | Irradiation volume | 5000cc |
| 5 | Size of sample chamber | 17.2cm (dia) 20.5cm(ht) |
| 6 | Shielding material | Lead and stainless steel |
| 7 | Weight of the unit | 5600kg |
| 8 | Size of the unit | 17.2cm(dia) 106.5cm(w) 150cm(ht) |
| 9 | Timer range | 6 seconds onwards |


Figure 1. a) Female pupa, b) Male pupa, c) Pupae sampled for irradiation, d) Gamma chamber used for irradiation (as. anal slit, gp. genital pore)

**Recording of quality parameters of parental generation**

Male pupae after exposure to different doses of gamma radiation were brought to the Insectary and confined to adult rearing cages. The quality parameter tests viz., adult emergence (%), deformation (%), survival under food stress (%) and adult longevity (days) and of parental generation were recorded.

Adult emergence (%): Fifty irradiated male pupae from each dose were taken in a glass Petri dish and kept in an adult emergence cage provided with 10% honey solution. After the complete ceasing of adult emergence (up to 5 days from the day of emergence), the number of adults emerged out of 50 pupae were worked out and expressed in percentage. Fifty unirradiated male pupae were also maintained as control and a similar procedure was followed.

$$\text{Adult emergence (\%)} \frac{\text{Number of adults emerged}}{\text{Total number of pupae kept for adult emergence}} \text{X100}$$

Deformation (%): After the complete ceasing of adult emergence, the number of deformed pupae, partially emerged adults and deformed moths with defective wings and other appendages were recorded and expressed as per cent deformation.

Adult longevity of irradiated males (Days): It was conducted by confining freshly emerged moths to adult rearing cages provided with an adult diet. Cages were checked for adult mortality and the average longevity of adult moths was worked out and expressed in days.

Survival under food stress (%): This experiment was conducted by confining 10 freshly emerged adult male moths from irradiated pupae into separate adult rearing cages without adult diet and water. The number of moths that were survived after 48 hrs of commencement of test was recorded and expressed as per cent survival under food stress.

**Recording of quality parameters of F1 generation**

Freshly emerged irradiated males (IM) are confined with unirradiated females (UF) in 1:1 ratio (10UF×10IM) into cages (30×30×30 cm) provided with 10% honey solution soaked cotton swabs. After 2 days, potted corn plants (4-5 leaf stage) were provided for oviposition. Egg masses from each cross were collected daily and hatched neonates were inoculated onto the artificial diet. Quality parameters of F1 generation viz., larval duration (days), pupal recovery (%), pupal weight (gm/10 pupae), adult emergence (%), sex ratio, adult longevity (days) and survival under food stress (%) of F1 generation were recorded as follows;

Larval duration (Days): Eggs laid by females that were mated with irradiated males were allowed for hatching. After hatching the neonates were inoculated on larval artificial diet. Larval duration represents the period between egg hatching and initiation of pupation.

Pupal recovery (%): Pupal recovery was calculated by dividing the number of pupae produced by the total number of neonate larvae inoculated onto the artificial diet and expressed in per cent.

Pupal weight: It is the weight of 10 pupae resulted from the cross between irradiated males and unirradiated females.

Sex ratio: It is measured as number of males to females. Sexing was done during pupal stage based on distance between genital pore and anal slit. In females, the distance between genital pore and anal slit is more compared to males.

Other parameters viz., adult emergence, deformation, adult longevity and survival under food stress of $F_1$ generation were recorded by following the procedure followed for recording the quality parameters of parental generation.

## Male sterility in parental and F1 generation of Fall armyworm

Male pupae of 7 days old (48 hrs. before adult emergence) were exposed to gamma radiation at 25, 50, 75, 100, 125, 150, 175 and 200 Gy using gamma chamber at IIHR, Bengaluru, Karnataka, India.

Irradiated males(IM) from each dose were confined with an equal number of unirradiated females(UF) (10UF×10IM) of the same age into cages (30×30×30cm) provided with potted corn plants for oviposition. Eggs from each cage were sampled and inoculated on corn leaves held in Petri dishes. After 5 days of inoculation, the number of unhatched eggs and hatched larvae were counted. Similar procedure was followed for control using unirradiated males (UM) and unirradiated females (UF) of same age (10UF×10UM). The percentage of sterility was calculated by using the following formula (Toppozada, Abdallah, & Eldefrawi, 1966);

$$\text{Male sterility}(\%)=100-\left(\frac{a\times b}{A\times B}\right)\times 100$$

Where,

a = Number of eggs/female in treatment

b = Percent egg hatch in treatment

A= Number of eggs/female in control

B= Per cent egg hatch in control

(Where; treatment refers to mating between unirradiated females and irradiated males. Control refers to mating between unirradiated females and unirradiated males).

Corrected Sterility was computed according to the formula given by Seth and Reynolds (1993).

$$\%\ \text{Corrected sterility} = \frac{F_c - F_t}{F_t}\times 100$$

Where, $F_c$ = % egg hatch in control; $F_t$ = % egg hatch in treatment.

## Statistical Analysis

Data collected on quality parameters and male sterility were subjected to ANOVA using Honestly Significant Differences (HSD) values calculated as Tukey Statistics at α = 0.05 using SPSS Software version 20 available at Department of Statistics and Computer Applications, S.V. Agricultural College, Tirupati, Acharya N.G. Ranga

Agricultural University, Andhra Pradesh, India. The mean of three replications for each parameter was separated by using HSD -Tukey test (α = 0.05) SPSS Software version 20.

## RESULTS

The significant differences among the different doses of gamma radiation on quality parameters of parental generation of Fall armyworm, *Spodoptera frugiperda* are presented in table 2. The percentage of adult emergence from the irradiated pupae was decreased with an increase in gamma radiation doses. Emergence of *Spodoptera frugiperda* adult at different doses (25 Gy to 200 Gy) ranged from 83.13% to 20.30%. The percentage of adult emergence at 25 Gy (83.13%) was statistically on par with the control (88.00%). Adult emergence at 50 Gy and 75 Gy are 79.46% and 75.90 %, respectively and were significantly different from control. 71.00% of adults were emerged from pupae irradiated at 100 Gy. But further increase in radiation dose (at 100 Gy onwards) has significantly declined the adult emergence to 58.70%, 36.30%, 27.00% and 20.30% at 125, 150, 175 and 200Gy, respectively (Table 2).

Table 2. Effect of gamma radiation on biological parameters of parental generation of fall armyworm, *Spodoptera frugiperda*.

| Radiation dose (Gy) | Adult Emergence (%)* | Deformed adults (%)* | Adult longevity (Days)** | Survival under food stress (%)* |
|---|---|---|---|---|
| 0 (Control) | 88.00[a] (69.74±1.02) | 3.00[e] (9.87±0.98) | 9.00[a] (3.16±0.09) | 76.20[a] (60.78±0.38) |
| 25 | 83.13[ab] (65.74±0.79) | 4.10[e] (11.53±1.32) | 8.67[a] (3.10±0.05) | 72.33[b] (58.24±0.21) |
| 50 | 79.46[bc] (63.05±1.07) | 5.00[de] (12.87±0.76) | 8.33[a] (3.05±0.04) | 67.50c (55.26±1.63) |
| 75 | 75.90[cd] (60.59±1.02) | 7.50[de] (15.78±1.35) | 7.50a (2.90±0.13) | 61.00[d] (51.34±0.34) |
| 100 | 71.00[d] (57.41±1.09) | 9.00[d] (17.43±0.57) | 6.00[b] (2.64±0.10) | 59.00[d] (50.16±0.37) |
| 125 | 58.70[e] (50.00±1.53) | 13.80[c] (21.73±1.29) | 5.00[bc] (2.44±0.00) | 47.00[e] (43.26±0.66) |
| 150 | 36.30[f] (36.99±1.99) | 17.00[c] (24.29±1.18) | 4.33[c] (2.30±0.15) | 41.00[f] (39.80±0.67) |
| 175 | 27.00[g] (31.25±1.49) | 27.20[b] (31.39±1.29) | 3.67[cd] (2.15±0.07) | 26.80[g] (31.15±0.93) |
| 200 | 20.30[h] (26.71±1.46) | 35.90[a] (36.77±1.52) | 2.50[d] (1.86±0.07) | 21.50[h] ( 27.61±0.54) |
| ANOVA | F=144.28; df=8,18; C.D.= 3.96; P<0.01 | F=60.98; df=8,18; C.D.=3.54; P<0.01 | F=24.84; df=8,18; C.D.=0.29; P<0.01 | F=242.02; df=8,18; C.D.= 2.26; P<0.01 |

Within a column, means followed by the same letter are not significantly different (α = 0.05), (Honestly significant difference (HSD) Tukey's statistics at α = 0.05 using SPSS software version 20). Figures in the parenthesis are transformed values ± standard errors. *Arc sine transformation; ** Square root transformation.

Deformation includes deformed pupae/adults, partially emerged adults, adults with defective wings, legs and other appendages as a result of exposure to gamma radiation (Fig. 2). The formation of deformed pupae/adults ranged from 4.10 to 9.00% at radiation doses ranging from 25 to 100 Gy. Percentages of deformation at 25, 50 and 75 Gy were statistically on par with control. Deformation at 100 Gy (9.00%) was on par with radiation doses ranging from 25 to 75 Gy. The percentage of deformation was increased with increase in gamma radiation doses at 125 (13.80%), 150 (17.00%), 175 Gy (27.20%) and 200 Gy (35.90%), respectively.


Figure 2. Deformation of fall armyworm due to irradiation of male pupae at 125, 150, 175 and 200 Gy.

Longevity is the duration of irradiated males survived provided with an adult diet and water. Adult longevity of unirradiated males was 9 days. The longevity period decreased with an increase in radiation dose. The longevity of adult moths from the pupae irradiated at 25, 50 and 75 Gy was 8.67, 8.33 and 7.5 days respectively and on par with control. The longevity of irradiated males at 100 and 125 Gy was 6.00 and 5.00 days, respectively, which are on par with each other. Whereas males irradiated at 150, 175 and 200 Gy lived up to 4.33, 3.67 and 2.50 days respectively. Adult longevity of male moths was reduced by 50% at higher doses of 150 Gy onwards.

Males exposed to gamma radiation showed an inverse relationship between the percentage of survival under food stress and radiation doses. At 25 and 50 Gy, survival rates were 72.33% and 67.50%, respectively and were significantly different from the control (76.20%). No significant difference was found at 75Gy and 100 Gy with survival rates of 61% and 59%, respectively. Percentage of survival of male moths from the pupae irradiated at 125, 150, 175 and 200 Gy significantly reduced to 47.00%, 41.00%, 26.80% and 21.50% respectively.

It was found that radiation doses (up to 100 Gy) had least negative impacts on quality parameters of male moths. Whereas at radiation doses ranging from 125 to 200 Gy, the Quality parameters such as adult emergence, deformation, adult longevity and survival under food stress were severely affected.

Effect of gamma radiation on quality parameters in F1 generation of *Spodoptera frugiperda* are presented in table 3. Larval period had a positive relationship with the increasing doses of gamma radiation. Larval duration at 25, 50 and 75 Gy was 20.67, 21.33 and 22.50 days respectively, which are statistically on par with the control (20.33 days). Larval duration at 100(23.67 days) and 125 Gy (25.17 days) were statistically on par with each other. Larval duration significantly increased from 26.50 to 28.33 days at radiation doses ranging from 150 to 200 Gy, when compared to remaining doses (25-75 Gy). Larval duration was prolonged to 5-8 days at higher doses from 125 Gy onwards compared to control (Table 3).

The percentage of pupal recovery from larvae resulted from cross between unirradiated females and irradiated males decreased with increasing doses of gamma radiation. Pupal recovery at 25 Gy was 73.30% and on par with control (81.52%). No significant difference was found at 50 and 75 Gy with pupal recovery of 67.42% and 58.53%, respectively. Pupal recovery at 100 Gy was 51.33%. Significant reduction in pupal recovery was recorded at 125, 150, 175 and 200 Gy with 39.27%, 30%, 23.33 and 15.27% respectively.

Pupal weight decreased with increasing doses of gamma radiation. Pupal weight at 25 Gy was 2.03 gm and statistically on par with control (2.11 gm). At gamma radiation doses of 50 and 75 Gy, pupal weight was 1.90 and 1.86 gm and statistically on par and significantly different from control. Pupal weight at 100 Gy was 1.72 gm which slightly decreased from 75 Gy. A drastic decreasing trend was recorded at 125, 150, 175 and 200 Gy with 1.51, 1.25, 1.02 and 0.89 gm respectively and was statistically different.

Table 3. Effect of gamma radiation on biological parameters of F1 generation of fall armyworm, *Spodoptera frugiperda.*

| Radiation dose (Gy) | Larval duration (days)** | Pupal recovery (%)* | Pupal weight (gm/10 pupae)** | Adult emergence (%)* | Deformation (%)* | Adult longevity (days)** | Survival under food stress (%)* | Sex ratio (female: male) |
|---|---|---|---|---|---|---|---|---|
| 0 (Control) | 20.33[e] (4.62±0.09) | 81.52[a] (64.57±1.46) | 2.11[a] (1.76±0.003) | 84.35[a] (66.72±1.27) | 3.87[g] (11.32±0.53) | 8.50[a] (3.08±0.00) | 80.00[a] (63.41±0.00) | 1:0.85 |
| 25 | 20.67[e] (4.65±0.13) | 73.30[ab] (58.93±1.88) | 2.03[a] (1.74±0.01) | 80.47[a] (63.81±1.53) | 7.65[f] (16.04±0.37) | 7.67[ab] (2.94±0.07) | 70.00[b] (56.82±1.81) | 1:0.88 |
| 50 | 21.33[e] (4.72±0.09) | 67.42[bc] (55.18±0.66) | 1.90[b] (1.70±0.01) | 78.94[a] (62.68±0.79) | 7.79[f] (16.17±0.67) | 7.17[b] (2.85±0.07) | 63.33[bc] (52.75±2.00) | 1:0.96 |
| 75 | 22.50[de] (4.84±0.07) | 58.53[cd] (49.90±0.95) | 1.86[b] (1.69±0.01) | 72.87[b] (58.65±1.98) | 10.12[ef] (18.54±0.29) | 6.83[b] (2.79±0.07) | 60.00[c] (50.80±2.90) | 1:1.04 |
| 100 | 23.67[cd] (4.97±0.03) | 51.33[d] (45.74±4.71) | 1.72[c] (1.64±0.009) | 66.23[c] (54.47±1.28) | 12.60[e] (20.74±1.02) | 5.55[c] (2.55±0.00) | 52.00[d] (46.13±0.66) | 1:1.12 |
| 125 | 25.17[bc] (5.11±0.05) | 39.27[e] (38.73±2.53) | 1.51[d] (1.58±0.007) | 48.17[d] (43.93±0.56) | 23.22[d] (28.76±1.19) | 4.16[d] (2.27±0.03) | 38.89[e] (38.56±0.32) | 1:1.13 |
| 150 | 26.50[ab] (5.24±0.02) | 30.00[ef] (33.19±0.72) | 1.25[e] (1.50±0.01) | 40.26[e] (39.36±0.44) | 30.55[c] (33.53±0.95) | 3.83[de] (2.19±0.03) | 33.33[e] (35.25±0.50) | 1:1.16 |
| 175 | 27.67[a] (5.35±0.03) | 23.33f[g] (28.77±2.21) | 1.02[f] (1.42±0.01) | 27.67[f] (31.67±1.68) | 45.67[b] (42.49±0.38) | 3.00[e] (1.99±0.07) | 18.00[f] (25.07±0.86) | 1:1.18 |
| 200 | 28.33[a] (5.41±0.08) | 15.27[g] (22.88±1.85) | 0.89[g] (1.37±0.02) | 16.67[g] (24.07±0.68) | 50.00[a] (44.98±0.00) | 2.00[f] (1.73±0.00) | 10.67[g] (18.91±1.80) | 1:1.21 |
| ANOVA | F=15.66; df=8,18; C.D.=0.23; P<0.01 | F=80.39; df=8,18; C.D.= 4.76; P<0.01 | F=115.39; f=8,18; C.D.=0.04; P<0.01 | F=151.40; df=8,18; C.D.=3.73; P<0.01 | F=298.16; df=8,18; C.D.=2.17; P<0.01 | F=75.83; df=8,18; C.D.=0.16; P<0.01 | F=96.05; df=8,18; C.D.=4.52; P<0.01 | – |

Within a column, means followed by the same letter are not significantly different (α = 0.05) using Honestly significant difference (HSD) Tukey's statistics at α = 0.05 using SPSS software version 20. Figures in the parenthesis are transformed values ± standard errors. *Arc sine transformation; ** Square root transformation.

Production of females in F1 generation were more (1:0.85) in unirradiated control (UF×UM). Similar trend was observed at 25 and 50 Gy with sex ratio (female to male) of 1:0.88 and 1:0.96. As the radiation dose increased from 75 to 200 Gy, the sex ratio was slightly shifted in favour of males.

The percentage of adult emergence of *Spodoptera frugiperda* from pupae resulted from the cross between unirradiated females and irradiated males decreased with an increase in gamma radiation doses. These values were recorded as 80.47% and 78.94% at 25 and 50 Gy, respectively and were statistically on par with the control (84.35%). But, the adult emergence at 75 Gy (72.87%) and 100 Gy (66.23%) were statistically different from control. Further increase in radiation doses, adult emergence was declined to 48.17% (125 Gy), 40.26% (150 Gy), 27.67% (175 Gy) and 16.67% (200 Gy), respectively. Adult emergence was severely affected and decreased by <50% at 150 Gy onwards, when compared to control.

The percentage of deformation ranged between 7.65-10.12% at doses ranging from 25-75 Gy, which were statistically on par with control. Deformation at 100 Gy was 12.60 and statistically different from the control. The percentage of emergence of defective adults with deformation was significantly high at 125, 150, 175 and 200 Gy and was recorded as 23.22, 30.55, 45.67 and 50.00%, respectively compared to the remaining doses.

The longevity of adults from the pupae irradiated at 25 Gy was 7.67 days and on par with control (8.5 days). Radiation doses; 50 and 75 Gy showed no significant differences in adult longevity with 7.17 and 6.83 days, respectively. The longevity of irradiated males at 100 Gy was 5.55 days. Adult longevity period of male moths reduced to 4.16 and 3.83 days at 125 and 150 Gy, respectively. Adult longevity decreased significantly at 175 and 200 Gy with 3.00 and 2.00 days, respectively.

There was an inverse relationship between the percentage of survival and radiation doses. Survival of unirradiated males was 80%. Percentage of adult survival at 50 Gy (63.33%) was on par with 25 Gy (70%). No significant difference was observed in survival rate at 75 Gy (60.00%), which is statistically on par with 50Gy (63.33%). At 100 Gy, more than 50% of adults survived (52.00%) without an adult diet and water. A sudden decreasing trend of adult survival under food stress was recorded at 125 and 150 Gy with 38.89% and 33.33%, respectively. Adult survival was severely affected at 175 and 200 Gy with least survival rates of 18.00 and 10.67%, respectively.

Effect of gamma radiation on fecundity and male sterility in the parental generation of *Spodoptera frugiperda* among the different doses of gamma radiation were presented in table 4. Fecundity was decreased with increasing doses of gamma radiation. Radiation doses; 50, 75 and 100 Gy decreased the fecundity to 155.06, 131.50 and 118.67 eggs/female/day, respectively, and were significantly different from control (202.33 eggs/female/day). The fecundity of females that were mated with irradiated males of 125, 150, 175 and 200 Gy was significantly impaired with mean fecundity of 80.00, 53.67, 41.00 and 28.00 eggs/female/day, respectively (Table 4).

The percentage of male sterility had an inverse relationship with increasing doses of gamma radiation. The percentage sterility from the unirradiated females mated with irradiated males at 25 Gy was 14.25%. Further, increase in radiation doses to 50 and 75 Gy, sterility percentage was also increased to 36.51%and 64.89%, respectively and they were significantly different from 25 Gy. More than 80% sterility was obtained at 100 Gy (81.89%). Male sterility was higher when unirradiated females crossed with males irradiated at 125, 150,175 and 200 Gy with sterility percentages of 91.58%, 96.81%, 98.52% and 99.25% respectively. The percentage of sterility significantly increased at radiation doses ranging from 100-200 Gy (Table 4).

Table 4. Effect of gamma radiation on fecundity and male sterility of parental generation of fall armyworm, *Spodoptera frugiperda*.

| Radiation dose (Gy) | Fecundity** | Egg hatch (%)* | Male Sterility (%)* | Corrected Sterility (%)* |
|---|---|---|---|---|
| 0 (Control) | 202.33[a] (14.26±0.19) | 89.33[a] (70.98±1.28) | --- | --- |
| 25 | 189.00[b] (13.78±0.05) | 82.00[b] (64.88±0.74) | 14.25[g] (22.13±0.98) | 8.20[f] (16.57±1.14) |
| 50 | 155.06[c] (12.49±0.17) | 74.00[c] (59.33±0.75) | 36.51[f] (37.16±0.52) | 17.16[e] (24.43±0.98) |
| 75 | 131.50[d] (11.51±0.20) | 60.33[d] (50.94±0.52) | 64.89[e] (53.64±0.18) | 32.46[d] (34.71±0.61) |
| 100 | 118.67[e] (10.94±0.18) | 46.67[e] (43.06±1.71) | 81.89[d] (64.59±0.94) | 47.76[c] (43.69±1.90) |
| 125 | 80.00[f] (8.90±0.15) | 31.67[f] (34.22±0.74) | 91.58[c] (73.11±0.06) | 64.89[b] (53.65±0.88) |
| 150 | 53.67[g] (7.39±0.08) | 27.00[f] (31.29±0.37) | 96.81[b] (79.70±0.38) | 69.77[b] (56.62±0.40) |
| 175 | 41.00[h] (6.48±0.21) | 16.33[g] (23.72±1.84) | 98.52[ab] (83.02±0.54) | 81.72[a] (64.77±1.97) |
| 200 | 28.00[i] (5.37±0.27) | 12.00[g] (20.08±2.06) | 99.25[a] (85.05±0.57) | 86.57[a] (68.65±2.20) |
| ANOVA | F=335.30; df=8,18; C.D.=0.53; P<0.01 | F=211.93; df=8,18; C.D.=3.77; P<0.01 | F=1429.96; df=7,16; C.D.=1.84; P<0.01 | F=179.26; df=7,16; C.D.=4.28; P<0.01 |

Within a column, means followed by the same letter are not significantly different using Honestly significant difference (HSD) Tukey's statistic at α = 0.05 using SPSS software version 20. Figures in the parenthesis are transformed values ± standard errors.*Arc sine transformation; ** Square root transformation. Fecundity refers to eggs/female/day, confined with 10 Unirradiated Females×10 Irradiated Males in case of Treatment and 10 Unirradiated Females×10 Unirradiated Males in Control).

The present study found that a radiation dose of 100 Gy had induced 81.89% sterility with the least negative effects on adult emergence (71.00%), deformation (9%), adult longevity(6 days) and survival under food stress (59.00%). Based on these observations and comparison with all other doses of gamma radiation, a radiation dose of 100 Gy was found as suitable dose to induce enough sterility in the wild female population without affecting the biological parameters of irradiated males.

Effect of gamma radiation on fecundity and male sterility in the F1 generation of *Spodoptera frugiperda* among the different doses of gamma radiation were presented in table 5. Egg laying abilities of unirradiated females mated with irradiated males from the pupae irradiated at 25, 50, 75 and 100 Gy were significantly decreased with mean fecundity of 180.67, 150.33, 128 and 109.67 eggs/female/day, respectively, when compared to control (191.67 eggs/female/day). Further increase in radiation doses to 125, 150, 175 and 200 Gy resulted in a significant reduction of fecundity to 67.67, 43.33, 29.00 and 16.00 eggs/female/day, respectively and were statistically different (Table 5).

Table 5. Effect of gamma radiation on fecundity and male sterility of F1 generation of fall armyworm, *Spodoptera frugiperda*.

| Radiation dose (Gy) | Fecundity** | Egg hatch (%)* | Male Sterility (%)* | Corrected sterility (%)* |
|---|---|---|---|---|
| 0 (Control) | 191.67a (13.88±0.11) | 87.00a (69.46±4.02) | --- | --- |
| 25 | 180.67b (13.48±0.14) | 73.00b (58.69±0.98) | 20.62f (26.97±1.05) | 16.09g (23.58±1.35) |
| 50 | 150.33c (12.30±0.12) | 64.00c (53.13±1.38) | 42.19e (40.49±0.90) | 26.44f (30.87±1.73) |
| 75 | 128.00d (11.35±0.24) | 53.33d (46.90±1.95) | 67.19d (55.04±0.87) | 38.70e (38.40±2.31) |
| 100 | 109.67e (10.52±0.04) | 35.00e (36.22±1.93) | 86.23c (68.22±0.93) | 59.77d (50.64±2.16) |
| 125 | 67.67f (8.28±0.19) | 19.67f (26.28±1.05) | 95.21b (77.36±0.59) | 77.39c (61.62±1.15) |
| 150 | 43.33g (6.65±0.13) | 9.33g (17.62±1.80) | 99.03a (84.37±0.48) | 89.27b (71.02±1.94) |
| 175 | 29.00h (5.46±0.29) | 2.67gh (9.26±1.13) | 99.79a (87.45±0.48) | 96.93a (80.02±1.22) |
| 200 | 16.00i (4.09±0.36) | 0.00h (0.00±0.00) | 100a (90.00±0.00) | 100a (90.00±0.00) |
| ANOVA | F=308.46; df=8,18; C.D.=0.61; P<0.01 | F=156.76; df=8,18; C.D.=5.66; P<0.01 | F=988.11; df=7,16; C.D.=2.24; P<0.01 | F=213.98; df=7,16; C.D.=4.95; P<0.01 |

Within a column, means followed by the same letter are not significantly different using Honestly significant difference (HSD) Tukey's statistics at α = 0.05 using SPSS software version 20. Figures in the parenthesis are transformed values ± standard errors.*Arc sine transformation; **Square root transformation. Fecundity refers to eggs/female/day, confined with 10UF×10IM in case of Treatment and 10UF×10UM in Control

The percentage of inherited male sterility increased with increasing doses of gamma radiation. At a gamma radiation dose of 25 Gy, the percentage of male sterility was 20.62%. Further, increase in radiation doses to 50 and 75 Gy, percentage of sterility was also increased to 42.19% and 67.19%, respectively and they were significantly different from 25 Gy. At a gamma radiation dose of 100 Gy, the percentage sterility was recorded as 86.23%. Male sterility was higher when normal females crossed with males irradiated at 125, 150,175 and 200 Gy with sterility percentages of 95.21%, 99.03%, 99.79% and 100% respectively.

In the present study, it was found that inheritance of male sterility in F1 generation was more compared to the male sterility in parental generation. The gamma radiation dose of 100 Gy induced 86.23% sterility with the least negative effects on larval duration (23.67 days), pupal recovery (51.33%), pupal weight (1.72 gm/10 pupae), adult emergence (66.23%), deformation (12%), adult longevity (5.55 days) and survival under food stress (52.00%). Based on these observations and comparison with all other doses of gamma radiation, a radiation dose 100 Gy was found to be more desirable to induce enough sterility in the wild female population without affecting the biological parameters of irradiated males. It clearly indicated the increasing trends in inheritance of male sterility from parental generation to F1 generation through irradiated males of parental generation. Inheritance of male sterility from parental sterile males to F1 generation was more and increasing trend was observed with an incremental increase in gamma radiation dose by 25 Gy.

## CONCLUSIONS AND DISCUSSIONS

Exposure of mature pupae of *Spodoptera frugiperda* to gamma radiation (Co-60 source) at doses ranging from 25 to 100 Gy had least negative impacts on adult emergence and deformation. Further increase in radiation doses ranged between 125-200 Gy significantly decreased the adult emergence with increased percentage of deformation. Percentage of adult emergence was 71.00% at 100 Gy with deformation of 9.00%. Whereas further increase in radiation dose from 100 to 125 Gy; adult emergence was drastically reduced to 58.70% with increased percentage of deformation (13.80%). The present results could be due to the residual effects of high doses of gamma radiation (125-200 Gy) in parental and $F_1$ generations of FAW. The residual effects of gamma radiation were magnified in $F_1$ generation compared to parental generation. It could be due to the increased damage to the somatic cells at higher doses of gamma radiation (125 Gy onwards). Similar results were reported by Ibrahim & El-Naggar (2001) that irradiation of six-day old male pupae of *Spodoptera littoralis* at doses >100 Gy significantly decreased the adult emergence and adult emergence was completely ceased at 200 Gy. Boshra & Mikhaiel (2006) irradiation of male pupae of *Ephestia calidella* at 200, 400, 600 and 800 Gy of gamma radiation decreased adult emergence to 85.9, 68.8, 40% and 11.2% respectively. Similarly, Dhoubi & Abderrahmane (2002) reported only 6% of adult emergence at 500 Gy in *Ectomylois ceratoniae*. In the present study, radiation doses at 125 Gy onwards significantly increased the percentage of deformation in *Spodoptera frugiperda.* These results are corrobarated with earlier reports by Hasaballa, Ahmed, & Rizk (1985) in *Spodoptera littoralis* and reported that increasing doses of gamma radiation increased the percentage of deformation and complete lethality was observed at 350 and 400 Gy. The current findings are inclined with Seth et al (2020) who found that adult emergence of *Maruca vitrata* was severely affected at 150 and 200 Gy. No emergence of adult at 250 Gy. They also reported that percentage of malformed adults increased at 150 Gy (24.50%) and 200 Gy (100%). The present research results on effect of radiation doses ranging from 25 to 75 Gy has showed least negative impact on adult emergence of *Spodoptera frugiperda*. The similar findings are also reported by Abass, Salem, Abd-E-Hamid, Gabarty, & Embaby (2017) that radiation doses 25, 50 and 75 Gy resulted in adult emergence of 93.33, 81.88 and 75.35% respectively. Similarly, Ramesh, Garg, & Seth (2002) also reported that, radiation dose of 70 Gy had no negative impact on adult emergence (75.50%) of *Spodoptera litura.* Nearly 80% of Adult emergence was recorded in current studies which are on par with the findings of Arthur et al (2016), who reported 81.00% of adult emergence at 50 Gy in *Spodoptera frugiperda*. They also found that radiation dose of 200 Gy drastically affected the adult emergence and reduced to 10.00%. Pransopon, Sutantawong, & Hormchan (2000) found no significant differences in adult emergence and deformation at radiation doses 50-100 Gy in *Helicoverpa armigera*.

In the current study, the percentage of deformation was increased with increase in radiation doses at 150 and 200 Gy. These results are in agreement with Arthur et al (2013) who irradiated the pupae of *Spodoptera frugiperda* at 50, 100, 200 and

300 Gy and found least adult emergence (10.00%) at 200 Gy. Whereas at 300 Gy, eclosions of adults were completely ceased and they found that percentage of adult emergence at 50 Gy (81.00%) was on par with unirradiated control (85.00%).

The longevity of adults decreased as radiation dose increased. The present results on effect of gamma radiation on adult longevity and survival of FAW are on par with Seth et al. (2020) who reported that, longevity of irradiated males was sharply declined with increase in radiation doses from 150 to 250 Gy in *Maruca vitrata.* Similarly, Pransopon, Sutantawong, & Hormchan (2000) also found that higher doses of gamma radiation (150 Gy) significantly reduced the longevity of irradiated males from 13.35 days (Control) to 9.45 days (150 Gy) in *H. armigera.* Recently, Osouli, Ahmadi, & Kalantarian (2021) studied the radiation biology in *H. armigera* and found that longevity of adults decreased from 17.28 days (control) to 12.21 days (at 250 Gy). Ali, Rizwana, Ahmad, Hassan, & Ali (2014) also reported that unirradiated adults of *Pectinophora gossypiella* lived up to 11 days, whereas at 65 Gy, longevity of irradiated males decreased to 6.93 days.

Developmental period of larvae resulted from cross between normal females and parental males irradiated at doses ranging from 25 to 100 Gy prolonged the larval duration to 3 days. Whereas at radiation doses ranging from 125 to 200 Gy increased the larval duration from 5 to 8 days more, compared to unirradiated control. These results are on par with reports of Abass, Salem, Abd-E-Hamid, Gabarty, & Embaby, (2017) who reported slight increase in larval period at doses from 25 Gy (24.33 days) to 75 Gy (26.5 days), indicating that radiation doses up to 100 Gy were not had much negative impacts on larval development period. Larval period was increased with increasing radiation doses from 20.80 days (unirradiated control) to 27.2 days (at 175 Gy) in *Spodoptera frugiperda* (Arthur & Aguiler, 2002). Sayed & El-Helay (2018) also reported that larval duration of *S. littoralis* increased to 15.10 days at 100 Gy, compared to unirradiated control (13.80 days), but further increase in radiation doses significantly increased the larval duration.

In the present study, gamma radiation doses showed significant variation in pupal recovery. At 100 Gy, percentage of pupal recovery was 51.33%, further increase in radiation doses from 100 to 125 Gy reduced the pupal recovery to 39.27%. Pupal recovery was drastically affected at radiation doses ranged between 150 Gy (30.00%) to 200 Gy (15.27%). The present findings were inclined with the reports of Seth *et al*. (2020), in *Maruca vitrata* who found that percentage of pupal formation was decreased to 14.70% compared to 68.00% at 100 Gy. Pupal recovery of unirradiated control was 74.00%. Larval and pupal mortality were increased at 150 Gy onwards in *S. littoralis* (Abass, Salem, Abd-E-Hamid, Gabarty, & Embaby, 2017). Arthur, Arthur, & Machi (2016) also found drastic reduction in pupal formation of *S. frugiperda* at 200 Gy (30.00%) compared to control (95.00%), Whereas at 100 Gy, pupal recovery was 70.00%. It clearly indicates that radiation doses higher than 100 Gy had much negative effects on pupal recovery due to increased percentage of larval mortality.

Pupal weight at unirradiated control was 2.11 g/10 pupae. There was a sharp decline in pupal weight with increase in radiation doses from 50 Gy (1.90 g) to 100 Gy

(1.72 g). Pupal weight was significantly decreased at 125 Gy onwards from 1.51g/10 pupae (125 Gy) to 0.89 g/10 pupae (200 Gy). The similar results were reported by El-Naggar, Megahed, Sallam, & Ibrahim (1984) reported that the pupal weight was significantly decreased at radiation doses higher than 100 Gy in $F_1$ generation and radiation doses higher than 50 Gy in $F_2$ generation of *Agrotis ipsilon*.

There was no significant difference in adult emergence of $F_1$ generation at 25 and 50 Gy, compared to unirradiated control. A sharp decline in adult emergence was recorded at 75 and 100 Gy. Percentage of adult emergence at 100 Gy was 66.23% with least percentage of deformation (12.60%). Adult emergence was drastically decreased from 48.17% (125 Gy) to 16.67% (200 Gy) with increased percentage of deformation (23.22-50.00%), indicating that radiation doses that are higher than 100 Gy had much negative impacts on emergence of $F_1$ adults. These results are in line with Arthur, Arthur, & Machi (2016) who reported least percentage emergence of $F_1$ adults (10.00%) of *S. frugiperda* at 200 Gy. The similar results reported by Pransopon, Sutantawong, & Hormchan (2000) in *H. armigera* that radiation doses higher than 100 Gy significantly increased the emergence of deformed adults with decreased emergence of $F_1$ active moths. The present findings are very close with the reports of Carpenter, Young, Knipling, & Sparks (1986) that 58.00% of $F_1$ adults of *S. frugiperda* were emerged at 100 Gy, further increase in radiation dose to 150 Gy, decreased the adult emergence to 20.00% with increased percentage of deformation and adult mortality. Recently, Osouli, Ahmadi, & Kalantarian (2021) also found that radiation doses; 150 and 200 Gy decreased the percentage of $F_1$ adult emergence in *H. armigera.* Seth, Khan, Rao, & Zarin (2016) reported significant decrease in adult emergence with high rates of defective adults at 130 Gy compared to 100 Gy in $F_1$ generation of *Spodoptera litura*.

Longevity of irradiated adults of $F_1$ generation at radiation doses from 25 (7.67 days) to 75 Gy (6.83 days) was not significantly different. Percentage of survival of irradiated adults under food stress at 25 to 75 Gy was vary from 60.00% to 70.00%. Percentage of survival of irradiated adults at 100 Gy was 52.00%. Further increase in radiation doses from 125 to 200 Gy was ranged between 38.89-10.67%. For success of any SIT programme, minimum of 50% of irradiated males should survive under food stress for at least 48 hours, which reflects the ability of adults to survive in released environment. Sterile males must live for at least 6 days to meet the pre-mating period 2 days and mating period of 4 days, which allows the sterile males to copulate with wild females to induce sterility in wild population of target insect. Current findings are on par with the reports of Seth et al (2020), in *Maruca vitrata* who found that radiation dose, 100 Gy had not negative impact on longevity of $F_1$ adults (7.28 days). But radiation dose, 200 Gy has reduced the longevity by 3.65 days compared to 100 Gy. Osouli, Ahmadi, & Kalantarian (2021) also reported significant decrease in longevity adults of $F_1$ generation from 17.28 days (control) to 12.21 days (250 Gy) in *Helicoverpa armigera* due to increased rates of adult mortality at higher doses. Salem, Fouda, Abas, Ali, & Gabarty (2014) also reported high percentage of pupal (59.90%) and adult mortality (49.30%) at 150 Gy in $F_1$ generation of *Agrotis ipsilon*.

Ali, Rizwana, Ahmad, Hassan, & Ali (2014) reported significant decrease in longevity of irradiated males of *Pectinophora gossypiella* ($F_1$ generation) with incremented increase in gamma radiation doses.

There was no much differences in sex ratio among the radiation doses. The proportion of females were high in unirradiated control (1:0.85 F:M). Radiation doses up to 75 Gy had not showed many differences in sex ratio of females to males. Comparatively high number of males were formed at radiation doses ranging from 100 to 200 Gy with female to male sex ratio of 1:1.12 - 1:1.21. These results were similar with the reports of Seth et al (2020) in *Maruca vitrata*, that female to male sex ratio at 100, 150 and 200 Gy was 0.79:1, 0.71:1 and 0.58:1, respectively. Whereas in unirradiated control female to male sex ratio was 1.03:1. Similar results were reported by Abass, Salem, Abd-E-Hamid, Gabarty, & Embaby (2017) who found high number of males (50) out of 100 pupae at 75 Gy compared to control (51 females and 49 males) in *Spodoptera littoralis*.

Lepidopteran species are more resistant to the sterilizing effects of radiation than insects of any other order (Lachance, 1985). As a consequence, the greater amount of radiation required to achieve full sterility in males may reduce their competitiveness and performance in the field (Suckling, Hackett, Barrington, & Daly. 2002). One approach to reducing these negative effects is the use of inherited sterility or F1 sterility (Carpenter, Bloem, & Bloem. 2001).

The present investigations were conducted on parental and F1 sterility of Fall armyworm and results are discussed here with appropriate literature on FAW and other related lepidopteran pests. Number of eggs laid by female and per cent egg hatch was significantly decreased as the gamma radiation dose was increased. At 100 Gy, the number of eggs laid by unirradiated females crossed with parental males emerged from irradiated pupae was 356 eggs/female and percentage of egg hatch was 46.67%. Whereas at 200 Gy the number of eggs laid by unirradiated females crossed with irradiated males was significantly reduced to 56.00 eggs and percentage of egg hatch was 12.00%. Therefore, the parental generation of *Spodoptera frugiperda* exhibited 81.89 and 99.25 percent sterility at 100 and 200 Gy, respectively. In the $F_1$ generation, at 100 Gy the total number of eggs and percentage of egg hatch was recorded as 329.00 eggs and 35.00% respectively. At 200 Gy total number of eggs laid and percentage of egg hatch was significantly reduced to 32.00 eggs and cent percent respectively. Therefore in $F_1$ generation, 86.23 and 100% sterility were recorded at 100 and 200 Gy, respectively. These results could be due to the increased damage to germ cells male gonads at higher doses of gamma radiation of 125 Gy onwards. Radiation induced germ cell damage could resulted in mutation in reproductive gonads of emerged male moths. These results are similar to Seth et al. (2020), who found that number of eggs laid /female and percent egg hatch in parental generation of *Maruca vitrata* was decreased as radiation dose increased. At 200 Gy the number of eggs laid/female was reduced to 99.3 eggs with egg hatch of 21.10%. They also found that 150 and 200 Gy as higher radiation doses in inducing male sterility. Further they found that radiation dose 200 Gy has induced 100 % sterility in $F_1$ generation.

In the present study; fecundity and fertility (egg hatch) were decreased with increase in radiation doses. Male sterility was increased with incremental increase in radiation doses. These trends were observed in both parental and $F_1$ generation of FAW. It was found that radiation doses higher than 100 Gy (*i.e.* 125, 150, 175 and 200 Gy) induced >90% of sterility both in parental and $F_1$ generation but these doses showed negative impacts on quality parameters of irradiated male moths of parental generation and also severely affected the biological parameters of $F_1$ generation.

In the current study, radiation dose 100 Gy was identified as optimum dose as it induced male sterility of 81.89% in parental and 86.23% in $F_1$ generation without any deleterious effects on adult emergence, adult longevity and survival which are directly related to mating ability of sterile males in inducing male sterility and its inheritance to subsequent generation. The progeny of irradiated males were more sterile than their male parents, this phenomenon has been accepted in several species of Lepidoptera. These results are in accordance with Abass, Salem, Abd-E-Hamid, Gabarty, & Embaby (2017) who found that radiation doses; 150, 200, 250 and 300 Gy had negative impacts on survival percentages of larvae, pupae and adults of $F_1$ generation of *Spodoptera littoralis.* They also found that 100 Gy has induced male sterility 64.30% without affecting the emergence of sterile males and their survival. Although male sterility of 90.11-94.60% was recorded at radiation doses 200-300 Gy, but they severely affected the adult emergence. Sallam, El-Shall, & Mohamed (2000) also reported that reproductive potential of irradiated males of *Earias insulana* decreased at 150 and 200 Gy. Salem, Fouda, Abas, Ali, & Gabarty (2014) tested the sub-sterilizing doses of 50, 100 and 150 Gy on full grown pupae of *Agrotis ipsilon* and found that percentage of larval and pupal mortality, larval and pupal durations increased at 150 Gy. These results are in line with Pransopon, Sutantawong, & Hormchan (2000) who studied the effect of radiation doses (50, 100, 150 and 200 Gy) on quality parameters and male sterility of *H. armigera* and found that percentage of male sterility increased with increase in radiation doses but radiation dose (150 and 200 Gy) significantly increased the percentage of deformation. $F_1$ progeny was more sterile than irradiated parental male in Diamondback moth, when male pupae irradiated at 50 to 250 Gy (Sutrisno, Hoedaya, Sutardji, & Rahaya, 1991). The present findings are on par with Arthur & Aguiler (2002) irradiated the male pupae of *Diatraea saccharalis* and *S. frugiperda* at gamma radiation doses of 50, 100, 125, 150 and 175 Gy. They found that percentage of male sterility in *D. saccharalis* at 100 Gy was 85.00%; whereas at 125 and 150 Gy, cent percent sterility was recorded. Percentage of inherited male sterility in $F_1$ generation was 95.70% at 100 Gy without affecting the longevity of sterile males. In *Spodoptera frugiperda* fecundity was decreased with increased doses of gamma radiation. Percentage of sterility was increased from 15.00% (50 Gy) to cent percent (200 Gy). Inheritance of male sterility at 100 Gy from parental males (sterile) to $F_1$ progeny was almost increased by 37.00% compared to parental generation. Inheritance of male sterility from $F_1$ to $F_2$ generation was decreased at all the radiation doses tested. They also reported 93-100% of male sterility at radiation doses 125-200 Gy in parental and $F_1$ generation of *Spodoptera frugiperda.* Arthur et al. (2013) also studied the effect of gamma radiation on quality parameters and male sterility of *S. frugiperda* at radiation doses vary from 50 to 300 Gy. Percentage of sterility was increased from 20% (at 50 Gy) to cent percent (at 200 and 300 Gy). 50% of male sterility was reported at 100 Gy without affecting the emergence of $F_1$ adults. Only 10% of adult emergence was recorded at 200 Gy. Further they concluded that radiation dose of 100 Gy was sterilizing dose to adults of Fall armyworm and 200- 300 Gy was the lethal dose and can be used for phytosanitary treatment of FAW. Osouli, Ahmadi & Kalantarian (2021) studied the radiation biology and inherited sterility in *H. armigera* and found that number of eggs laid per female and their hatchability declined with increase in radiation doses. Percentage of egg hatch was reduced from 90.70% (unirradiated control) to 49.50% (in parental generation) and 35.70% (in $F_1$ generation) at 100 Gy in *S.litura* (Seth, Khan, Rao, & Zarin, 2016).

The present findings are in line with Salem, Fouda, Abas, Ali, & Gabarty (2014) reported that fecundity and fertility were decreased with increase in radiation doses. At 100 Gy; 78% of male sterility was reported in parental generation of *Agrotis ipsilon.* Fecundity and egg hatch decreased from 106 eggs/female (control) to zero (65 Gy) and 80.57% to cent percent as the radiation doses increased from 35 Gy to 65 Gy in *Pectinophora gossypiella* (Ali, Rizwana, Ahmad, Hassan, & Ali, 2014). Recently, Sayed & El-Helay (2018) studied the effect of gamma radiation on *Spodoptera littoralis* at radiation doses of 40-100 Gy. Percentage of sterility was increased from 11.00% (unirradiated control) to 55.70% (100 Gy) and also suggested 100 Gy as suitable dose in inducing sterility. Larval and pupal duration were remain unaffected at 100 Gy. The present results with respect to inheritance of male sterility in *Spodoptera frugiperda* are in line with Rahman, Rahman, Islam, & Huque (2002) who found that sterility of $F_1$ generation of *Spilosoma obliqua* was increased compared to the parental generation. The sterility of $F_1$ generation was more i.e. 79% and 91% at 100 and 150 Gy respectively compared to 44 and 73% of parental sterility. Boshra & Mikhaiel (2006) also studied effect of gamma radiation on *Ephestia calidella* (Guenee) and found decrease in number of eggs/female from 256.5 eggs/female at 0 Gy to 66.6 eggs/female at 350 Gy. At a dose of 300 Gy, treated females were 100% sterile when mated with treated males. They also found that doses of 300 and 350 Gy led to the production of 83.9% and 90.2% sterile eggs, respectively.

The present research findings on radiation induced male sterility in parental and its inheritance to $F_1$ generation of *S. frugiperda*. Radiation dose; 100 Gy was the most appropriate dose in inducing 81.89% male sterility in parental and 86.23% of male sterility in $F_1$ generation without causing deleterious effects on quality of sterile male moths, which is very important for success of SIT programme.

## ACKNOWLEDGEMENT

The first author is thankful to Acharya N.G. Ranga Agricultural University, Guntur for providing fellowship and ICAR-Indian Institute of Horticultural Research. Bengaluru for radiation facility during my post-graduation.

## REFERENCES

Abass, A.A., Salem, H.M., Abd-E-Hamid, N.A., Gabarty, A., & Embaby, D.M. (2017). Effects of gamma irradiation on the biological activity of the cotton leaf worm, *Spodoptera littoralis* (Boisd.). *Journal of Nuclear Technology in Applied Science.* 5(10), 19-26.

Ali, S. S., Rizwana, H., Ahmad,S. S., Hassan, I., & Ali, S. S. (2014). Effects of Gamma Radiation on Mature Larvae of *Pectinophoragossypiella* (Saunders) and their $F_1$ Progeny. *Journal of Basic & Applied Sciences.* 10, 504-508.

Anonymous. (2022-23). Annual Report, 2022-23, Ministry of Agriculture and Farmers Welfare, Government of India. Available at https://agricoop.gov.in/.

Arthur, V. & Aguiler, J.A. (2002). The use of gamma radiation to control two serious pests of Brazilian Agriculture, *Diatraea saccharalis* and *Spodoptera frugiperda*. *Arab Journal of Nuclear Sciences and Applications*. 126(4), 85-92.

Arthur, V., Arthur, P.B., & Machi, A. R. (2016). Pupation, adult emergence and $F_1$ egg hatch after irradiation of *Spodoptera frugiperda* (Lepidoptera: Noctuidae) last instars. *Florida Entomologist*. 99(6), 59-61.

Arthur, V., Arthur, P.B., Franco, S.S.H., Silva, C.A.S., Machi, A.R., Franco, J.G., & Harder, M.N.C. (2013). Effects of gamma radiation on larvae of *Spodoptera frugiperda* (Lepidoptera: Noctuidae) Fall armyworm. *International Nuclear Atlantic Conference*. 24-29.

Barreto, M.R., Loguercio, L.L., Valicente, F.H., & Paiva, E. (1999). Insecticidal activity of culture supernatants from *Bacillus thuringiensis* Berliner strains against *Spodoptera frugiperda* Smith (Lepidoptera: Noctuidae) larvae. *Neotropical Entomology.*28(4), 675-685.

Boshra, S.A. & Mikhaiel, A.A. (2006). Effect of gamma irradiation on pupal stage of*Ephestiacalidella* (Guenee). *Journal of Stored Products Research.* 42, 457-467.

Calkins, C.O. & Parker, A.G. (2005). Sterile insect quality. In V.A. Dyck., J. Hendrichs and A.S. Robinson (eds.) *Sterile insect technique: principles and practice in area-wide integrated pest management*. Dordrecht, The Netherlands: Springer. 269-296.

Carpenter, J. E., Bloem, S., & Bloem, K. A. (2001). Inherited sterility in *Cactoblastis cactorum* (Lepidoptera: Pyralidae). *Florida Entomologist.* 88(1), 77-84.

Carpenter, J.E., Young, J.R., Knipling, E.F., & Sparks, A.N. (1986). Fall armyworm (Lepidoptera: Noctuidae): Inheritance of gamma-induced deleterious effects and potential for pest control. *Journal of Economic Entomology*. 76: 378-382.

Collins, S.R., Weldon, C.W., Banos, C., & Taylor, P.W. (2008). Effects of irradiation dose rate on quality and sterility of Queensland fruit fly, *Bactroceratryoni* (Froggatt). *Journal of Applied Entomology.* 132(5), 398-405.

Collins, S.R., Weldon, C.W., Banos. C., & Taylor, P.W. (2009). Optimising irradiation dose for sterility induction and quality of Queensland fruit flies, *Bactroceratryoni* (Froggatt). *Journal of Economic Entomology.* 102(5), 1791-1800.

Dhoubi, M.H. & Abderahmane, C.T. (2002). The effect of sub sterilizing doses of gamma radiation on the pupae of the Carob moth, *Ectomyeloisceratoniae* (Lepidoptera: Pyralidae). *International Atomic Energy Agency*. 43-48.

Dyck, V.A., Hendrichs, J., & Robinson, A.S. (2005). Sterile insect technique: principles and practice in area-wide integrated pest management. Dordrecht, The Netherlands: *Springer.* 787-790.

El-Naggar, M.M., Megahed, Sallam, H.A., & Ibrahim, S.M. (1984). Inherited sterility among *Agrotis ipsilon* laboratory population, exposed to gamma irradiations. *Insect Science and its Applications.* 5(6), 501-503.

Hasaballa, Z.A., Ahmed, M.Y., & Rizk, M.M. (1985). Effect of gamma radiation on the immature stages of *Corcyra cephalonica*. *Assuit Journal of Agricultural Sciences.* 16, 291-298.

Hendrichs, J., Vreysen, M.J.B., Enkerlin, W.R., & Cayol, J.P. (2005). Strategic options in using sterile insects for area-wide integrated pest management. In V.A. Dyck., J. Hendrichs and A.S. Robinson (eds.) *Sterile Insect Technique. Principles and Practice in Area-Wide Integrated Pest Management. Springer.* Dordrecht, The Netherlands. 563-600.

Ibrahim, S.M. & El-Naggar, E.M. (2001). Radiationinduced change in mating and reproductive potential of the cotton leafworm, *Spodoptera littoralis*(Boisd.). *Arab Journal of Nuclear Science and Applications*. 34(1), 245 -253.

Knipling, E.F. (1979). The Basic Principles of Insect Population Suppression and Management. U.S. Department of Agriculture. Agriculture Handbook. No. 512. Washington, D. C.

Lachance, L. E. (1985). Genetic methods for the control of lepidopteran species. *USDA Agriculture Research Service.* 28, 40.

Montezano, D.G., Specht, A., Sosa-Gomez, D.R., Roque-Specht, V.F., Sousa-Silva, J.C., Paula-Moraes, S.V., Peterson, J.A., & Hunt, T.E. (2018). Host Plants of *Spodoptera frugiperda* (Lepidoptera: Noctuidae) in the Americas. *African Entomology*. 26(2), 286-300.

Osouli, S., Ahmadi, M., & Kalantarian, N. (2021). Radiation biology and inherited sterility in *Helicoverpa armigera* (Hubner) (Lepidoptera:Nuctuidae). *International Journal of Tropical Insect Science*. 41, 2421–2429. doi:10.1007/s42690-020-00418-y.

Pransopon, P., Sutantawong, M., & Hormchan, P. (2000). Effects of gamma radiation on mature pupae of the cotton bollworm, *Helicoverpa armigera* (Hubner) and their F1 progeny. *Kasetsart Journal (Natural Sciences)*. 34(3), 401-407.

Prasanna, B.M., Huesing, J.E., Eddy, R., & Peschke, V.M. (2018). Fall armyworm in Africa: A guide for integrated pest management. *First Edition*. CIMMYT, Mexico. 1(7), 1-109.

Rahman, R., Rahman, M.M., Islam, S., & Huque, R. (2002). Observations on the growth parameters of *Spilosoma oblique* (Lepidoptera: Arctiidae) reared on artificial diets and reproductive competence of this irradiated pest and its progeny. *International Atomic Energy Agency*. 7235, 1011-4289.

Ramesh, K., Garg, K. A., & Seth, R. K. (2002). A interaction of sub-sterilizing dose gamma radiation and thiodicarb treatment for management of the tobacco caterpillar *Spodoptera litura*. *Phytoparasitica*. 30(1), 7-17.

Reichard, R.E. (2002). Area-wide biological control of disease vectors and agents affecting wildlife. *RevueScientifique Technique Office International des Epizooties.* 21(1), 179-185.

Salem, H. M., Fouda, M. A., Abas, A. A., Ali, W. M., & Gabarty, A. (2014). Effects of gamma irradiation on the development and reproduction of the greasy cutworm, *Agrotis ipsilon. Journalof Radiation Research and Applied Sciences.*7, 110-115.

Sallam, H.A., El-Shall, S.S.A., & Mohamed, H.F. (2000).Inherited sterility in progeny of gamma irradiated spiny bollworm, *Earias insulana*(Boisd). *Arab Journal of Nuclear Science and Appl*ications. 33(1), 263.

Sayed, W.A.A. & El-Helaly, A.M.A. (2018). Effect of gamma irradiation on thesusceptibility of the cotton leaf worm, *Spodoptera littoralis* (Boisd.) (Lepidoptera:Noctuidae) to the infectionwith nucleopolyhedrosis virus. *Egyptian Journal of Biological Pest Control*. 28, 73.

Seth, R.K. & Reynolds, S.E. (1993). Induction of inherited sterility in the tobacco hornworm, *Manduca sexta* (Lepidoptera: Sphingidae) by substerilizing doses of ionizing radiation. *Bulletin of Entomological Research.* 83, 227-235.

Seth, R.K., Khan, Z., Rao, D.K., & Zarin, M. (2016). Flight activity and mating behaviour of irradiated *Spodoptera litura* (Lepidoptera: Noctuidae) males and their $F_1$ progeny for use of inherited sterility in pest management approaches. *Florida Entomologist*. 99(1),119-130.

Seth, R.K., Patilb, B.V., Khana, Z., Zarina, M., Hanchinalb, S. G., Haverib, R. V., & Krishna, A.G. (2020). Radiation biology of a serious tropical pigeon pea pest, *Maruca vitrata* (Fabricius) (Lepidoptera: Crambidae) and potential of radiation mediated 'inherited ($F_1$) sterility technique' for the pest suppression. *International Journal of Radiation Biology*. 96(4), 532-544. doi:10.1080/09553002.2020.170.

Sharanabasappa, Kalleshwaraswamy, C.M., Asokan, R., Swamy, H.M.M., Maruthi, M.S., Pavithra, H.B., Kavita Hegde, Shivaray Navi, Prabhu, S.T., & Goergen, G. (2018). First report of the fall armyworm, *Spodoptera frugiperda* (J.E. Smith) (Lepidoptera: Noctuidae), an alien invasive pest on maize in India. *Pest Management in Horticultural Ecosystems*. 24(1), 23-29.

Stokstad, E. (2017). New crop pest takes Africa at lightning speed. *Science*. 356(6337), 473-474.

Suby, S.B., Soujanya, P.L., Yadava, P., Patil, J., Subaharan, K., Prasad, G.S., Babu, K.S., Jat, S.L., Yathish, K.R., Vadassery, J., Kalia, V.K., Bakthavatsalam, N., Shekhar, J.C., & Rakshit, S. (2020). Invasion of fall armyworm, *Spodoptera frugiperda* in India: Nature, distribution, management and potential impact. *Current Science*. 119(1), 44-51.

Suckling, D. M., Hackett, J. K., Barrington, A. M., & Daly, J. M. (2002). Sterilizations of painted apple moth *Teia anartoides* (Lepidoptera: Lymantridae) by irradiation. *New Zealand Plant Protection*. 55: 7-11.

Sutrisno, S., Hoedaya,M. S.,Sutardji, D., & Rahaya, A. (1991). Radiation induced $F_1$sterility in diamond back moth, *Plutella xylostella* L. and tropical army worm, *Spodoptera litura.* 23-36. In: Proc. Radiation Induced F1Sterility in Lepidoptera for Area – WideControl, Phoenix, Arizona.

Togbe, C.E., Zannou, E., Gbehounou, G., Kossou, D., & Van Huis, A. (2014). Field evaluation of the synergistic effects of neem oil with *Beauveria bassiana* (Hypocreales: Clavicipitaceae) and *Bacillus thuringiensis var. kurstaki* (Bacillales: Bacillaceae). *International Journal of Tropical Insect Science*. 34(4), 248-259.

Toppozada, A., Abdallah, S.A., & Eldefrawi, M.E. (1966). Chemosterilization of larvae and adult of the Egyptian cotton leafworm, *Spodoptera littoralis* by *Apholate, Metepa* and *tepa*. *Journal of Economic Entomology.* 59,1125.

Vishwakarma, R., Pragya, K., Patidar, S., Das, S.B., & Nema, A. (2020). First report of fall armyworm, *Spodoptera frugiperda* (J.E. Smith) (Lepidoptera: Noctuidae) on maize (*Zea mays*) from Madhya Pradesh, India. *Journal of Entomology and Zoology Studies.* 8(6), 819-823.

Wan, J., Cong, H., Chang-you, L., Hong-xu, Z., Yong-lin, R., Sheng, X.L., Bin, Z., Xi, Q., Qiang, W., Mckirdy, S., & Fang-hao, W. (2021). Biology, invasion and management of the agricultural invader: Fall armyworm, *Spodoptera frugiperda* (Lepidoptera: Noctuidae). *Journal of Integrative Agriculture*. 20(3), 646-663.