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Identification of effective *gamma* irradiation dose for the management of *Callosobruchus chinensis* L. infestations on stored chickpea

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Abstract
Chickpea is the leading pulse crop in terms of area and production in the Indian subcontinent. Bruchids (*Callosobruchus chinensis* L.) are the major biotic factor causing severe economic losses in stored chickpeas. They enter storage via several routes and hence, the proper disinfestation of bruchid infested grains is highly necessary before storage. The current study compared the efficacy of four *Gamma* irradiation doses (0.1, 0.2, 0.3, and 0.5 kGy based on Cobalt^{60} source) with the previously recommended phosphine fumigation dose and an untreated control. Among the irradiation doses, 0.2, 0.3, and 0.5 kGy completely eliminated all the infestation parameters; however, these doses proved lethal for seed germination. However, a dose of 0.1 kGy was found to be equally effective in reducing infestation parameters without having a lethal effect on seed germination. Apart from this, the percent reduction was better over grains exposed to recommended dosage of phosphine and untreated control. Hence, irradiation with 0.1 kGy would be the most effective, efficient, and cost-effective method of disinfesting bruchid-infested chickpea grains. This method would be a better combination before storing grains in modern packaging materials such as LDPE, HDPE, PPW, and PICS bags, as the initial elimination of infestation would prevent further perpetuation inside bags, as bruchid does not actively enter the bags by puncturing but rather passively enters through natural openings (gunny bags). The current findings would also provide an opportunity to identify the effective irradiation doses for the other major bruchid species that infest chickpea and other pulse crops.

Keywords: Bruchids, *C. chinensis*, phosphine, *Gamma* irradiation, storage

1. Introduction

Pulses are important crops for vegetarian population because they serve as cheapest source of proteins (20–25%) and other essential nutrients (Patterson *et al.* 2009) [15]. Furthermore, pulse root nodules contribute significantly to soil fertility enhancement through symbiotic nitrogen fixation (72–320 kg/ha/year) (Department of Pulses Development, 2018) [8]. Furthermore, crop residues contribute organic matter to soil fertility (Sardana *et al.*, 2010), and these crops can be effectively accommodated in a variety of cropping systems. India contributes one-third of the world's pulse production. During 2021-22, the country produced a record amount of pulses (27.69 million tonnes) from a 35 million ha area with a productivity of 649 kg/ha, achieving self-sufficiency for domestic pulses demand (Anonymous, 2022) [4]. The major pulses cultivated in India are lentil, chickpea, pigeonpea, mungbean, urdbean, and dry pea wherein, chickpea contribute 48% of the total production, followed by Pigeonpea (17%), blackgram (10%), greengram (7%), and other pulses 18% towards total pulses production (Anonymous, 2021) [4].

Chickpea is the most important pulse crop grown across India's arid and rainfed areas. When compared to other pulse crops, the seeds are an excellent source of high quality protein (18–22) (Ercan *et al.*, 1995) [10]. Furthermore, its seeds are high in energy (52–70% CHO, 416 calories/100 gm), fat (4-10%), minerals, and vitamins. It also aids in cholesterol reduction (Ali and Prasad, 2002) [3]. India accounts for 65.39 per cent of world's chickpea production. In 2018, the area under chickpea cultivation was 9.53 million ha, with a yield of 9.05 million tonnes and a productivity of 951 kg/ha. More than 90% of chickpea production is produced in Madhya Pradesh, Rajasthan, Karnataka, Uttar Pradesh, and Andhra Pradesh. Chickpea is grown on 5.62 lakh hectares in Uttar Pradesh, with an output of 6.26 lakh tonnes and a productivity of 1114 kg/ha (Directorate of Pulses Development, 2018) [8].

Besides production constraints like seasonality and low productivity, the biotic and abiotic factors contribute significantly in reducing chickpea production at field and storage conditions.

The major biotic factors inflicting heavy grain losses under stored conditions are bruchids or pulse beetles (*Callosobruchus* spp., Chrysomelidae: Coleoptera), which sometimes exceed field level losses. Several bruchid species (up to 1700 species) have been reported to infest stored pulses (Romero and Johnson, 2004) [17], with the bean beetle (*Callosobruchus chinensis* L.) inflicting up to 100% grain damage under unmanaged conditions (Southgate, 1978; Talekar, 1988; Mishra *et al*., 2017) [19, 21, 13]. Aside from bruchids, other pests found in stored chickpeas include the Khapra beetle, *Trogoderma granarium* Everts. Lesser grain borer, *Rhizopertha domanica* Fab. (Rathore and Sharma, 2002).

When pulses are stored in huge quantities at one place, they become vulnerable to insect pest attack due to their high nutritional value. The bean beetle (*C. chinensis*) causes initial infestation from field and along with secondary/lateral infestations, causes considerable economic damage during the storage period and the losses may reach upto 100%, if not intervened (Srivastava and Pant, 1989; Ramzan *et al*., 1990). Several traditional methods of stored pest management failed to provide a comprehensive solution for a variety of reasons (Mishra *et al*., 2017) [13]. Several chemical-based options were widely used, resulting in several health, environmental, and resistance issues (Nayak *et al.* 2020) [14]. Only a few prophylactic (Malathion, Deltamethrin) and fumigant (Aluminium Phosphide) chemicals are recommended for bruchids, and they are being used indiscriminately, posing potential future consequences such as resistance, residues, and associated health hazards. Adult bruchids prefer natural openings on gunny bags to enter and infest stored grains, as opposed to other insects that physically puncture and enter the bags. Because gunny bags are used in the majority of Indian grain storages, it is critical to find alternative bags that do not have natural openings. Though bags with no openings prevent bruchid entry, they cannot prevent the perpetuation of infestations, if the infestations enters these bags. As a result, proper modern grain disinfestation methods for *C. chinensis* management in chickpeas are lacking and must be identified. It was discovered that irradiating grains with gamma rays was an effective method of eliminating existing infestations. Considering above points, the present study attempted to identify the effective gamma irradiation doses in comparison to currently available aluminium phosphide.

2. Material and Methods

2.1 Experimental site, location, and chickpea variety

The experiments were conducted under laboratory conditions at Department of Entomology, Chandra Shekhar Azad University of Agriculture & Technology and ICAR-Indian Institute of Pulses Research, Kanpur, during 2020-21 and 2021-22. Geographically, the district Kanpur Nagar is located in the subtropical alluvial tract of central plains of river Ganga-Yamuna, between latitude 26^0 29’ North and longitude $79^0$31’ and $80^0$34’ East. It is situated at an elevation of 125.9 meter above mean sea level. The annual mean rainfall for the district headquarters of Kanpur city is 812 mm, received from mid-June to mid-October with the scattered showers in winter. Kanpur's weather remains hot during the summer months of March to June. Throughout the season, Kanpur also experiences heat waves. The monsoon comes in Kanpur around mid-June, bringing hot and humid weather till September end. The warm humid conditions prevailing between March to August. The chickpea variety ‘Udai’ (KPG-59) was selected to assess the different gamma irradiation doses for eco-friendly management of bruchid species, *Callosobruchus chinensis* L. The seeds were obtained from Section of Economic Botanist (Legumes), Chandra Shekhar Azad University of Agriculture & Technology, Kanpur.

2.2 Maintenance of insect culture and utilization for experiments

The pure stock culture of pulse beetle species *C. chinensis* was obtained from Division of Crop Protection, ICAR-Indian Institute of Pulse Research, Kanpur. The culture was multiplied on fresh and infestation free chickpea grains as the available protocol (Strong *et al.* 1960) under controlled laboratory conditions (27±2 ºC and 65±5% RH, 10:14 light:dark) (Aidbhavi *et al.* 2021) [2].

2.3 Experimentation and observations

To assess the efficacy of modern disinfestation methods in removing bruchid infestations, the initial infestation was created on chickpea grains by exposing grains to *C. chinensis* at the rate of 5 pairs per 100g of grains. The released adults were allowed for egg laying for the period of 72 h, further, the infested grains along with adult insects were be exposed to four irradiation doses, one phosphine dosage along with untreated control (Table 1).

2.3.1 Fumigation: The required quantity of grains of chickpea (35 kg each) were fumigated with Aluminium phosphide (Celphos®) @ 0.009 g per one kg of grains for seven days (quantity calculated from the recommended dose of 9 gram per tonne given by FCI). The fumigation was done in plastic airtight drums sealed properly with washer and lock rings, and the aluminium phosphide tablets were handled safely under the fumehood to avoid self-exposure toxic phosphine gas. Post fumigation, the initial observations were recorded before keeping the treated seeds for incubation until F1 adults emergence. Then the final observations on infestation parameters were recorded.

2.3.2 Irradiation: Required quantity of chickpea grains were exposed to gamma radiation @ 0.1, 0.2, 0.3 and 0.5 kGy for a fixed time at BARC authorized irradiation facility at Unnao, Uttar Pradesh. The source of irradiation was $Cobalt^{60}$ based gamma radiation. Four samples of 100 gram each were exposed to four irradiation doses separately, whereas one set of four samples were treated with fumigation to understand the comparative efficacy, and one set was kept untreated that served as control. There were 24 samples of 100 gram each were prepared. Before irradiation, the grains were infested with adult bruchid beetles at the rate of 5 pairs per 100 gram seeds and allowed for 72 hours for oviposition. After 72 hours, the beetles were removed and infested grains were applied with one fumigation and four irradiation treatments. The treated grains were observed for initial observations and then stored until emergence of first generation under laboratory condition in separate jars to record final observations.

Table 1: The modern disinfestation methods to manage bruchids infestation

Treatment No.	Treatment details
T_1	Fumigation with phosphine @ 3 tablets/ tonne for 7 days
T_2	Irradiation with gamma rays @ 0.1 kGy
T_3	Irradiation with gamma rays @ 0.2 kGy
T_4	Irradiation with gamma rays @ 0.3 kGy
T_5	Irradiation with gamma rays @ 0.5 kGy
T_6	Control

2.3.3 Experimental observations:

The initial and final observations on adult mortality, grain infestation, hatching success of eggs, grain damage and weight loss, were recorded from each sample of 100g grains to understand the efficacy of different treatments in preventing infestation on grains. The adult mortality owing to treatment with dis-infestation treatments were recorded and the per cent adult mortality was calculated by using the formula:

$$\text{Per cent adult mortality} = \frac{\text{Total number of insects died}}{\text{Total number of insects released}} \times 100$$

The infestation on grains was counted using hand lens. The total number of seed with eggs were divided by the total number of seeds present in each sample, and the per cent grain infestation was estimated with the following formula:

$$\text{Per cent infestation of grains} = \frac{\text{Total number of seeds with eggs}}{\text{Total number seeds}} \times 100$$

The hatching of eggs was determined by examining them under under stereo-binocular microscope for the appearance of frass build up and transformation of transparent eggs into brown colour (Giga and Smith, 1987). A representative sample of 25g grains was drawn from each sample. The total number of eggs deposited and total number of eggs hatched were counted in 25g grains and the per cent hatching success was estimated with the following formula:

$$\text{Per cent hatching success} = \frac{\text{Total number of eggs hatched}}{\text{Total number of eggs laid}} \times 100$$

The grain damage caused by *C. chinensis* damage was recorded from samples. The grains from each sample were separated into damaged (grains with characteristic holes) and undamaged ones. Using this data, the per cent grain damage was calculated using the following formula given by Boxall (1986) [6].

$$\text{Per cent grain damage} = [Nd / (Nd + Nu)] \times 100$$

Where, Nu-number of undamaged grains, and Nd-number of insect damaged grains.

The grain weight was recorded twice during pre-incubation and post adult emergence. The grains of each sample were separated into damaged (grains with characteristic damage holes) and undamaged ones and weighed separately using electronic precision weighing balance (Model: ACZET 202). Per cent weight loss was calculated using the formula given by Adams (1976) as follows:

$$\text{Weight loss in percentage} = \frac{(UNd) - (DNu)}{U\,(Nd + Nu)} \times 100$$

Where, U- weight of undamaged grains, Nu- number of undamaged grains, Nd- number of damaged grains, D- weight of damaged grains.

The gamma irradiation was proven to affect the seed viability at higher dosages. Twenty-five random seeds from each treatment were taken and placed on moistened germination paper and was kept in germination chamber at 25–30 °C and 90–95 per cent relative humidity. The germination count was taken after seven days of incubation. The germination percentage was calculated by using following formula:

$$\text{Germination percentage} = \frac{\text{Seeds germinated}}{\text{Total seeds}} \times 100$$

3. Results

The modern disinfestation methods such as gamma irradiation and phosphine fumigation used to ascertain their efficacy in preventing bruchid infestation demonstrated significantly varied infestation parameters when compared to untreated control. The irradiation doses included 0.1, 0.2, 0.3 and 0.5 kGy, whereas, the phosphine treatment included 0.009 g per tonne of grains. In both the treatments, the same set of untreated grains were served as control. The efficacy studies were conducted in first and validation experiments during 2020-2021 and 2021-2022, respectively.

3.1 Grain infestation (%): During first year (2020-21), the per cent grain infestation caused by *C. chinensis* on chickpea seeds before subjecting them to different disinfestation treatments was significantly differed (Table 1 and Figure 1). The least per cent grain infestation was found in treatments of *Gamma* radiation with dose 0.3 kGy (63.58±4.463), followed by phosphine fumigation (64.69±2.625), *Gamma* radiation with dose of 0.5 kGy (67.75±2.895), 0.1 kGy (68.38±2.128) and untreated control (68.62±1.828). The highest per cent grain infestation was seen in *Gamma* radiation with dose of 0.2 kGy (69.34±3.302). All the treatments were on par with each other. Similarly in validation experiment (2021-22) (Table 3 and Figure 2), the least per cent grain infestation was found in grains pre disinfested with phosphine fumigation (64.26±4.278) followed by, *Gamma* radiation with dose of 0.5 kGy (67.05±3.892), 0.1 kGy (68.49±3.223), 0.3 kGy (69.08±1.350) and *Gamma* radiation with dose of 0.2 kGy (69.53±4.750). The highest per cent grain infestation was seen in untreated control (71.86±1.727). All the treatments were on par with each other as the infestation was made to happen before applying the treatments to their disinfestation efficacy.

3.2 Hatching success (%): The disinfestation treatments demonstrated significantly variable effect on hatching success of eggs laid on chickpea grains in response to different treatments (Table 2 and Figure 1). The zero per cent hatching success was recorded on grains exposed to three *Gamma* irradiation doses (0.5, 0.3 and 0.2 kGy). This was followed by the grains exposed to 0.1 kGy which demonstrated 7.02±1.02 per cent hatching success. Whereas, the grain exposed to recommended phosphine fumigation recorded the hatching success of 14.91±1.53 which was significantly lower than irradiation doses. The highest per cent hatching success was seen in untreated control (53.04±2.155) significantly higher than all other treatments. However during 2021-22, the *Gamma* radiation doses such as 0.5, 0.3 and 0.2 kGy caused cent percent reduction in hatching success, followed by the next higher dose (kGy) that caused nearly 99 per cent reduction (1.03±0.355) which was on par with previous three doses. Whereas, the phosphine fumigated grains recorded higher but statistically par hatching success (13.23±0.786) than those received irradiation doses. However, the highest per cent hatching success was seen in untreated control (58.82±8.950) (Table 3 and Figure 2).

3.3 Grain damage (%): The per cent grain damage owing to exposure of *C. chinensis* pre-infested chickpea grains to different irradiation doses and recommended phosphine concentration was varied significantly between treatments during first and validation experiments (Table 3 and Figure 2). During 2020-21, the least per cent grain damage (0%) was found in grains exposed to three *Gamma* radiation doses (0.5, 0.3 and 0.2 kGy), followed by *Gamma* radiation with dose of 0.1 kGy (4.68±0.534) and phosphine fumigation (13.46±0.451). The highest per cent hatching success was seen in untreated control (54.51±2.584) which differed significantly from all other treatments. Similar trend was observed during 2021-22 wherein the least per cent grain damage of zero per cent was appeared in grains received three *Gamma* radiation doses (0.5, 0.3 and 0.2 kGy) which was at par with the next higher dose of 0.1 kGy (0.84±0.211). However, the grain damage recorded for grains exposed to differed phosphine fumigation (13.12±0.788) was significantly higher than those exposed to irradiation doses. The highest per cent hatching success was seen in untreated control (58.80±2.121) which differed significantly from all other treatments (Table 3 and Figure 2).

3.4 Grain weight loss (%): During 2020-21, the observations revealed that there was a significant difference among the treatments tested (Table 2 and Figure 1). The zero per cent weight loss was recorded in grains exposed to *Gamma* radiation doses of 0.5, 0.3 and 0.2 kGy which were at par each other. This was followed by the dose 0.1 kGy (5.38±0.727%) that differed statistically with previous three treatments. Whereas, the treatment phosphine fumigation recorded significantly higher seed weight loss (11.99±0.468) when compared to four irradiation doses. Overall, the irradiation doses and phosphine fumigation recorded significantly lower seed weight loss when compared to the grains in untreated control (41.67±0.637). Similarly during validation experiment conducted during 2021-22, the observations revealed significant difference among the treatments (Table 3 and Figure 2). The grains exposed to three gamma irradiation doses (0.5, 0.3 and 0.2 kGy) suffered least per cent weight loss (0.00±0.00) which was followed by and significantly differed with the *Gamma* radiation dose of 0.1 kGy (2.76±0.836) and phosphine fumigation (11.41±0.794). The highest per cent weight loss was seen in untreated control (42.29±0.634) which differed significantly from all other treatments.

3.5 Adult mortality (%): Adult mortality was varied owing to exposure to different irradiation doses, phosphine fumigation and in untreated control (Table 2 and Figure 1). It was observed that the irradiation doses of 0.5, 0.3 and 0.2 kGy caused complete mortality of adults which were at par each other. It was followed by the treatment with the phosphine fumigation (75.00±6.455) differing significantly with *Gamma* radiation with dose of 0.1 kGy (90.00±4.082). However, the least per cent or no adult mortality was recorded in untreated control (0.00±0.00) which differed significantly from all other treatments. Similarly during 2021-22, the data on adult mortality differed significantly between treatments (Table 3 and Figure 2). The irradiation doses 0.5, 0.3 and 0.2 kGy caused cent per cent mortality of adults which were at par each other. This was followed by phosphine fumigation treatment (72.50±4.787) which differed significantly from *Gamma* radiation with dose of 0.1 kGy (97.50±2.500). No adult mortality was observed in untreated control which differed significantly from all other treatments.

3.6 Germination (%): The germination of chickpea seeds upon exposure to irradiation doses and phosphine fumigation was varied significantly between treatments (Table 2 and Figure 1). Treated seeds were kept for germination and it was found that the least per cent germination was demonstrated in treatment having *Gamma* radiation with dose of 0.5 kGy (0.00±0.00) followed by 0.3 kGy (14.00±2.582), 0.2 kGy (30.00±2.582) and0.1 kGy (78.00±2.582), which differed significantly each other. Whereas, the seeds exposed to phosphine fumigation recorded 93.00±2.517 per cent germination which was at par with seeds in untreated control as the latter recorded 99±1 per cent germination. Both these treatments differed significantly from all other treatments. Similarly during 2021-22, the grain damage caused by *C. chinensis* was varied significantly between different disinfestation treatments applied (Table 3 and Figure 2). Treated seeds were allowed for germination and it was found that the nil germination was demonstrated in seeds exposed to *Gamma* radiation with dose of 0.5kGy, followed by 0.3kGy (15.00±2.517%), 0.2kGy (30.00±2.582%), and 0.1kGy (80.00±3.651%), where were on par at each other. Whereas the phosphine fumigated seeds recorded 97.00±1.915 per cent germination which was on par with untreated control (99±1). Both these treatments differed significantly from all other treatments.

Table 2: Infestation and developmental parameters of *C. chinensis* on chickpea grains owing to disinfestation with irradiation and phosphine during 2020-21

Treatment No.	Treatment details	Grain infestation (%)	Hatching success (%)	Grain damage (%)	Adult mortality (%)	Grain weight loss (%)	Germination (%)
		Mean ± S.E.	Mean ± S.E.	Mean ± S.E.	Mean ± S.E.	Mean ± S.E.	Mean ± S.E.
T_1	Phosphine fumigation (3 tab/ton for 7 days)	64.69±2.625^{a}	14.91±1.530^{c}	13.46±0.451^{b}	75.00±6.455^{b}	11.99±0.468^{c}	93.00±2.517^{e}
T_2	*Gamma* Irradiation (0.1 kGy)	68.38±2.128^{a}	7.02±1.019^{b}	4.68±0.534^{a}	90.00±4.082^{c}	5.38±0.727^{b}	78.00±2.582^{d}
T_3	*Gamma* Irradiation (0.2 kGy)	69.34±3.302^{a}	0.00±0.00^{a}	0.00±0.000^{a}	100.00±0.00^{c}	0.00±0.00^{a}	30.00±2.582^{c}
T_4	*Gamma* Irradiation (0.3 kGy)	63.58±4.463^{a}	0.00±0.00^{a}	0.00±0.000^{a}	100.00±0.00^{c}	0.00±0.00^{a}	14.00±2.582^{b}
T_5	*Gamma* Irradiation (0.5 kGy)	67.75±2.895^{a}	0.00±0.00^{a}	0.00±0.00^{a}	100.00±0.00^{c}	0.00±0.00^{a}	0.00±0.00^{a}
T_6	Control	68.62±1.828^{a}	53.04±2.155^{d}	54.51±2.584^{c}	0.00±0.00^{a}	41.67±0.637^{d}	99.00±1.000^{e}
Grand mean		67.06	12.93	12.43	77.5	10.12	68.33
SE (m)		1.224	0.479	0.450	1.273	0.188	0.913
ANOVA 'F'		0.61	158.14	303.65	370.66	1226.8	273.17

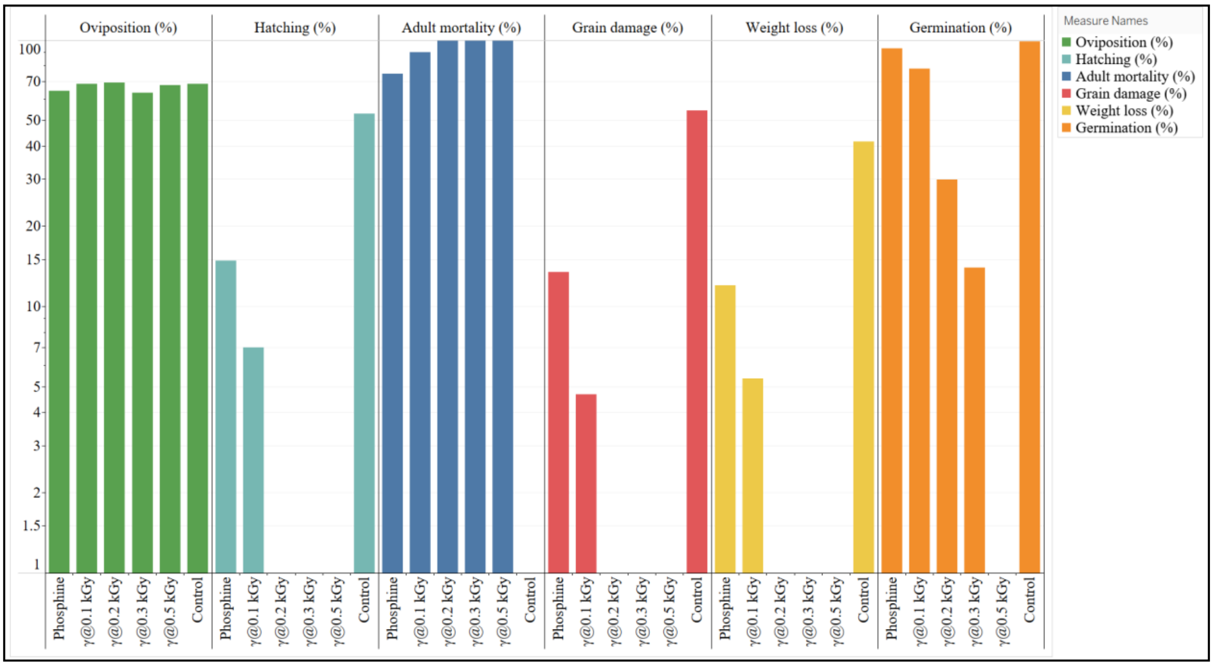

Fig 1: Effect of irradiation doses in comparison to phosphine and untreated control, on various infestation parameters of *C. chinensis* on stored chickpeas during 2020-21

Table 3: Infestation and developmental parameters of *C. chinensis* on chickpea grains owing to disinfestation with irradiation and phosphine during 2021-22

Treatment No.	Treatment details	Grain infestation (%)	Hatching success (%)	Grain damage (%)	Adult mortality (%)	Grain weight loss (%)	Germination (%)
		Mean ± S.E.	Mean ± S.E.	Mean ± S.E.	Mean ± S.E.	Mean ± S.E.	Mean ± S.E.
T_1	Phosphine fumigation (3 tab/ton for 7 days)	64.26±4.278^{a}	13.23±0.786^{a}	13.12±0.788^{b}	72.50±4.787^{b}	11.41±0.794^{c}	97.00±1.915^{d}
T_2	*Gamma* Irradiation (0.1 kGy)	68.49±3.223^{a}	1.03±0.355^{a}	0.84±0.211^{a}	97.50±2.500^{c}	2.76±0.836^{b}	80.00±3.651^{c}
T_3	*Gamma* Irradiation (0.2 kGy)	69.53±4.750^{a}	0.00±0.000^{a}	0.00±0.000^{a}	100.00±0.00^{c}	0.00±0.00^{a}	30.00±2.582^{b}
T_4	*Gamma* Irradiation (0.3 kGy)	69.08±1.350^{a}	0.00±0.000^{a}	0.00±0.000^{a}	100.00±0.00^{c}	0.00±0.00^{a}	15.00±2.517^{a}
T_5	*Gamma* Irradiation (0.5 kGy)	67.05±3.892^{a}	0.00±0.00^{a}	0.00±0.00^{a}	100.00±0.00^{c}	0.00±0.00^{a}	0.00±0.00^{a}
T_6	Control	71.86±1.73^{a}	58.82±8.95^{b}	58.80±2.12^{c}	0.00±0.00^{a}	42.29±0.63^{d}	99.00±1.0^{d}
Grand mean		68.380	12.597	12.374	78.333	9.632	69.333
SE (m)		1.406	1.500	0.382	0.900	0.220	0.981
ANOVA 'F'		0.55	39.84	619.3	326.914	941.38	239.45

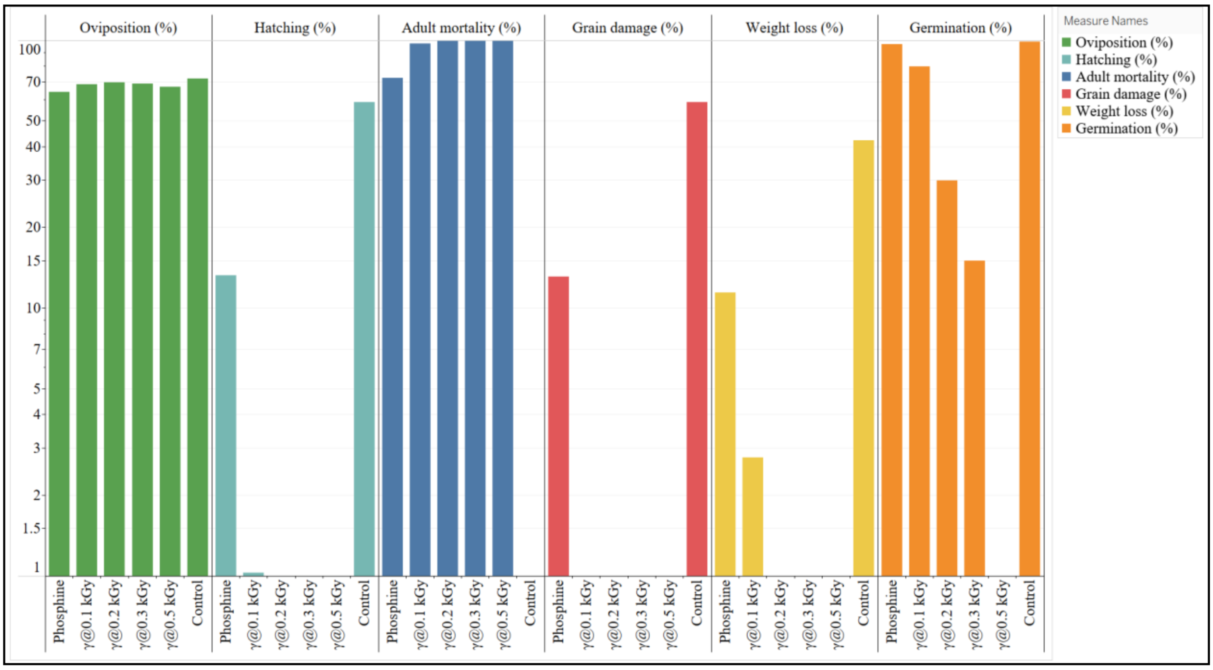

Fig 2: Effect of irradiation doses in comparison to phosphine and untreated control, on various infestation parameters of *C. chinensis* on stored chickpeas during 2021-22

4. Discussion

Numerous modern disinfestation methods were discovered and found effective for safe storage of food grains by protecting against stored grain insect species. Among those, fumigation with phosphine was very popular method because of its wider acceptability worldwide due to its cost-effectiveness, easy availability and handling, etc. (Nayak *et al.* 2020) [14]. In the present investigation, two modern disinfestation methods namely fumigation with recommended dosage of phosphine and irradiation with varied gamma radiation levels, were tried for effective disinfestation and safe storage of pulses. When the pre-infested (*C. chinensis*) chickpea grains were exposed to different treatments such as phosphine at recommended dosage (3 tab/ ton for 7 days), *Gamma* irradiation at four doses (0.1, 0.2, 0.3 and 0.5 kGy), along with an untreated control, the treatments demonstrated significant different effects on various infestation parameters. The least per cent infestation parameters were recorded in grains exposed to 0.2, 0.3 and 0.5 kGy, followed by 0.1 kGy, phosphine exposure and the highest was in untreated control. From the present study conducted during 2020-21 and 2021-22, it was observed that, the increasing the irradiation dosages resulted in complete reduction of hatching, damage and associated weight loss and also rapid reduction in per cent germination which is crucial parameter for a grain as a seed. So by considering the per cent germination, it can be considered that 0.1 kGy dosage looks optimum for the control of bruchids without affecting the seed/grain quality. Though Aluminium Phosphide is widely recommended in India, it has shown moderate effect in the present investigation for the control of bruchids compared to *Gamma* irradiation. From present study, it can be said that oil treatments has some residual effect against bruchid infestation for greater time than the phosphine fumigation and irradiation. But irradiation of lower dose can be considered for quicker disinfestation method.

Literature on phosphine fumigation along with gamma irradiation against pulse beetles especially *C. chinensis* on stored chickpeas, and their response is very scanty as only a few workers attempted to study the response of beetles to these treatments. However, the few available literature showed the similar results as discussed hereafter: the results are in accordance with the experiments conducted by Darfour *et al.* (2012) [7] wherein adults of *C. maculatus* released in cowpea seeds then irradiated at doses of 0.0, 0.25, 0.5, 0.75, 1.0 and 1.5 kGy at a dose rate of 1.074 kGyhr^{-1}. They found that irradiation at a dose of 0.25 kGy killed the *C. maculatus* within eight days and there was significant difference ($p<0.05$) in the per cent mortality between the irradiated and the non-irradiated weevils, and the per cent mortality increased with increase in the radiation dose. However 0.1 kGy was found effective against *C. chinensis* in chickpea.

Similar results were found in the experiments conducted by Enu and Enu (2014) [9] on maize and cowpea seeds which were infested with *Sitophilus zeamais* and *C. maculatus* respectively and the seeds were irradiated in a Cobalt^{60} *Gamma* cell with doses 40, 80, 150, 200, 300 and 500 Gy [Grays], further stored for 52 days. It was found that, both pulse beetles species were susceptible to gamma doses between 200-500 Gy. With respect to per cent adult mortality, Enu and Enu (2014) [9] on maize and cowpea seeds that as much as 100% mortality was recorded for both insect at 200, 300 and 500 Gy doses in line with present findings. In case of germination test, it was also found in the same experiment conducted by Enu and Enu (2014) [9] that the germination tests subsequently carried out showed that gamma irradiation at this dose had less effect on seed viability. However the present findings are in contrast where only 0.1 kGy (100 kGy) found effective to eliminate infestation without affecting seed germination. Timbadiya *et al.* (2018) [22] observed that the Gamma radiation can eliminate insect pests of stored grains as well as field crops more efficiently. Degenerative changes in the cells of pests occur due to deposition of energy in the water molecules and other bio-molecules especially to genetic materials. Therefore, normal development or reproduction of the pest may be prevented. It is applied to targeted insect pests hence, it is eco-friendly technology for insect pest management. Gamma radiation @ 25-1200 Gy can effectively suppress pests *viz*., grain weevil, mediterranean flour moth, Indian meal moth, cigarette beetle, medfly, onion fly, fall armyworm, tobacco budworm and african cotton leafworm.

Henceforth, irradiation is fast and broadly effective against insect pests, and it does not leave residues. Due to the massive effects on insect DNA and other biomolecules, irradiation is immune to resistance development. For stored product pests, irradiation may be particularly helpful in controlling phosphine and methyl bromide resistant populations and could help manage resistance by preventing the spread of resistant insects in exported grains (Follett *et al.*, 2020). Upadhyay *et al.* (2011) [23] reported that the few important methods such as ionizing irradiation are proved highly effective against stored grain insects.

5. Summary and conclusion

The present study investigated the efficacy of different gamma irradiation doses (in comparison to recommended phosphine dosage and untreated control) for effective disinfestation of chickpea grains infested with bruchid species (*C. chinensis*). It was clearly evident that the gamma irradiation with 0.1 kGy would be the highly effective option to eliminate the existing *C. chinensis* infestations on stored chickpeas without affecting the seed viability negatively. Hence, irradiation with gamma rays would serve as effective modern disinfestation option when storing grains in bags having no natural openings so as to prevent further perpetuation along storage period. The present findings also opens window to identify the effective irradiation doses for other major bruchid species infesting chickpea and other stored pulses.

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