

Low energy portable industrial radiography X-ray machine of irradiation of *Phthorimaea operculella* sterilization

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Summary Gamma ray's irradiation has long widely utilized in medical, industrial and agricultural research and applications. Many countries have approved its use as an effective tool for the sterile insect technique (SIT) within integrated pest management programs. The actual study evaluates the potential of using low-energy portable industrial radiography (LEPIR) X-ray machine (typically employed for nondestructive testing of materials) to sterilize the potato tuber moth (PTM) pupae and adult moths rather than gamma radiation that is routinely used in SIT programs. Our data are consistent with previous finding and reveal clear dose-dependent damaging detrimental effects on key biological parameters of the pest, including adult emergence, longevity, fecundity, fertility and F₁ egg hatchability at a dose of 150 Gy. These findings indicate that LEPIR X-ray machine may serve as a practical and alternative to gamma irradiation in any SIT program targeting the potato tuber moth.

Additional Keywords: low energy, potato tuber moth, radiation, SIT, X-ray

Introduction

Several studies have revealed that the sterile insect technique (SIT) is a safe, effective, and environmentally friendly technique for controlling or even eradicating pests. Furthermore, SIT has become a regular component of area-wide integrated pest management programs against various agricultural insect pests (Hendrichs *et al.*, 2009; Marec and Vreysen, 2019; Dyck *et al.*, 2021). Multiple pests have been effectively controlled using this technique, including fruit flies, tsetse flies, and potato tuber moth (Makee and Saour, 1999; Hendrichs *et al.*, 2009; Idris and Hussian, 2021). Basically, SIT depends on releasing sterile males of the insect of interest into a wild population, which decrease reproduction rates (Knipling, 1985).

The potato tuber moth (PTM) (*Phthorimaea operculella* Zeller) causes crop losses of up to 100% in over 90 countries in the world (Chandel *et al.*, 2020; Adhikari *et al.*, 2022). During the growing season, *Phthori-*

maea operculella (Zeller) larvae damage host foliage; however, as senescence approaches, the adult females deposit the eggs within soil cracks or directly on exposed tubers (Rondon, 2010). There is a resilient pupal stage in the pest's life cycle, which provides a critical bridge for population survival; concurrently, the highly mobile, nocturnal adults ensure continuity and expansion of infestations by dispersing spatially and oviposition precisely (Fenemore, 1979). Syria cultivates about 24,789 hectares of potatoes with estimated yield of 486,605 tons per year, and potato production depends on an excessive usage of chemical insecticides to control *P. operculella* infestation. It is well documented that these insecticides are expensive, nonselective, and pose an environmental threat. Moreover, *P. operculella* has developed resistance to most insecticides, reducing their effectiveness (Idris and Shoaib, 2019; Idris *et al.*, 2021).

Several studies have demonstrated that gamma radiation and X-rays can be potentially used in SIT programs to induce sterility among insect pests (Saour and Makee, 1997; Makee and Saour, 1999; 2003; Idris and Shoaib, 2019; Wang *et al.*, 2023; Cho *et al.*, 2026). There are, however, some significant disadvantages of using gamma radi-

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ation over X-ray technology, particularly when it comes to application logistics and regulatory restrictions (Kaboré *et al.*, 2023). A common method of radiation delivery in SIT programs is the Cobalt-60 isotope, which is strictly regulated with plenty of security concerns, radioactive disposal problems, complicating procurement and management (Mastrangelo *et al.*, 2010; Urquidi *et al.*, 2015). On the other hand, X-rays are more flexible practically because they are not subject to the same regulatory restrictions, as it requires fewer shielding and safety measures, making them more appropriate for pest control applications (Liang *et al.*, 2019; Abdelhafiz *et al.*, 2024). In addition, X-ray technology has become increasingly popular as a safer, more efficient alternative that induces pest sterility without affecting commodity quality due to recent advancements. In particular, low-dose X-ray treatments provide a biosecurity barrier against cryptic pests, thus bypassing the regulatory and environmental challenges associated with chemical fumigants (Follett *et al.*, 2013; Praveen *et al.*, 2025).

Even though X-ray treatments are capable of achieving high levels of sterility, they tend to preserve almost all insects' biological functions such as longevity, flight, and mating behavior better than gamma radiation. In SIT programs, this is crucial for achieving successful pest control by producing sterile males that fly farther, live longer, and court females more effectively (Wang *et al.*, 2023; Huang *et al.*, 2025). A study on *Cydia pomonella* L. combining SIT with X irradiation found that X-ray treatment effectively sterilized male moths without significantly compromising their mating competitiveness, but 366 Gy of X-ray caused complete sterility in males. Compared to non-irradiated males, X-rays reduced mating competitiveness and lifespan, but gamma radiation is more damaging to flight muscles, wings, and overall vigor, making X-rays less damaging. Also, both 91.2 Gy of X-rays and 124.9 Gy of gamma radiation caused 99% sterility in male Mediterranean fruit fly (*Ceratitis capitata*), but X-rays required lower doses and

caused less biological damage (Mastrangelo *et al.*, 2009; Zhang *et al.*, 2023). Moreover, in Cotton bollworm (*Helicoverpa armigera*), 200 Gy of X-ray caused inherited sterility, while 400 Gy caused complete egg infertility, showing dose flexibility (Chu *et al.*, 2026).

Photonic ionizing radiation, including X-rays and gamma rays, has been extensively used in insect pest management and control programs. However, despite their widespread application, limited information is currently available regarding the potential advantages and effectiveness of low-energy X-ray radiation within Sterile Insect Technique (SIT) programs (Pernicka and McLean, 2007; Russel and Bardley, 2015). On the other hand, in the traditional academic research and nondestructive testing of materials (NDT), the low-energy, portable industrial radiography (LEPIR) X-ray machines are utilized. Low-energy portable industrial radiography X-ray machine, with anode water-cooling and 100% duty cycle, is usually used to perform research and services in nondestructive testing of materials. However, it can be also considered as a powerful tool to provide irradiation for research works in phytosanitary, in stored product pest control and in SIT pest management programs. This type of X-ray machine is capable to provide irradiation doses up to 400 Gy at once, without interruption, for the selected kV and FPID that situated between 40 and 100 cm. In addition, these types of X-ray machines are portable and require little shielding to comply with the safety protection regulations from ionizing radiation, thus, the irradiation can be performed in both research laboratory or in nondestructive testing laboratory (Martin, 2006; Maharaj, 2008; Bushong and Goerner, 2012; Kwon *et al.*, 2022). Moreover, this type of X-ray machine, due to its light safety protection shielding, can be used as an integral part of low-production commercial system for irradiation treatment of single layers of grains, seeds or any agriculture products moving over a belt (Hallman, 2013; Indiarito *et al.*, 2020; Zhang and Zhou, 2022). Consequently, this system will overcome the public concerns of consum-

ing irradiated agriculture products such as the one that commercially irradiated using Cobalt-60 radioisotope due to the believe that these commodities may have been polluted and become radioactive (Fox, 2002; Gunes and Tekin, 2006; Maherani *et al.*, 2016; Castell-Perez and Moreira, 2021).

Thus, the study aimed to investigate the potential of low-energy X-ray irradiation as a substitute for conventional irradiation techniques, while also assessing whether the sterilization process negatively affected important biological and performance parameters of *P. operculella* pupae and adult moths instead of using gamma rays' radiation.

Materials and methods

Characterizations of the Smart 160W industrial X-ray machine

A directional beam portable industrial radiography X-ray machine with anode water cooling and 100% duty cycle at 20°C was used to irradiate *P. operculella* at pupae and adult moth stages. The type of the X-ray machine that has been recruited in this study is YXLON International- Smart 160W. The working range of this equipment can be adjusted from 10 kV to 160 kV. The operation current of the tube of this X-ray machine is fixed and equal to 4 mA. The conical shape of the radiation beam has an angle of 40°. In order to obtain a circular shape of the field of radiation, the axe of the radiation beam had been adjusted to be vertical on the irradiation plane. The diameter and the area of each circle with homogeneous irradiation field depend on the vertical distance between the focal spot of the X-ray tube and the plane of irradiation (Bryant and McIntire, 1985; Halmshaw, 1995).

The paragraph output radiation doses of the X-ray machine were measured in the radiography laboratory of the Atomic Energy Commission of Syria by using an ionization chamber that was calibrated in the Dosimetry laboratory of the International Atomic Energy Agency (IAEA). The measurements were performed for the whole operation kV

range, starting from 20 kV to 160 kV with 20 kV increment, by positioning the thin spherical sensor of the ionization chamber at the horizontal plan of irradiation at a vertical distance equal to 40 (cm), between the focal spot of the X-ray machine to the horizontal plan of irradiation distance (FPID), and exposing the sensor to X-ray radiation at every cited kV for one minute. The result of these measurements was taken as an accumulated electric charge in (Coulomb/min) unit and it was transformed to the (Gray/h) unit to draw the exposure curve of the relation between the irradiation doses in (Gray/h) for every applied kV at the cited FPID.

To respond to the different irradiation needs, the sensor of the ionization chamber was exposed for another FPID that equals to 50, 60, 75, and 100 cm respectively and the results of these exposures are shown in Table 1 and in Figure 1 (Ma *et al.*, 2001; Pernicka and McLean, 2007). The air kerma rate was measured by a reference ionization chamber PTW 34069 and determined using the following equation:

$$K_{air} = M_0 \cdot N_k \cdot K_{T,P} \cdot K_H \cdot K_{pol} \cdot K_s$$

Where:

K_{air} : air kerma rate (Gy/min)

M_0 : average reading of the ionization chamber in (nC/min).

N_k : calibration factor of the ionization chamber in term of air kerma rate in (Gy/nC).

$K_{T,P}$: correction factor for air temperature and air pressure

K_H : correction factor for humidity

K_{pol} : correction factor for polarity

K_s : correction factor for recombination

Insects stock culture

The insects used in this study were selected from our laboratory stock culture, which is renewed each year with a field collection of PTM individuals. They were reared on wax coated potato slices, maintained at a constant temperature of 25±1°C, with 70±5% relative humidity, and 12-hour light-darkness cycle as described by Saour and Makee (1997). The larvae were reared on

Table 1. Irradiation doses of the X- ray machine at the applied kV and for five values of FPID distances performed at X-ray irradiation of the potato tuber moth *Phthorimaea operculella*.

Operating potential (KV)	Dose (Gy/h) at FPID= 40 cm	Dose (Gy/h) at FPID= 50cm	Dose(Gy/h) at FPID=60cm	Dose(Gy/h) at FPID=75cm	Dose(Gy/h) at FPID= 100cm
20	87.8	56.2	39.0	25.0	14.0
40	125.8	80.5	55.8	35.8	20.1
60	170.1	108.9	75.6	48.4	27.2
80	201.9	129.2	89.6	57.4	32.3
100	221.6	141.8	98.4	63.0	35.4
120	237.6	152.1	105.5	67.6	38.0
140	247.2	158.2	109.8	70.3	39.6
160	253.6	162.3	112.6	72.1	40.6

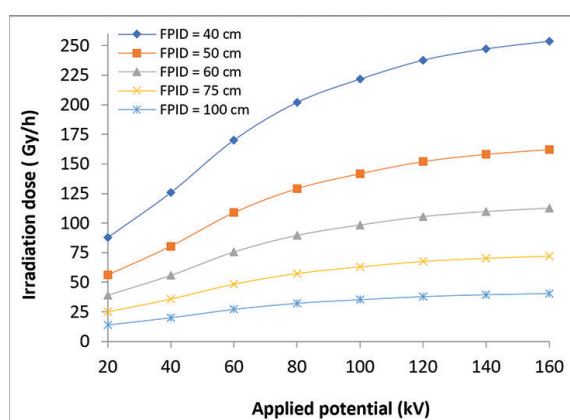


Figure 1. Curves of the irradiation doses as a function of the applied kV at five values of FPID performed at X-ray irradiation of the potato tuber moth *Phthorimaea operculella*.

wax-coated potato slices, which were laid over a layer of sand in plastic containers (40 cm x 25 cm x 10 cm) in which they pupated. As new adults emerged, they were collected and kept in 800ml transparent plastic jars (10-12 pairs per jar); a filter paper band was added to the bottom of every jar to promote oviposition, and 10% sucrose solution was provided as a food source. In addition to keeping females and males together until death, the eggs were collected daily, counted, and left until they hatched on new wax-coated potato slices. In the experiments, all the eggs, pupae and adults (male and female) used were randomly collected from the lab. colony at ≤ 24 h old. The stage (pupae, adult) that did not meet IAEA standards for quality control, such as undersized or malformed, were discarded. All experiments

were repeated three times.

Effect of X-ray irradiation of *P. operculella* pupae on adult emergence, longevity, fecundity and hatchability

Pupae $n=120$ were divided into four groups for X-ray irradiation with 0, 100, 150, and 200 Gy doses (each pupae group placed in plastic Petri dishes 9 cm diameter). Irradiation of the PTM pupae and adults was conducted at FPID equal to 50 cm at potential difference equal to 100 kV. After adult insect emergence, irradiated males and female moths in each group were paired individually in a 350 mL transparent plastic box provided with a band of filter paper for oviposition and 10% sucrose solution as a food source. At each studied dose, the adult males and female moths were counted as they emerged and kept for oviposition until death. Eggs laid at each dose were collected, counted, and incubated for hatching for determining the hatchability.

Effect of X-ray irradiation of *P. operculella* adults on adult longevity, fecundity and hatchability

A group of 160 newly emerged females and males were exposed to X-ray irradiation doses (0, 100, 150, 200 Gy). The irradiated males and female moths of each dose were paired individually in the same above-mentioned 350 mL transparent plastic boxes and were kept to oviposition until they died; laid eggs were counted and set aside for determining the hatchability.

Effect of X-ray irradiation of adults on the fecundity and hatchability of *P. operculella* after crosses of irradiated with non-irradiated males and females

N=400 pupae were individually placed in transparent plastic tubs (7 x 1.2 cm), and after adults' emergence, 80 females and males were chosen and exposed to X-ray irradiation different doses (0, 100, 150, 200 Gy). Irradiated females were divided into four groups (different dose exposure) and paired with 80 non-irradiated males (20 couples/group). Similarly, 80 emerged males exposed to X-ray irradiation at different doses (0, 100, 150, 200 Gy), were divided into four groups, and paired with 80 non-irradiated females. During each treatment, twenty pairs of males and females were placed in a breeding box containing cotton soaked in a sugar solution (10%) and filter paper surrounded for oviposition. After each dose treatment, the adults of both males and females were kept for oviposition until death. Eggs were collected, separated and counted daily to determine egg hatch.

Statistical analysis

All statistical analyses were performed at $P < 0.05$, using SAS Institute, Cary, North Carolina, USA's P Stat View statistical software (version 5.0). ANOVA-Tukey HSD tests were used to determine the statistical significance of differences in means in emergence, adult longevity, fecundity, and hatchability data, and a Student's T-test was used to examine the variance in fecundity and hatchability between crosses of irradiated with non-irradiated males and females.

Results

Values of the measured output radiation doses of the X-ray machine

The values of the measured output radiation doses of the X-ray machine taken for eight values of kV that are, (20, 40, 60, 80, 100, 120, 140, 160) kV at every one of the five values of FPID that are 40, 50, 60, 75, and 100 cm are consigned in Table 1. The curves of

the measured irradiation doses for the applied kV on the X-ray tube at each of the five cited values of FPID in Figure 1 reveal that the exposure dose increases by increasing the applied kV between the anode and the cathode of the X-ray tube, and the irradiation dose increases by decreasing the applied vertical value of FPID.

Diameter of the circular areas of irradiation

The diameter of each one of the five circles that have homogenous irradiation dose taken at the five values of FPID is presented in Table 2. The recorded values were calculated by using the defined angle of the radiation beam divergence of the X-ray tube and the applied values of FPID. The diameters of the circular areas of irradiation vs the FPID values where the centers of all circles are located at the central axis of the radiation beam are shown in Figure 2. The optical photo during X-ray irradiation of *P. operculella* pupae and adult moths is presented in Figure 3.

Effect of X-ray irradiation of *P. operculella* pupae on adult emergence, longevity, fecundity and hatchability

A significant, dose-dependent decreasing effects has been observed on many critical biological parameters including adult emergence, male and female moths longevity and fecundity (Table 3). A complete adult emergence was observed at the highest dose of 200 Gy. Furthermore, F_1 egg hatch-

Table 2. Diameter of the circular areas of the homogenous Irradiation doses at five FPID distances performed at X-ray irradiation of the potato tuber moth *Phthorimaea operculella*.

FPID (cm)	Diameter of the circular area of irradiation(cm)
20	14.6
40	29.1
60	43.7
80	58.2
100	72.8

ability has been completely inhabited at the dose of 150 Gy.

Effect of X-ray irradiation of *P. operculella* adults on adult longevity, fecundity and hatchability

Adult longevity was not significantly impacted by any of the test doses when compared to the untreated control group. Conversely, both fecundity and F_1 egg hatchability confirmed a dose-dependent decreasing as the irradiation dose increased. Remarkably, F_1 egg hatch was almost completely inhibited by 150 Gy (Table 4).

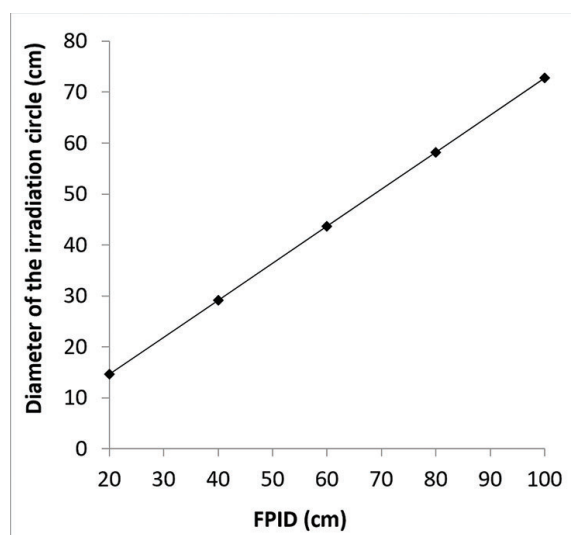


Figure 2. Diameters of the circular area of the homogeneous irradiation dose vs the vertical values of FPID performed at X-ray irradiation of the potato tuber moth *Phthorimaea operculella*.

Effect of X-ray irradiation of adults on the hatchability and fecundity of *P. operculella* after crosses of irradiated with non-irradiated males and females

Fecundity and F_1 egg hatchability of offspring from all treatment crosses (normal females X treated males, treated females X normal males) declined with increasing X-ray dose. A notable sex-specific effect of irradiation was observed: crosses involving irradiated females paired with normal males exhibited significantly higher fecundity and F_1 egg hatchability compared to the reciprocal crosses in which irradiated males were paired with normal females (Table 5).

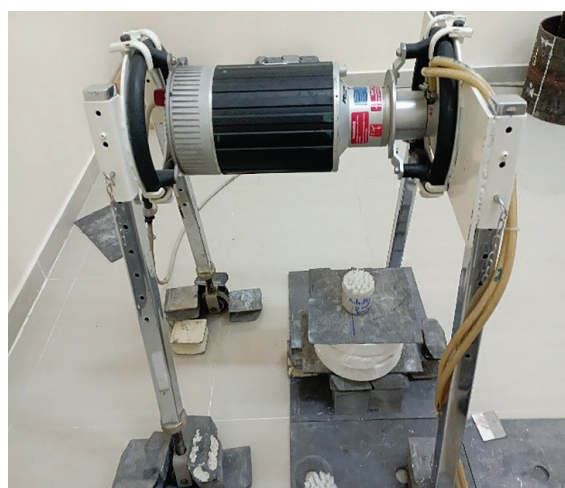


Figure 3. YXLON International - Smart 160W X-ray machine during irradiation for sterilisation of *Phthorimaea operculella* pupae and adults.

Table 3. Effect of X-ray irradiation of *Phthorimaea operculella* pupae on adult emergence, longevity, fecundity, and hatchability.

Dos (Gy)	n	Emergence (%) (Mean $\pm$ SD)	Adult Longevity (♀ , day) (Mean $\pm$ SD)	Adult Longevity (♂ , day) (Mean $\pm$ SD)	No. Eggs (♀ /total) (Mean $\pm$ SD)	Hatchability (%) (F_1) (Mean $\pm$ SD)
0	30	93 $\pm$ 2.5 A	10 $\pm$ 0.9 A	9.3 $\pm$ 1.3 A	58.9 $\pm$ 4.5 A	85.1 $\pm$ 8.6 A
100	30	30 $\pm$ 4.6 B	5.4 $\pm$ 1.1 B	6.4 $\pm$ 1.5 B	4.3 $\pm$ 2.9 B	1.1 $\pm$ 0.7 B
150	30	6.7 $\pm$ 2.6 C	1.4 $\pm$ 1.2 C	1.7 $\pm$ 0.7 C	1.3 $\pm$ 1.2 C	0 B
200	30	0 C	0 D	N/A D	N/A C	N/AB
Df		2	2	2	2	2
F- value		62.875	629.459	481.588	2158.897	1926.132
p		<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

Means ($\bar{x} \pm \text{SD}$) followed by different capital letters in columns are significantly different at $p < 0.05$ (Tukey HSD test).

Table 4. Effect of X-ray irradiation of *Phthorimaea operculella* adults on adult longevity, fecundity, and hatchability.

Dose (Gy)	n	Adult Longevity (♀, day) (Mean ± SD)	Adult Longevity (♂, day) (Mean ± SD)	No. Eggs (♀/total) (Mean ± SD)	Hatchability (%) (Mean ± SD)
0	20	9.6 ± 1.3 A	9.85 ± 1.3 A	56.85 ± 5.7 A	93.6 ± 5.03 A
100	20	9.3 ± 1.2 A	9.65 ± 1.6 A	15.2 ± 4.3 B	6.65 ± 2.04 B
150	20	6.25 ± 1.3 A	9.6 ± 1.4 A	5.1 ± 1.2 C	0 C
200	20	6.35 ± 1.0 A	9.2 ± 1.5 A	0.15 ± 0.3 D	0 C
Df		3	3	3	3
F- value		0.335	0.777	1007.147	5699.981
p		0.8036	0.5105	<0.0001	<0.0001

Means ($\bar{x} \pm SE$) followed by different capital letters in columns are significantly different at $p < 0.05$ (Tukey HSD).

Table 5. The effect of X-ray irradiation of *Phthorimaea operculella* adults on the fecundity and hatchability after crosses of irradiated with non-irradiated males and females.

Dose (Gy)	n	(T♀ X N♂)		(N♀ X T♂)	
		No. Eggs (Mean ± SD)	Hatchability (%) (Mean ± SD)	No. Eggs (Mean ± SD)	Hatchability (%) (Mean ± SD)
0	20	72.9 ± 5.07 Aa	77.4 ± 4.7 Aa	78 ± 5.1 Aa	73.9 ± 4.7 Aa
100	20	38.8 ± 7.9 Bb	25.55 ± 4.6 Bb	52.2 ± 8.9 Ba	43.1 ± 5.9 Ba
150	20	26.8 ± 5.7 Cb	8.2 ± 1.6 Cb	38.8 ± 8.3 Ca	32.3 ± 5.9 A Ca
200	20	10.2 ± 2.4 Db	0 Db	18 ± 3.8 Da	14 ± 3.14 A Da
Df		3	3	3	3
F-value		440.527	2078.554	268.187	281.993
p		<0.0001	<0.0001	<0.0001	<0.0001

Means ($\bar{x} \pm SD$) followed by different capital letters in columns are significantly different at $p < 0.05$ (Tukey HSD test). Means ($\bar{x} \pm SD$) followed by different small letters in rows (between no. of eggs and hatchability in each cross with opposite) are significantly different at $p < 0.05$ (two-proportion z-test).

Discussion

X-irradiation produced dose-dependent biological effects that varied by life stage and sex. When pupae were irradiated, it decreased adult emergence, longevity, and fecundity, completely preventing emergence at 200 Gy and fully inhibiting F_1 egg hatch at 150 Gy. In adults, longevity was unaffected, but fecundity and egg hatch declined with increasing dose, with total inhibition at 150 Gy. Cross-mating experiments revealed females are more strongly sterilized by irradiation than males, as irradiated females × normal males produced fewer offspring than

the reciprocal cross.

Our study revealed that *P. operculella* pupae irradiated with X-rays decreased adult emergence and lifespan as well as fecundity, ending with a complete inhibition of F_1 egg hatchability at 150 Gy. There has been evidence that X-ray irradiation or gamma radiation has a significant negative impact on a variety of biological parameters in *P. operculella* (Saour and Makee, 1997; Cho *et al.*, 2021). Accordingly, several studies on lepidopteran and dipteran pests including *Ephestia elutella* (Hübner) (Lepidoptera: Pyralidae), *Cydia pomonella* (Lepidoptera: Tortricidae), *Spodoptera litura* (Fabricius) (Lepidoptera:

Noctuidae), *Aedes aegypti* L. (Diptera: Culicidae), and *Bactrocera dorsalis* (Hendel) (Diptera: Tephritidae) showed that X-ray irradiation at definite doses resulted in a decrease in adult emergence, longevity, sterility, fecundity, and a zero F₁ egg hatch (Chang *et al.*, 2016; Zhao *et al.*, 2022; Jiang *et al.*, 2022; Wang *et al.*, 2023; Zhang *et al.*, 2023; Chen *et al.*, 2025). Thus, many studies on diverse insect species support these findings, and highlight the biological effects of X-ray radiation. Some of the comparative studies of X-ray and gamma irradiation indicated that X-ray can be as effective as or, in some cases, more effective than gamma irradiation depending on the applied dose, the insect species and the developmental stage (Hendrichs *et al.*, 2009; Yamada *et al.*, 2023).

The results indicate that X-ray irradiation of adults could be a promising phytosanitary measure against *P. operculella* because as the dose increases, fecundity and egg hatch are clearly reduced, even though adult longevity is not significantly affected (Hallman and Hellmich, 2009). Moreover, due to the higher sensitivity of females than males, treatment success depends on achieving complete sterility, especially in females, rather than causing immediate death; this finding is in accordance with international phytosanitary evidence, which indicates that irradiation can be beneficial when it induces sterility or F₁ sterility rather than direct death (Follett, 2024). As a result of cross-mating results, X-ray irradiation is an effective technique for supporting SIT programs, since irradiated adults still mate but produce fewer viable offspring; this makes sterile males especially important, since they can compete with wild males and reduce reproduction without killing them immediately (Saour and Makee, 1997; Dyck *et al.*, 2021).

Regarding the target developmental stage of PTM for SIT, fertility was strongly suppressed after X-ray irradiation of both pupal and adult stages, but survival effects were different; whereas pupal irradiation reduced adult emergence more strongly, adult irradiation caused only sterility, with little effect on longevity; overall, the study

suggests that male-only release of irradiated *P. operculella* would be the most practical approach to SIT (Makee and Saour, 1999; 2003; Marec and Vreysen, 2019).

The current research indicates that X-ray irradiation doses cause sterilization of *P. operculella*, imparting the same sterilization properties as gamma in earlier studies (Saour and Makee, 1997). However, other studies have shown that X-rays can be equally effective, if not superior, to gamma rays for sterilizing many other species. For example, X-ray irradiation produced male sterility comparable to gamma rays in *A. aegypti* pupae and adults in comparison to gamma rays (Wang *et al.*, 2023). Low-rate of irradiation in the smart 160W industrial X-ray machine could explain why insect sterility is higher at high doses as compared to gamma radiation doses. However, when used in SIT at the same radiation dose, there is a clear difference between the effects of high and low radiation dose rates on insect reproduction. In accordance with the results of LEPIR X-ray machine irradiation (low-energy), Bakri *et al.* (2021) reported that the application of high doses at low dose rates results in higher sterility, which explains why high doses may be more effective when low dose rates are applied.

Conclusion

The findings of this study have particularly important implications for the SIT on the PTM control because they demonstrate that low-energy LEPIR X-ray machine irradiation can be an effective substitute for gamma radiation in inducing PTM sterility. Observed reductions in reproductive capacity demonstrate that this approach has the potential to suppress pest populations effectively. Furthermore, the dose-dose rate relationship provides valuable insight into optimizing irradiation protocols, which can increase the efficiency and cost-effectiveness of SIT programs. Further research should explore the potential of X-ray-based sterilization for use as an alternative to gamma radiation in the SIT against *P. operculella*.

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Φορητή βιομηχανικής χρήσης συσκευή ακτίνων-Χ χαμηλής ενέργειας για τη στείρωση της φθοριμαίας *Phthorimaea operculella*

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Περίληψη Η ακτινοβολία γ χρησιμοποιείται εδώ και πολλά χρόνια σε ευρεία κλίμακα στην ιατρική, βιομηχανική και γεωργική έρευνα και τις εφαρμογές τους. Πολλές χώρες έχουν εγκρίνει τη χρήση της ως αποτελεσματικό εργαλείο για την τεχνική εξαπόλυσης στείρων εντόμων (Sterile Insect Technique, SIT) στο πλαίσιο ολοκληρωμένων προγραμμάτων διαχείρισης επιβλαβών οργανισμών. Η παρούσα μελέτη αξιολογεί τη δυνατότητα χρήσης μιας φορητής βιομηχανικής συσκευής ακτίνων Χ χαμηλής ενέργειας (Low-Energy Portable Industrial Radiography, LEPIR), η οποία χρησιμοποιείται συνήθως για μη καταστροφικούς ελέγχους υλικών, για τη στείρωση νυμφών και ακμαίων της φθοριμαίας της πατάτας (*Phthorimaea operculella*), ως εναλλακτική της ακτινοβολίας γ που χρησιμοποιείται συνήθως στα προγράμματα SIT. Τα αποτελέσματα μας συμφωνούν με προηγούμενα ευρήματα και καταδεικνύουν σαφείς, δοσοεξαρτώμενες επιζήμιες επιδράσεις σε βασικές βιολογικές παραμέτρους του εντόμου, όπως η έξοδος των ακμαίων, η μακροβιότητα, η γονιμότητα, η αναπαραγωγική ικανότητα, καθώς και η εκκολαψιμότητα των αυγών της πρώτης θυγατρικής γενιάς (F1), σε δόση 150 Gy. Τα ευρήματα αυτά υποδεικνύουν ότι η συσκευή ακτίνων Χ LEPIR μπορεί να αποτελέσει μια πρακτική και αξιόπιστη εναλλακτική λύση έναντι της ακτινοβολίας γ σε προγράμματα SIT που στοχεύουν στον σκώρο της πατάτας.

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