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Suppression of *Cadra cautella* (Lepidoptera: Pyralidae) development by phytosanitary irradiation doses and their impacts on physiochemical and microbiological quality of dates

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Research Paper

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Abstract

Cadra cautella is a serious insect pest of stored figs and dates. The irradiation sensitivity of different development stages of *C. cautella* and large-scale testing of the proposed irradiation quarantine doses (50–500 Gy), were investigated. The impact of a PI dose of 400 Gy on the physiochemical and microbiological quality of dry dates (Bartamoda cv.) stored at room temperature was also investigated. An irradiation dose of 100 Gy prevented egg hatching in the F1 generation when 1–3 days old eggs were irradiated. Irradiation doses of 200 and 300 Gy prevented adult emergence when 2nd and 4th instar larvae were irradiated. When the pupae stage was irradiated, an irradiation dose of 400 Gy prevented the hatchability of F1 generation, indicating that this stage was the most radio-tolerant. The results of large-scale testing of the proposed phytosanitary irradiation dose (400 Gy) applied to 18, 0000 pupae resulted in no reproduction (zero hatching of F1 generation). There were no significant differences in the physiochemical properties of stored dates during the storage period at room temperature. Stable ESR signal intensity was recorded for 6 months in all parts of the irradiated fruits, and the intensity was highest in the kernel. The PI dose of 400 Gy also slightly reduced all microorganisms' counts. In conclusion, the dose level of 400 Gy stopped the reproduction potential of *C. cautella*. and they maintained the quality characteristics of dry date Bartamoda fruits during storage at room temperature for 6 months in tightly closed packages.

Introduction

Egypt produces about 1.6 million tonnes of all types of dates annually (*Phoenix dactylifera* L.): dry, semi-dry, and soft. However, about 50% of this production is lost due to insect infestation and microbial infection during post-harvest storage (Issa *et al.*, 2021; Salem *et al.*, 2021). Gamma irradiation technology is effective in eliminating insect and microbial infestations throughout the storage period of fruits without leaving harmful residues in treated products, saving consumer health and the environment, unlike the use of pesticides (Al Qahtani *et al.*, 2012; Huang *et al.*, 2019; Zarbakhsh and Rastegar, 2019; Bisht *et al.*, 2021). Date fruits include abundant nutrients and carbohydrates, fibre, and lipids. Gamma irradiation treatment improves the storability of date fruits and maintains their quality for long periods during good storage conditions. Treatment with gamma rays slows down the rate of physiological changes that occur in fruits due to respiration processes (Farag *et al.*, 2013). Many researchers found that gamma irradiation significantly reduces weight loss in irradiated date fruits compared to non-irradiated dates, which prolongs the fruit shelf life. The irradiation treatment did not significantly affect the physiochemical characteristics (total soluble solids (TSS; %), moisture content (%), and pH). On the other hand, irradiation may cause a non-significant breakdown of some sugars (disaccharides) such as sucrose, into monosaccharides, like glucose and fructose. Still, it does not affect the taste of the fruits (El-Beltagi *et al.*, 2019). Browning (darkening in colour) may increase in irradiated date fruits, but it remains insignificant with low doses up to 1 kGy. It is worth noting that browning also occurs in non-irradiated dates when stored at room temperature in places where the temperature is relatively high, as in some Arab countries (Farag *et al.*, 2013). Contamination of dates with microorganisms including bacteria, fungi, and yeast is the main cause of date rot and spoilage during storage, especially at high temperatures and relative humidity. Irradiation doses in the range of 2–3 kGy

cause a great reduction in these microorganisms and consequently increase the shelf life. An irradiation dose of less than 1 kGy effectively disinfest dates without significantly changing their characteristics (da Silva Aquino, 2012; Farag *et al.*, 2013). Therefore, this study was conducted on dry date fruits of the Bartamoda cultivar to confirm the safety and efficacy of using phytosanitary irradiation in the disinfestation of dates.

The fig moth, *Cadra cautella* (Walker) (Lepidoptera: Pyralidae), is a worldwide serious pest of dates and other crops, in the field and storage. Infestation by this pest significantly limits the sale and export of dates (Husain *et al.*, 2017). Adults *C. cautella* live for about 10 days and do not eat, but may drink if water is available. The total larval duration is 32 days at 25°C. A mean ovipositional is 6 days yielding 213 eggs per female, with hatchability 85%, at 25°C. When the larva matures, it will actively leave the food source and search for a site to pupate. The larva pupates in a silk cocoon (Husain *et al.*, 2017). Two main factors contributing to the seriousness of *C. cautella* are the ability to develop resistance from using chemical insecticides for disinfestation and the tendency of larvae to feed inside date fruits (Attia and Greening, 1981; Dakhil, 1987). Using methyl bromide and phosphine fumigants as a quarantine treatment has been recently restricted from being used as fumigants to control insect pests in food products due to its depletion of the ozone layer, leaving health hazards residues and leading to insect resistance (Dakhil, 1987; Taylor, 1994; Hallman, 2013).

Previous studies have reported the effect of gamma irradiation on the control of *C. cautella*, such as Amoako-Atta and Partida (1976), Amoako-Atta and Mills (1977), Al-Taweel *et al.* (1990), Ahmed *et al.* (1974), Calderon and Gonen (1971), and Brower (1980). However, there needs to be more information regarding applying phytosanitary irradiation as a quarantine treatment to overcome quarantine barriers in trade and prevent the spread of insect pests to new areas. It is approved by regulatory bodies in many countries worldwide (IPPC, 2011). Phytosanitary irradiation has been recognised as an effective and promising technology alternative to harmful fumigants (Neven, 2010; Antonio *et al.*, 2012). The main advantages of phytosanitary irradiation as a quarantine treatment are that it is an environmentally friendly, non-thermal process that does not leave any residues in the treated products, a continuous process, and is more effective in killing various development stages, especially the larval stage inside large fruits such as dates, mangoes, tomatoes, etc. Several studies have reported the effectiveness of phytosanitary irradiation on common insect pests infesting agriculture products (Hallman, 2013; Gabarty *et al.*, 2020; Hammad *et al.*, 2020). More research is needed to establish a generic phytosanitary dose for insects and fruits. The results of the present work will be submitted to support the generic phytosanitary irradiation dose.

The main aims of the present work are to assess the effect of different gamma irradiation doses on various development stages of *C. cautella*, determine the most radio-resistance stage, and conduct large-scale tests to confirm and establish phytosanitary irradiation efficacy. Another goal was to investigate the impact of phytosanitary gamma irradiation dose on the date's physiochemical properties and microbiological aspects.

Materials and methods

Rearing technique of C. cautella

Fig moths, *C. cautella* were reared for 5 years in the Entomology Laboratory at the Plant Protection Research Institute, Dokki, Giza, Egypt. Fig moth larvae were reared in plastic jars of 1-litre volume on an artificial diet consisting of ground wheat (250 g), ground sugar (25 g), dry yeast (25 g), and glycerol (37.5 g) (Hussain, 1985). Adult moths were introduced into chimney glass cages. The cage had two openings, one at the top covered with gauze after placing moths inside the cage and the other at the bottom covered with gauze with holes wide enough to allow eggs to pass through. A Petri dish was put under each cage to collect eggs that passed through the gauze. Newly laid eggs were collected daily from the Petri dishes. All insect life stages were reared in an incubator at 25 ± 2°C and 65 ± 5% relative humidity in continuous darkness. The life cycle of insects from egg stage to adult was 28 days in the case of rearing on an artificial diet, while 40 days on a date diet. The longevity of adults at the optimal temperature was 8 days.

Gamma irradiation of C. cautella *development stages*

For the irradiation of fig moth eggs, each sample comprised of 30 eggs (1-day-old) placed in a test tube and exposed to 50, 75, 100, 150, and 200 Gy (five replicate samples were used for each treatment dose). Similarly, 3-day-old eggs (30 eggs per sample) were exposed to 50, 75, 100, 150, 200, 250, 300, 350, and 400 Gy of gamma radiation (five replicate samples for each treatment). Five replicates of non-irradiated eggs were used as controls in the two experiments. The number of hatching larvae in each replicate was counted and transferred to date fruits. The percentage of egg hatch and adult emergence were determined. Five pairs of fig moth adults (one male and one female in each replicate) resulting from each irradiation dose treatment were collected by test tube and introduced into chimney glass cages until mating. The kind of sex was determined on the third day of the 5th instar larvae based on the presence of the dark testes on the dorsal surface of the larvae, in the case of males and its absence in the case of females (Bolesh and Marzke, 1966). Furthermore, the end of the abdomen of the male moth is pointed, while the end of the female moth is circular. Newly resulting laid eggs were collected in Petri dishes and counted daily to calculate the percentage of egg hatch for the F1 generation resulting from irradiated eggs.

For the irradiation of the larvae stage, the date with 2nd instar larvae (6-day old) and the date with 4th instar larvae (18-day old) were put in a small plastic box ($15 \times 15 \times 10\ cm^3$) and were exposed to 50, 75, 100, 150, 200, 250, 300, and 350 Gy of gamma radiation (five replicate samples were used for each treatment dose). The number of larvae in each replicate was 20 larvae. Two groups of non-irradiated 2nd and 4th instar larvae with a date were used as controls (five replicates for each group). Larval mortality and adult emergence data were determined. Five pairs of emerged fig moth adults (one male and one female in each replicate) and five replicates of non-irradiated eggs were used as a control in the two experiments which were introduced into chimney glass cages to breed until mating. Newly laid eggs were collected and counted daily to determine the percentage of F1 generation hatching eggs.

For the irradiation of fig moth pupae, the date with 20 pupae (3-day-old) in a small plastic box ($15 \times 15 \times 10\ cm^3$) was exposed to 50, 75, 100, 150, 200, 250, 300, 350, 400, 450, and 500 Gy of gamma radiation (five replicates were used for each treatment). Similarly, five replicates of non-irradiated pupae were used as control. The number and percentage of emerging adults were recorded. Five pairs of emerging fig moth adults (one male and one female in each replicate and control group) from each

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irradiated dose were introduced into chimney glass cages to breed. Newly laid eggs were collected and counted daily to determine the percentage of F1 generation hatching eggs.

The irradiation of 1-day-old adult fig moths involved samples of 20 adults (ten male and ten female) in small test tubes exposed to 50, 100, 150, 200, 250, and 300 Gy of gamma radiation (five replicates for each treatment). Similarly, five replicates of non-irradiated adults were used as control. The number of dead adults was determined after 5 days. Five couples of alive F1 adults (one male and one female in each replicate and control group) were introduced into chimney glass cages resulting from each irradiation treatment dose. Newly laid eggs were collected and counted daily to determine the percentage of F1 generation hatching eggs.

In large-scale confirmatory tests, 18,000 3-day-old pupae of *C. cautella* stock colony were irradiated with the proposed irradiation dose (400 Gy) that produced zero egg hatch in the F1 generation when the most radio-tolerant stage (pupae) were irradiated. In this experiment, approximately 600 pupae with dates (male and female) from 3-day-old were placed into ventilated containers ($15 \times 15 \times 10\ cm^3$) and irradiated at 400 Gy. This was repeated 30 times. Control experiments (non-irradiated pupae) involved five replicate samples, each of 150 pupae (male and female). This resulted in parent adults from the control experiment and from each irradiated dose being introduced into chimney glass cages to lay eggs. Newly laid eggs were collected and counted daily to derive the egg hatch data for F1 generation. The level of confidence (C) associated with treating a large number of *C. cautella* with zero survival was estimated using the equation: $C = 1 - (1 - Pu)^n$, where Pu (0.0001) is the acceptable level of survival and n is the number of treated insects (Couey and Chew, 1986).

Irradiation procedure

Gamma radiation was processed using the Indian ^{60}Co Gamma Chamber (4000A) at the National Centre for Radiation Research and Technology (NCRRT), Nasr City, Cairo, Egypt. The average gamma dose rate was 0.7967 kGy h^{-1}. Alanine dosimeters, traceable to the UK National Physical Laboratory, were used to calibrate the irradiator and measure the average absorbed dose. Detailed dose mapping was conducted by the Department of Radiation Protection and Dosimetry at NCRRT. Eggs and adults were irradiated at different doses after putting them in a small test tube. However, pupae and larval stages were irradiated in a small plastic box ($15 \times 15 \times 10\ cm^3$). Dry date fruits were irradiated with the established phytosanitary dose of 400 Gy after packaging in transparent low-density polyethylene bags to study its impact on the physiochemical and microbiological aspects during storage at room temperature.

Physiochemical measurements on date fruits

Dry date fruits (Bartamoda cv.) were harvested from adult palms grown in a private orchard in Qena Governorate during the growing season 2021. Date samples were free from any postharvest treatment. The dates were transferred to Food Irradiation, Microbiology, and Entomology NCRRT Laboratories, Nasr City, Cairo, Egypt. The experimental samples were randomly chosen from the clean and healthy identical fruits.

The dates of the fruits irradiated with 400 Gy and non-irradiated (control) samples were stored at room temperature for 6 months (from November to April 2021–2022). Six replicates were used in all experimental measurements; each replicate was about 150 g of dates (the average weight of the fruit is 5.3 ± 1.3 g). Three replicates of the fruit were allocated to calculate the weight loss percentage over the 6-month storage period. The remaining three replicates were used in other measurements.

Weight loss

Samples of packaged dates were weighed at monthly intervals for 6 months by an electronic balance with a sensitivity of about 0.01 g, and the differences between the weights were recorded at the beginning and end of the storage periods to calculate the percentage of weight loss through the following equation (Farag *et al.*, 2013):

$$\text{Weight loss (\%)} = \frac{\text{Initial weight of fruits} - \text{Fruit weight at each sampling date}}{\text{Initial weight of fruits}} \times 100$$

Total soluble solids

Ten grams of fruit flesh were cut into small pieces, soaked in 100 ml of distilled water for 1 h, then blended using an electric blender and filtered by Whatman filter paper. The values of TSS were measured in the filtered solution using a handle refractometer (0-30 – Brix % mass sucrose, ATC) at room temperature of 25°C (Feldsine *et al.*, 2002; Paez *et al.*, 2016).

Moisture content

The seeds were removed from the fruits, and 10 g of fruit flesh from each replicate was cut into small pieces. The samples were dried at 105°C for a constant weight (2 h or more) according to AOAC (2006). The percentage of moisture was calculated from the following equation:

$$\text{Moisture (\%)} = (\text{sample weight before drying} - \text{sample weight after drying}/\text{sample weight before drying}) \times 100$$

pH value

The pH values were measured by using the pH-meter Beekman Model with a combination electrode at 25°C as mentioned by AOAC (2006). Ten grams of fruit flesh were cut into small pieces, soaked in 100 ml of distilled water for 1 h, blended using an electric blender, and filtered by Whatman filter paper. The pH values were measured for the filtered solution.

Determination of monosaccharide

Samples were prepared after 6 months (the end of the storage period), according to Chaira *et al.* (2007). The monosaccharide contents were quantified by high-performance liquid chromatography (HPLC) on a Shimadzu Shim-Pack SCR-101N column (7.9 mm × 30 cm) using deionised water as the mobile phase (flow rate: 1 ml min^{-1} at 40°C) and refractive index was detected as described by Sesta (2006) and Ramchoun *et al.* (2017).

UV scanning (browning)

Ten grams of fruit flesh were cut into small pieces, soaked in 100 ml ethanol for 95% to 12 h at room temperature, and filtered by Whatman filter paper. The ethanol extraction was measured by UV–visible analysis at 420 nm using a UVKON 860 spectrophotometer (Farag *et al.*, 2013).

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Sensory evaluation

Twenty panelists assessed sensory evaluation according to Omolola *et al.* (2017); Jo *et al.* (2018); and El-Dein *et al.* (2018). They include appearance, colour, taste, odour, and texture. The tests were performed at the end of the storage period (after 6 months). A scale of 1–10 (1 is very bad, and 10 is excellent) was used for sensory evaluation. Non-irradiated (control) samples, free of any insect infestation and clean, were selected to be fairly evaluated with the irradiated samples.

Electron spin resonance detection

The different parts of the fruit (flesh, kernel, calyx cap) were ground. The electron spin resonance (ESR) measurements were carried out after irradiation (zero time) and after 6 months on the same samples. The free radicals created electron paramagnetic resonance (EPR) signals were recorded at room temperature by an X-band EMX spectrometer (Bruker, Germany) located at NCRRT, Cairo, Egypt, using a standard rectangular cavity of ER 4102 (Gohn, 1986; Aleksieva and Yordanov, 2018).

Microbiological assessment

The total aerobic bacterial count was enumerated on plate count agar medium (Difco, USA) using the standard plate count technique. After tenfold serial dilutions of samples, 1 ml of the three appropriate serial dilutions was plated (in duplicate) on Petri dishes. The inoculated plates were incubated at 30°C for 48–72 days. After the incubation period, the colonies forming units were counted and expressed as CFU g^{-1} (APHA, 1992).

Total fungi and yeast counts

Total fungi and yeasts were counted on Czapek Dox yeast extract agar medium using the standard pour plate technique. The inoculated plates were incubated at 27°C ± 1 for 3–5 days, and then the appearance colonies were counted and expressed as CFU g^{-1} (Koburger and Marth, 1984).

Total coliforms and Escherichia coli

Total coliforms and *E. coli* were counted on the Charm Peel plate EC microbial test (Kit, code, PP-EC, 100k) according to the Charm Operators Manual. The inoculated plates were incubated at 35°C ± 1 for 24 h, and then the plates were observed for colour colonies. Red colonies represent coliform bacteria, while blue-black colonies represent *E. coli*. This test has been certified by AOAC Research Institute as Performance Test Method no. 061501.

Statistical analysis

All statistical analyses were performed at a 5% significance level with the least significant difference using the SPSS (Statistical Package for Social Sciences, ver. 17.0) computer program. For the statistical analysis of (tables 1–6), the mean values and standard deviations (SD) for all measurements were calculated over five replicates. One-way analysis of variance (ANOVA) followed by post hoc test (Tukey) was performed to analyse the significant difference between all irradiated groups.

In the case of tables 8–13, the mean values and SDs for all measurements were calculated over three replicates. The experiment's design was completely randomised. Two-way ANOVA and two independent sample *t*-tests were used to compare the two levels of factors, followed by a post hoc test (Duncan) to analyse the significant difference between all the tested groups.

Results

Effect of gamma irradiation on C. cautella development stages

Gamma irradiation effects on eggs stage of C. cautella

The impact of gamma irradiation on 1-day-old eggs of the fig moth *C. cautella* is shown in table 1. These results show that an irradiation dose of 150 Gy completely prevented adult emergence from irradiated eggs (1-day-old). In comparison, a lower irradiation dose (100 Gy) prevented the hatching of eggs laid by the F1 generation. Results in table 2 indicate that 3-day-old eggs were more radio-tolerant than 1-day-old eggs. The higher irradiation dose of 250 Gy prevented adult emergence. At the same time, the 100 Gy irradiation dose also prevented egg hatching of F1 generation-laid eggs.

Gamma irradiation effects on larvae stage of C. cautella

Results for the irradiation of fig moth 2nd and 4th instar larvae are given in tables 3 and 4. An irradiation dose of 200 Gy prevented adult emergence from irradiated 2nd larval instars, so no viable eggs were produced. A higher irradiation dose of 250 Gy prevented adult emergence from the irradiated 4th larval instar. These data indicate that the 4th instar larval form was more radiation-tolerant than the 2nd larval instar.

Gamma irradiation effects on pupae and adult stage of C. cautella

Irradiation of *C. cautella* pupae is given in table 5, and it is revealed that the most radio-tolerant stage of *E*phestia *cautella* was the 3-day-old pupae. An irradiation dose of 400 Gy almost completely prevented adult emergence and eggs laid by the F1 generation from hatching. If the prevention of egg hatching from F1 generation is used as a criterion for measuring the efficacy of irradiation, 400 Gy is required. Irradiation of the adult stage at 300 Gy table 6 resulted in 80% adult mortality, while only 150 Gy prevented F1 generation hatch (prevent F1 egg hatch).

Large-scale confirmatory tests of irradiating C. cautella

In the large-scale validation tests, a radiation dose of 400 Gy applied to 18,000 *C. cautella* pupae resulted in zero hatchability percentage (no reproduction) at F1 generation, indicating that this dose is sufficient to control *C. cautella* and provide quarantine security. Assuming a required efficacy of 99.99%, $C = 1 - (1 - 0.0001)^{18,000}$, our confidence level was 83.5%. In non-irradiated control, 500 pupae of *C. cautella* produced an average of 2600 hatching larvae (table 7).

Effect of the phytosanitary irradiation dose (400 Gy) on the physiochemical characteristics of dry dates 'Bartamoda cv.'

Effect of phytosanitary irradiation dose (400 Gy) on weight loss (%) of Bartamoda dates

Table 8 shows the weight loss percentage weight loss percentage in Bartamoda dry dates during the 6-month storage period at room temperature. There was a slight gradual increase in weight loss percentage with the increased storage period at room temperature. It is clear from the displayed values that the rate of weight loss was generally low during the storage period. It ranged between 0.11 ±

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Table 1. Effect of gamma radiation on 1-day-old eggs of *C. cautella*

Dose (Gy)	No. of hatched eggs, mean ± SD	Hatchability (%)	No. of emerging adults, mean ± SD	Adult emergence (%)	F1 generation	
					Fecundity	No. of hatched eggs, mean ± SD
Control	27.8 ± 1.3[a]	92.7	25 ± 1.9[a]	83.3	170.8 ± 21[a]	148 ± 15.4[a]
50	17.5 ± 2.4[b]	58.3	11.6 ± 2.7[b]	38.6	93 ± 18.5[b]	46.8 ± 7.2[b]
75	10.8 ± 2.2[c]	36	6 ± 1.6[c]	20	39 ± 7.9[c]	10.4 ± 3.2[c]
100	5.2 ± 2.9[d]	17.3	2 ± 0.7[d]	6.7	14 ± 4.9[d]	0 ± 0
150	1 ± 0.7[e]	3.3	0 ± 0	0.0	0 ± 0	0 ± 0
200	0.0 ± 0.0	0.0	0 ± 0	0.0	0 ± 0	0 ± 0

The no. of eggs irradiated in each rep. is 30. The post hoc test is Tukey. Means followed by the same letters are not significantly different at the 0.05 level compared between the groups.

Table 2. Effect of gamma radiation on 3-day-old eggs of *C. cautella*

Dose (Gy)	No. of hatched eggs, mean ± SD	Hatchability (%)	No. of emerging adults, mean ± SD	Adult emergence (%)	F1 generation	
					Fecundity	No. of hatched eggs, mean ± SD
Control	27 ± 1.8[a]	90	25 ± 1.6[a]	83.3	171 ± 15[a]	149.8 ± 9.4[a]
50	21 ± 1.5[b]	70	16 ± 3.2[b]	53.3	80 ± 12.8[b]	50.8 ± 11[b]
75	16 ± 2.3[c]	53.3	11.2 ± 2.4[c]	37.3	39.4 ± 6.8[c]	6.2 ± 1.9[c]
100	9.2 ± 0.8[d]	30.7	4.2 ± 1.9[d]	14	28.8 ± 5.4[c]	0 ± 0
150	4.8 ± 1.6[e]	16	0.8 ± 0.8[d]	2.7	8.6 ± 8.8[d]	0 ± 0
200	3 ± 1.5[ef]	10	0.4 ± 0.5[d]	1.3	0 ± 0	0 ± 0
250	0.8 ± 0.8[f]	2.7	0 ± 0	0.0	0 ± 0	0 ± 0
300	0.4 ± 0.5[f]	1.3	0 ± 0	0.0	0 ± 0	0 ± 0
350	0.2 ± 0.4[f]	0.7	0 ± 0	0.0	0 ± 0	0 ± 0
400	0 ± 0	0.0	0 ± 0	0.0	0 ± 0	0 ± 0

The no. of eggs irradiated in each rep. is 30. The post hoc test is Tukey. Means followed by the same letters are not significantly different at the 0.05 level compared between the groups.

Table 3. Effect of gamma radiation on 2nd larval instars of *C. cautella*

Dose (Gy)	No. of larvae dead, mean ± SD	Larval mortality (%)	No. of emerging adults, mean ± SD	Adult emergence (%)	F1 generation	
					Fecundity	No. of hatched eggs, mean ± SD
Control	0.0 ± 0.0[e]	0	18.6 ± 1.14[a]	93	145.8 ± 21.4[a]	136.6 ± 19.3[a]
50	1.2 ± 0.4[e]	6	12.6 ± 2.1[b]	63	80.8 ± 11.9[b]	40.6 ± 6.6[b]
75	4.2 ± 1.3[d]	21	9 ± 2.24[c]	45	52.4 ± 7.7[c]	22.4 ± 3.8[c]
100	5.8 ± 1.5[d]	29	5.2 ± 1.3[d]	26	18.8 ± 3[d]	5.6 ± 1.1[d]
150	10.6 ± 1.1[c]	53	1.4 ± 1.14[e]	7	7 ± 2.5[d]	1.4 ± 1.7[d]
200	15.4 ± 1.1[b]	77	0 ± 0	0.0	0 ± 0	0 ± 0
250	18.4 ± 1.34[a]	92	0 ± 0	0.0	0 ± 0	0 ± 0
300	18.8 ± 1.3[a]	94	0 ± 0	0.0	0 ± 0	0 ± 0
350	19.2 ± 1.1[a]	96	0 ± 0	0.0	0 ± 0	0 ± 0

The no. of larvae irradiated in each rep. is 20. The post hoc test is Tukey. Means followed by the same letters are not significantly different at the 0.05 level compared between the groups.

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Table 4. Effect of gamma radiation on 4th larval instars of *C. cautella*

Dose (Gy)	No. of larvae dead, mean ± SD	Larval mortality (%)	No. of emerging adults, mean ± SD	Adult emergence (%)	F1 generation	
					Fecundity	No. of hatched eggs, mean ± SD
Control	0.0 ± 0.0^{f}	0.0	18 ± 1.6^{a}	90	174.6 ± 16.5^{a}	162.6 ± 17.7^{a}
50	0.2 ± 0.4^{f}	1	15.2 ± 0.8^{b}	76	105.6 ± 9.3^{b}	54 ± 13.3^{b}
75	2 ± 1.6^{f}	10	13 ± 1.9^{c}	65	74.4 ± 8.2^{c}	31.6 ± 5^{c}
100	4.8 ± 0.8^{e}	24	10.8 ± 1.3^{d}	54	60.6 ± 9.9^{c}	20.4 ± 2.7^{cd}
150	9.4 ± 1.14^{d}	47	6.4 ± 1.1^{e}	32	35.8 ± 6.3^{d}	10.6 ± 2.7^{de}
200	14 ± 1.6^{c}	70	1.2 ± 0.8^{f}	6	15.4 ± 9.2^{e}	3.2 ± 0.8^{e}
250	16 ± 1.2^{b}	80	0.4 ± 0.5^{f}	2	1.8 ± 2.5^{e}	0 ± 0
300	17.6 ± 1.14^{ab}	88	0 ± 0	0.0	0 ± 0	0 ± 0
350	19 ± 1^{a}	95	0 ± 0	0.0	0 ± 0	0 ± 0

The no. of larvae irradiated in each rep. is 20. The post hoc test is Tukey test. Means followed by the same letters are not significantly different at the 0.05 level compared between the groups.

Table 5. Effect of gamma radiation on the pupae stage of *C. cautella*

Dose (Gy)	No. of emerging adults, mean ± SD	Adult emergence (%)	F1 generation	
			Fecundity	No. of hatched eggs, mean ± SD
Control	18.6 ± 1.14^{a}	93	124.8 ± 17.7^{a}	104.2 ± 10.8^{a}
50	15.4 ± 0.9^{b}	77	95 ± 11.8^{b}	72.2 ± 4.9^{b}
75	11 ± 2.2^{c}	55	70.8 ± 16.1^{c}	46.4 ± 5.2^{c}
100	10 ± 2.1^{c}	50	49.8 ± 6.1^{d}	29.2 ± 5.2^{d}
150	6 ± 2.9^{d}	30	30.4 ± 7.8^{e}	16.4 ± 5.3^{e}
200	4.2 ± 1.9^{de}	21	21 ± 6.8^{ef}	7.8 ± 2.7^{ef}
250	2 ± 1.1^{e}	10	13.4 ± 4.3^{ef}	4.6 ± 1.1^{f}
300	1 ± 0.7^{e}	5	10.2 ± 6.6^{f}	2.8 ± 1.9^{f}
350	0.6 ± 0.5^{e}	3	4.2 ± 4^{f}	1 ± 1^{f}
400	0.2 ± 0.4^{e}	1	0 ± 0	0 ± 0
450	0.0 ± 0.0	0.0	0 ± 0	0 ± 0
500	0.0 ± 0.0	0.0	0 ± 0	0 ± 0

The no. of pupae irradiated in each rep. is 20. The post hoc test is Tukey. Means followed by the same letters are not significantly different at the 0.05 level compared between the groups.

Table 6. Effect of gamma radiation on the adult stage of *C. cautella*

Dose (Gy)	No. of dead adults, mean ± SD	Adult mortality (%)	F1 generation	
			Fecundity	No. of hatched eggs, mean ± SD
Control	0.0 ± 0.0^{d}	0.0	149 ± 43.9^{a}	127.8 ± 35.4^{a}
50	3.6 ± 1.14^{c}	18	121.8 ± 50^{ab}	59.2 ± 29.8^{b}
100	4.2 ± 1.3^{c}	21	84.6 ± 19.2^{b}	8.8 ± 2.9^{c}
150	5.4 ± 1.3^{c}	27	65.2 ± 11.4^{bc}	0 ± 0
200	9.2 ± 0.8^{b}	46	38.6 ± 18.6^{bc}	0 ± 0
250	14.8 ± 1.5^{a}	74	16.6 ± 9.5^{c}	0 ± 0
300	16 ± 0.7^{a}	80	15.6 ± 11.1^{c}	0 ± 0

The no. of adults irradiated in each rep. is 20. The post hoc test is Tukey. Means followed by the same letters are not significantly different at the 0.05 level compared between the groups.

Table 7. Large-scale confirmatory tests irradiating pupal stage of *C. cautella*

Dose (Gy) Target dose	No. of replicates	No. of irradiated pupae	No. of eggs	No. of hatching larvae
400	30	18,000	0	0
Control	5	500	3100	2600

0.005 and 0.10 ± 0.005% in control and irradiated samples at the end of the storage period. The weight loss percentage for irradiated fruits was slightly less than for non-irradiated fruits, but the differences were insignificant.

Effect of phytosanitary irradiation dose (400 Gy) on moisture content (%) of Bartamoda dates

Moisture content of control and irradiated date fruits Bartamoda variety was ~10.8 and 10.45%, respectively, at zero time, as shown in table 9. These values slightly decreased after 6 months of storage at room temperature to 9.45 and 9.58% in control and irradiated dates. There was no significant effect of the phytosanitary irradiation dose (400 Gy) on the moisture loss in dry dates.

Effect of phytosanitary irradiation dose (400 Gy) on TSS of Bartamoda dates

TSS decreased gradually during storage at room temperature, as shown in table 10. The low dose of gamma irradiation (400 Gy) had no significant effect on TSS in irradiated dates.

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Table 8. Effect of phytosanitary irradiation dose (400 Gy) on weight loss (%) of Bartamoda dates during storage at room temperature

	Weight loss (%) Mean ± SD					
	Storage period (months)					
Treatment	1	2	3	4	5	6
Control	–	–	0.06 ± 0.02^{bcd}	0.09 ± 0.02^{bc}	0.11 ± 0.01^{ab}	0.11 ± 0.005^{ab}
400 Gy	–	–	0.03 ± 0.07^{cd}	0.06 ± 0.02^{bcd}	0.10 ± 0.01^{bcd}	0.10 ± 0.005^{bcd}

The post hoc test is Duncan. Means followed by the same letters are not significantly different at the 0.05 level compared between the groups. Independent samples *t*-test for weight loss (%) (df = 9, *t*-value = –0.48, *P* = 0.649).

Effect of phytosanitary irradiation dose (400 Gy) on pH values of Bartamoda dates

pH values of non-irradiated and irradiated dates 'Bartamoda variety' were recorded to be ~5.67 and 5.71, respectively, at the beginning of the storage period, then non-significantly decreased to 5.60 and 5.59 at the end of the storage period at room temperature shown in table 11.

Effect of phytosanitary irradiation dose (400 Gy) on the browning of Bartamoda dates

The browning values were measured chemically at 420 nm, as shown in fig. 1. At the beginning of the storage period, the browning values in the control and irradiated samples ranged between 1.18 and 1.17. The browning increased significantly at the end of the storage period in the irradiated and control samples, reaching 1.41 and 1.43, respectively. No significant differences existed between the browning values of non-irradiated (control) and irradiated dates.

Chromatogram of HPLC analysis of sugar content in non-irradiated and irradiated Bartamoda dates

HPLC profile analysis of Bartamoda dates is shown in figs 2–4. The results show the presence of major peaks as sucrose, glucose, and fructose. As shown in fig. 4, sucrose in irradiated samples (4.8 mg ml^{-1}) was lower than that in non-irradiated samples (5.63 mg ml^{-1}). In contrast, irradiated fruits' glucose and fructose content was slightly higher than that of non-irradiated fruits, where it was 4.48 and 2.82 mg ml^{-1} and 4.08 and 2.74 mg ml^{-1} in non-irradiated samples, respectively.

The ESR intensity of different parts of irradiated and non-irradiated Bartamoda dates

Figure 5 shows the intensity of the free radical signal presented in the different parts (flesh, kernel, calyx cap) of the irradiated and non-irradiated date fruit. The signal was present in all the non-irradiated and irradiated parts of the fruit but stronger in the irradiated parts. Results concluded that the signal intensity increased by increasing the storage period at room temperature in the irradiated and non-irradiated samples. It was also noted that the signal intensity was significantly higher in the kernel of the fruit and significantly lower in the fruit flesh samples, whether irradiated or not.

Sensory evaluation of irradiated and non-irradiated Bartamoda dates

The sensory tests of irradiated and non-irradiated dates indicated no significant differences in colour, appearance, taste, odour, and texture, as shown in table 12. The irradiation did not cause any undesirable changes in the organoleptic characteristics of the fruits, as the panelists could not differentiate between irradiated and non-irradiated date fruits.

Effect of phytosanitary irradiation dose on the microbial load of Bartamoda dates (CFU g^{-1})

Table 13 shows that the initial total bacterial counts, total fungi and yeasts, and total coliform bacteria in the fruits of the date under investigation at zero time were 1.2×10^4, 2.7×10^3, and 1.1×10^2 CFU g^{-1}, respectively. *E. coli* was not discovered in the date fruit samples since their counts were below the detectable level (<10 CFU g^{-1}). Irradiation at the effective phytosanitary dose in preventing the reproduction (zero hatching of F1 generation) of *C. cautella* caused a non-significant reduction in all microbial counts, i.e. by only 20.8, 18.5, and 29%, respectively. During the storage of Bartamoda dates for 6 months at room temperature, total microbial counts decreased gradually, and the storage period increased.

Table 9. Effect of phytosanitary irradiation dose (400 Gy) on moisture content (%) of Bartamoda dates during storage at room temperature

	Moisture (%) Mean ± SD					
	Storage period (months)					
Treatments	1	2	3	4	5	6
Control	10.80 ± 0.1^{a}	10.70 ± 0.03^{a}	10.97 ± 0.02^{a}	9.89 ± 0.03^{ab}	9.79 ± 0.1^{ab}	9.45 ± 0.4^{b}
400 Gy	10.45 ± 0.1^{a}	10.84 ± 0.03^{a}	10.59 ± 0.02^{a}	10.13 ± 0.03^{a}	10.14 ± 0.1^{a}	9.58 ± 0.4^{ab}

The post hoc test is Duncan. Means followed by the same letters are not significantly different at the 0.05 level compared between the groups. Independent samples *t*-test for moisture (%) (df = 8, *t*-value = 0.07, *P* = 0.947).

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Table 10. Effect of phytosanitary irradiation dose (400 Gy) on TSS of Bartamoda dates during storage at room temperature

	TSS (%) Mean ± SD					
	Storage period (months)					
Treatments	1	2	3	4	5	6
Control	54.78 ± 0.86^{a}	54.63 ± 1.02^{a}	49.72 ± 0.86^{bcd}	48.06 ± 1.01^{bcd}	46.63 ± 0.85^{cd}	42.1 ± 1.02^{d}
400 Gy	54.38 ± 1.01^{a}	54.60 ± 0.68^{ab}	50.51 ± 0.91^{ab}	48.44 ± 0.65^{abc}	46.14 ± 0.86^{bcd}	42.28 ± 0.89^{bcd}

The post hoc test is Duncan. Means followed by the same letters are not significantly different at the 0.05 level compared between the groups. Independent samples *t*-test for TSS (%) (df = 9, *t*-value = 0.03, *P* = 0.98).

Table 11. Effect of phytosanitary irradiation dose (400 Gy) on pH of Bartamoda dates during storage at room temperature

	pH Mean ± SD					
	Storage period (months)					
Treatments	1	2	3	4	5	6
Control	5.67 ± 0.05^{a}	5.67 ± 0.01^{a}	5.57 ± 0.01^{a}	5.62 ± 0.02^{a}	5.63 ± 0.02^{a}	5.60 ± 0.02^{a}
400 Gy	5.71 ± 0.05^{a}	5.67 ± 0.01^{a}	5.56 ± 0.01^{a}	5.59 ± 0.02^{a}	5.59 ± 0.02^{a}	5.59 ± 0.02^{a}

The post hoc test is Duncan. Means followed by the same letters are not significantly different at the 0.05 level compared between the groups. Independent samples *t*-test for pH (%) (df = 8, *t*-value = −0.29, *P* = 0.779).

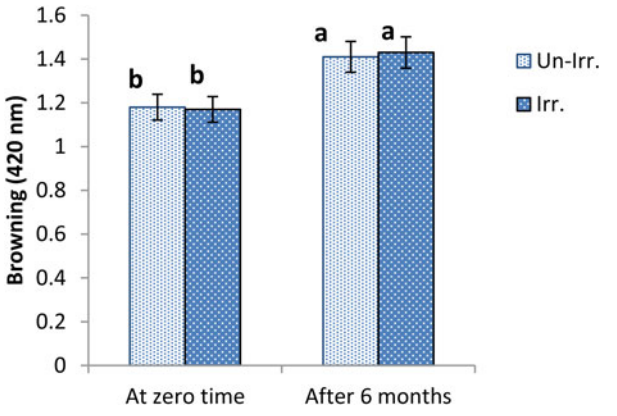

Figure 1. Effect of phytosanitary irradiation dose (400 Gy) on the browning in Bartamoda dates during storage at room temperature (The post hoc test is Duncan. Means followed by the same letters are not significantly different at the 0.05 level compared between the groups).

Discussion

Irradiation has grown as a phytosanitary treatment for insects in fresh commodities, stored products, and ornamentals. However, in the past, the guiding principle in quarantine treatment research has been that 99.9968% mortality was initially recommended for tropical fruits heavily infested with fruit flies. Nowadays, criteria such as the inability to reproduce (sterility – non-hatching eggs), non-completion of pest life stages, or non-emergence of adults were considered in Joint FAO (2004, 2022). Based on this concept, the suppression of *C. cautella* development by gamma irradiation doses and determining the required dose were studied.

The effects of gamma radiation on 1-day-old, 3-day-old eggs and 1-day-old adults (tables 1–3) show that a dose of 150 Gy prevents egg hatching in F1 generation. In comparison, the larval stage was more tolerant of radiation treatment than eggs and adults (tables 3 and 4). The dose levels of 200 and 250 Gy prevented egg hatching, resulting in irradiation of the 2nd and 4th, respectively, in the F1 generation. Omar (2017) found that a gamma irradiation dose of 250 Gy reduced the egg hatchability of *C. cautella* to 10%. Our results indicated that a gamma irradiation dose of 100 Gy reduced the 1-day-old eggs of *C. cautella* to 17.3%, whereas a reduction of 3-day-old eggs hatchability to 10% needed 200 Gy. Early, Cogburn *et al.* (1973) investigated the effect of six gamma irradiation doses in the range of 50–1000 Gy against all life stages of *C. cautella* and found the prevention of development of adults from irradiated eggs, and larvae were 200 and 300 Gy, respectively. These results agree with the results obtained in the present work, where we found that irradiation doses of 250 and 300 Gy prevented adult emergence from irradiated 3-day-old eggs and the 4th larval instars, respectively. Also, Ayvaz and Tuncbilek (2006) reported that a dose of 200 and 250 Gy applied to earlier and late larval stages of *Ephestia kuehniella* completely prevented adult emergence, respectively, indicating that the younger larval instars were more sensitive to irradiation than older ones. Ozyardimic *et al.* (2006) found that the required gamma irradiation doses to inhibit the development of the egg stage of Indian meal *Plodia interpunctella* and *E. cautella* were 450 and 300 Gy, respectively.

The results in table 5 indicate that the dose level of 400 Gy prevents the egg hatching of F1 generation resulting from irradiated 3-day-old pupae. So, the most radio-tolerant stage of *C. cautella* was 3-day-old pupae. Amoako-Atta and Partida (1976) reported that a dose of 200 and 300 Gy prevented the adult emergence of 2- and 4-day old pupae of *C. cautella*. While Amoako-Atta

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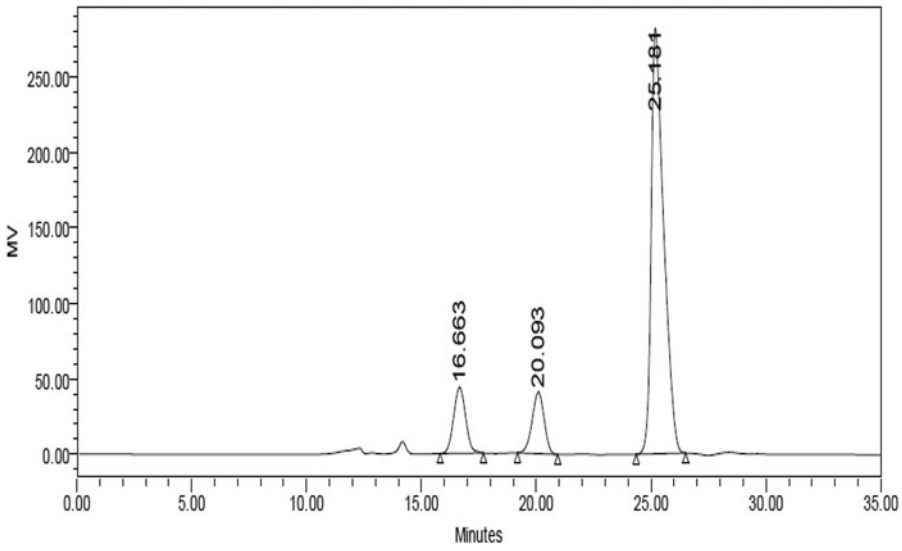

Figure 2. Chromatogram of HPLC analysis of sugars content in non-irradiated Bartamoda dates after 6 months of storage at room temperature.

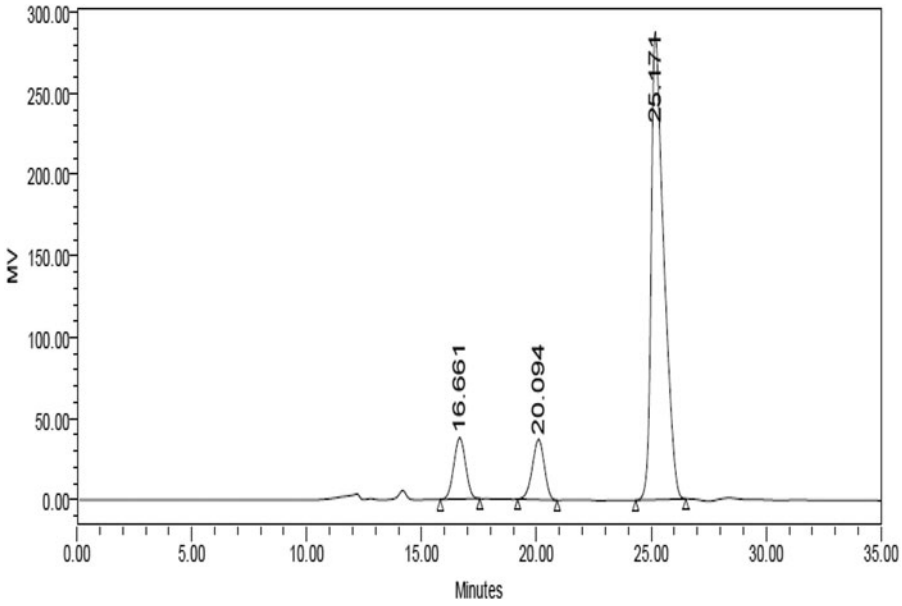

Figure 3. Chromatogram of HPLC analysis of sugars content in irradiated (400 Gy) Bartamoda dates after 6 months of storage at room temperature.

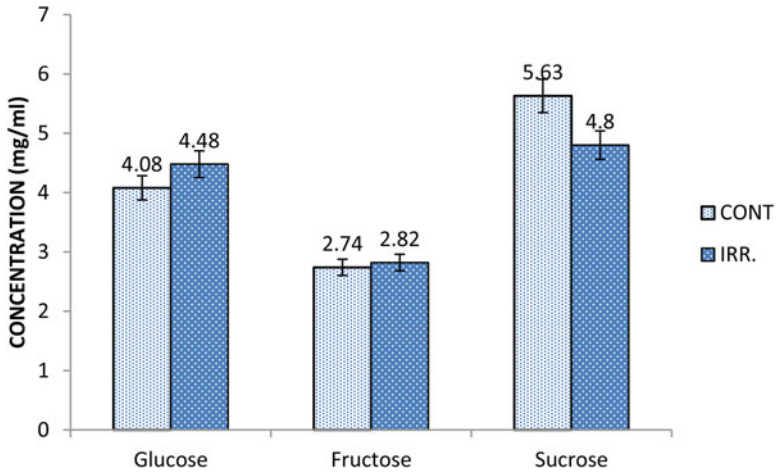

Figure 4. Effect of phytosanitary irradiation dose (400 Gy) on the sugars content (mg ml^{-1}) in Bartamoda date fruits during storage at room temperature.

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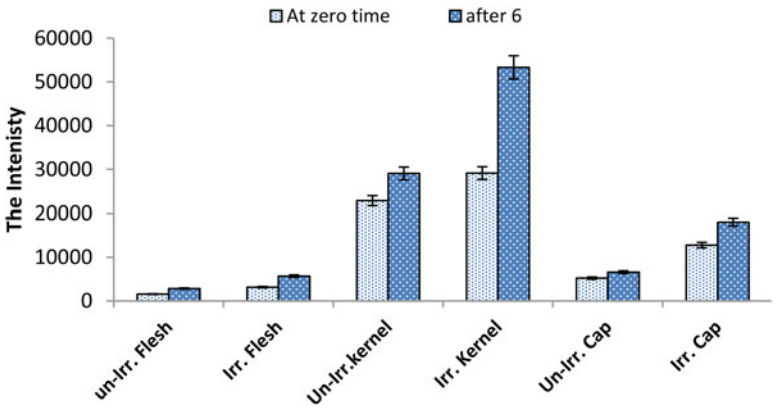

Figure 5. ESR intensity of different parts of irradiated (400 Gy) and non-irradiated Bartamoda dates during storage.

Table 12. Sensory evaluation of irradiated (400 Gy) and non-irradiated Bartamoda dates at the end of the storage period at room temperature (after 6 months)

Treatments	Colour	Appearance	Taste	Odour	Texture
Control	8.6 ± 0.66^{a}	6.0 ± 1.02^{b}	9.1 ± 0.90^{a}	10 ± 0.66^{a}	10 ± 1.01^{a}
400 Gy	8.9 ± 0.86^{a}	9.0 ± 1.00^{a}	9.5 ± 0.86^{a}	10 ± 0.98^{a}	10 ± 1.01^{a}

The post hoc test is Duncan. Means followed by the same letters are not significantly different at the 0.05 level compared between the groups. Independent samples *t*-test for pH (%) (df = 4, *t*-value = −0.96, *P* = 0.392).
Colour: light (1), dark (10); appearance; taste; odour: bad (1), very good (10); texture: soft (1), dry (10). (The panelists could not differentiate between irradiated and non-irradiated samples.)

Table 13. Effect of phytosanitary irradiation dose (400 Gy) on the microbial load of Bartamoda dry dates (CFU g^{-1}) during storage at room temperature

Storage period (months)	Non-irradiated dates				Irradiated dates			
	TBC	TM&Y	Coliform	*E. coli*	TBC	TM&Y	Coliform	*E. coli*
0.0	$1.2 \times 10^{4} \pm 2645.7^{ab}$	$2.7 \times 10^{3} \pm 305.5^{a}$	$1.1 \times 10^{2} \pm 45.46^{b}$	>10	$9.5 \times 10^{3} \pm 173.2^{ab}$	$1.2 \times 10^{3} \pm 152.7^{c}$	$2.0 \times 10^{2} \pm 10.00^{a}$	>10
2.0	$7.9 \times 10^{3} \pm 30{,}831.1^{a}$	$2.1 \times 10^{3} \pm 100.0^{b}$	$8.9 \times 10 \pm 18.88^{c}$	>10	$5.7 \times 10^{3} \pm 100.0^{b}$	$1.0 \times 10^{3} \pm 57.73^{cd}$	$7.0 \times 10 \pm 2.080^{d}$	>10
4.0	$3.3 \times 10^{3} \pm 115.47^{b}$	$4.6 \times 10^{2} \pm 11.54^{e}$	$5.7 \times 10 \pm 13.54^{de}$	>10	$1.5 \times 10^{3} \pm 100.0^{b}$	$8.5 \times 10^{2} \pm 20.00^{d}$	$5.0 \times 10 \pm 2.000^{e}$	>10
6.0	$9.7 \times 10^{2} \pm 20.0$	$8.8 \times 10^{2} \pm 20.00^{d}$	$3.2 \times 10 \pm 13.4^{f}$	>10	$8.0 \times 10^{2} \pm 26.45^{b}$	$2.9 \times 10^{2} \pm 11.54^{e}$	$2.5 \times 10 \pm 1.000^{f}$	>10

TBC, total aerobic bacterial count; TM&Y, total moulds and yeasts; coliforms, total coliform bacteria; *E. coli*, *Escherichia coli*.
The post hoc test is Duncan. Means followed by the same letters are not significantly different at the 0.05 level compared between the groups.

and Mills (1977) found that gamma radiation doses of 300 Gy to 8-day-old pupae of *C. cautella* affect the mating frequency of male moths. When the opportunity of mating was restricted, the mating frequency and the numbers and fertility of eggs laid by young females declined. Calderon and Gonen (1971) reported that doses of 400 and 450 Gy induced 99.9 and 99.25% sterility in females and males of *C. cautella*, respectively. These results show the same trend as those obtained in the current research. However, the difference was that previous research focused on irradiating the male or female separately. In the case of phytosanitary irradiation treatments, the studies are based on stopping the generation resulting from both irradiated sexes while achieving plant health. To achieve the purpose of irradiating food is to eliminate *C. cautella* from dates and fruits as per the recommendation found in Joint FAO (2004, 2022).

Based on the prevention of egg hatching from F1 generation when the most radio-tolerant stage is irradiated and used as a criterion for measuring efficacy, an irradiation dose of 400 Gy is required. This irradiation dose was proposed for large-scale tests to confirm the efficacy of phytosanitary treatment to control and quarantine *C. cautella* in date fruits. Similar results have been demonstrated by the effect of phytosanitary irradiation on some insects by many investigators. Follett and Armstrong (2004) found that an irradiation dose of 150 Gy applied to 92,660 melon fly late 3rd larval instars in papaya resulted in no survival of the adult stage, indicating that this dose is sufficient to provide quarantine security for export/import of papaya. Gabarty *et al.* (2020) found that the irradiation dose level of 150 Gy was applied to 17,000 3rd instar larvae of *Bactrocera zonata* in pomegranate fruits, resulting in non-F1 adults' production with a confidence level of 81.7%. Hammad *et al.* (2020) reported that a dose level of 650 Gy was used for the large-scale confirmatory tests applied to 27,754 adults of *Callosobruchus maculatus* in cowpea seeds, resulting in non-F1 adults' production with a confidence level of 93.77%.

The results of the physiochemical properties of dry date fruits as affected by phytosanitary irradiation dose indicated that this irradiation dose (400 Gy) did not cause a significant effect on the weight loss percentage, moisture content, pH, and TSS of irradiated dates (Bartamoda var.) during storage for 6 months. Many

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researchers concluded the same trend. Mohammadzai*et al.* (2010) reported that the low irradiation dose (up to 300 krad) did not affect the weight loss of dry dates. El-Beltagi *et al.* (2019) reported that the moisture content of some Egyptian dry date varieties is not significantly affected by the low irradiation dose (2.5 Gy). Farag *et al.* (2013) and El-Beltagi *et al.* (2019) found no significant effect of irradiation on the TSS and pH of dry date fruits. Zarbakhsh and Rastegar (2019) reported that the effect of gamma irradiation on the physiochemical properties depends on several factors, including fruit type, irradiation dose, and type of irradiation. Browning values of non-irradiated and irradiated dry dates significantly increased after 6 months of storage. However, the irradiation dose (400 Gy) did not significantly affect the browning value. The browning was reported to be due to the reaction of free sugars and amino acids known in the Maillard reaction besides the enzymatic and non-enzymatic browning reactions (Farag *et al.*, 2013). High doses of gamma rays (higher than 1 kGy) lead to an increase in darkening because of the non-enzymatic browning reactions, but low doses (less than 1 kGy) do not have a significant effect (Lee *et al.*, 2006). The brown colour of dry and semi-dry dates is also affected by storage temperature, as the browning increases with increasing temperature when dates are stored at room temperature.

In contrast, browning decreases significantly when dates are stored at cold temperatures in a refrigerator (Farag *et al.*, 2013). There was a slight decrease in sucrose content in irradiated dates because of its decomposition to glucose and fructose by gamma irradiation. The rate of decomposition of sucrose in fruits depends on the irradiation dose. The degradation of sucrose was parallel to changes in glucose and fructose (Ramírez-Cahero and Valdivia-López, 2018).

ESR analysis indicates that the signal of free radicals was present in both irradiated and non-irradiated samples. However, the signal in irradiated samples was stronger than that of non-irradiated because irradiation led to their doubling (Kuvykina *et al.*, 2022). The presence of free radicals in the non-irradiated fruits is due to the presence of sugar crystals and cellulose particles naturally in the date fruits (Chiappinelli *et al.*, 2019). In addition, the method of fruit dehydration, which depends on the high temperature, also affects the formation of free radicals, and these radicals are difficult to recombine due to the crystalline structure of the sugar molecules (Aleksieva and Yordanov, 2018; Kuvykina *et al.*, 2022). The signal of free radical intensity was significantly higher in the kernel of the dates in comparison to other parts. Farag *et al.* (2014) reported that the increase in the signal intensity in the kernel could be due to the lower percentage of moisture content inside the kernel. The increase in signal intensity by increasing the storage period in all samples is due to free radicals, whether naturally present or induced by irradiation. They are slow to recombine due to the natural shape of the crystals in sugar and cellulose particles. In addition, other factors help to stabilise or increase the intensity of the signal, such as storage at room temperature, low humidity, and storage in the dark. Many investigators reported that the signal of free radicals is useful for detecting irradiated food, especially in the hard parts of the fruits, such as the kernel and calyx cap of fruits (Guzik and Stachowicz, 2022; Kuvykina *et al.*, 2022).

Sensory evaluation was performed to determine whether the phytosanitary irradiation dose (400 Gy) on the irradiated dates had any undesirable effects; this was done so the consumer could accept it. There were no significant differences in the sensory scores of non-irradiated and irradiated samples, as the panelists could not differentiate between them. Other investigators have shown similar results (Ramadan *et al.*, 2016; El-Beltagi *et al.*, 2019).

The microbiological quality. As indicators, coliform bacteria and *E. coli* indicate the contamination by faecal resources and the possible presence of food-borne pathogenic bacteria. The moulds in the dates revealed the possible production of mycotoxins that are very serious to human health. The microbiological results of dry date fruits show a slight reduction, but insignificant, in all microbial counts tested. This slight decrease in the microbial counts could be due to the direct or indirect effect of irradiation on the microbial cell's DNA (Munir and Federighi, 2020). The high microbial counts in dates might be due to the natural microflora and contamination during harvesting, handling, and packaging. Other investigators have reported similar microbial counts (Abu-Zinada and Ali, 1982; Farag *et al.*, 2013). The phytosanitary irradiation dose applied in the present work reduced all the tested microbial counts to some extent. The reduction of microbial load of date fruits and other fruits by low irradiation doses has been reported by many investigators (Prakash *et al.*, 2002; Palekar *et al.*, 2004; Al-Farisi *et al.*, 2013; Farag *et al.*, 2013). Although the phytosanitary irradiation dose applied to dates in the present study was mainly to disinfest *C. cautella*, it also contributed to some reduction in microbial counts of irradiated dates without changes in the dates' physiochemical and sensory quality attributes. Thus, the phytosanitary irradiation dose can be recommended for commercial treatments of dates for quarantine purposes rather than harmful fumigation with methyl bromide to keep dates with good physiochemical and microbiological quality and free from insects for longer storage.

Conclusion

The irradiation dose of 400 Gy required to suppress the developmental stages was applied to 18,000 *C. cautella* pupae, resulting in zero hatchability percentage (no reproduction) at F1 generation, indicating that this dose is sufficient to control *C. cautella* and providing quarantine security with a confidence level of 83.5%. Furthermore, this dose maintained the quality characteristics of dry date Bartamoda fruits during storage at room temperature for 6 months. This irradiation dose did not result in any undesirable changes in the sensory and chemical characteristics of the irradiated fruits. It was possible to detect irradiated date fruits using the ESR method, which revealed constant signal intensity for a long time. Therefore, the study recommends using gamma irradiation as a safe alternative to methyl bromide to preserve dry date fruits during storage for long periods, provided the packages are sound and tightly closed.

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Competing interests. None.

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