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Research Article

EVALUATION OF LOW-ENERGY X-RAY AND GAMMA IRRADIATION FOR AFLATOXIN DECONTAMINATION IN WALNUT KERNELS: A COMPARATIVE STUDY

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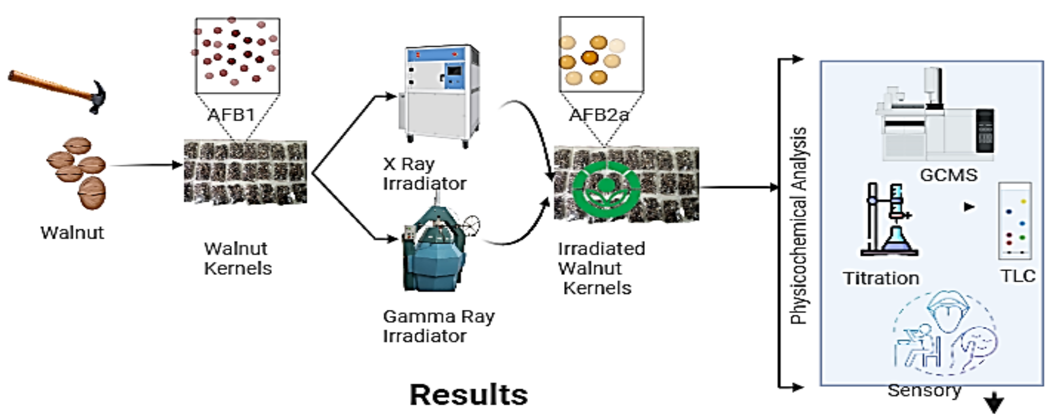
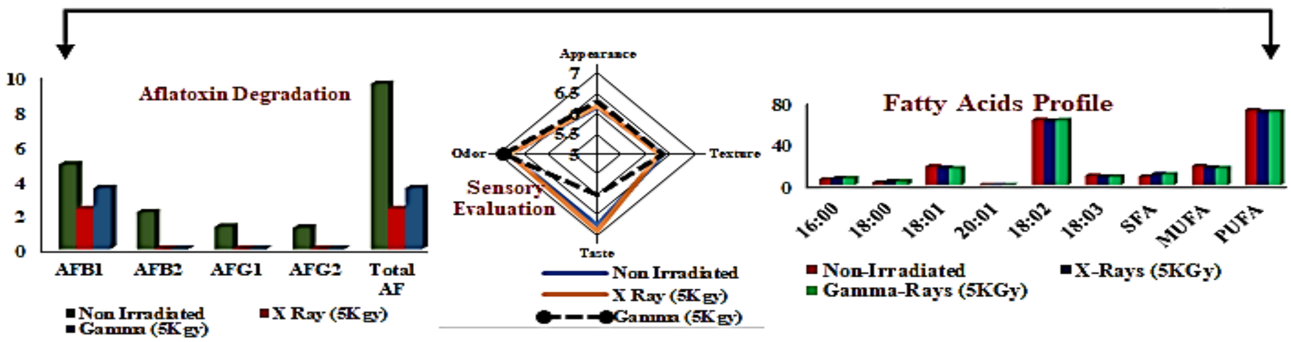
Abstract

Aflatoxins (AFs) are well-known major health hazards in dry nuts. The current study aimed to evaluate effectiveness of both irradiation sources (Gamma and X-Ray) to reduce AFs levels while preserving their nutritional integrity. Dry shelled of walnut kernels were exposed to 60Co and low-energy X-ray irradiations at doses of 1, 1.5, 3.5, and 5 kGy. A significant decrease in AFs content were observed with increasing dosage of both sources. AFB1 decreased from 4.89 ppb in the control to 2.32 ppb with X-rays and 3.53 ppb with γ-rays at 5 kGy. Additionally AFB2, AFG1 and AFG2 were completely eliminated after irradiation compared to their initial levels of 2.14 ppb 1.3 ppb and 1.23 ppb, respectively in the control. This resulted in a reduction of total AFs from 9.56 ppb to 2.32 ppb with X-rays and 3.53 ppb with γ-rays at 5 kGy. However, irradiation doses of 1, 1.5, 3.5, and 5 kGy resulted in minor increase POV and FFA of irradiated samples with increasing doses and did not lead to significant variation in overall fatty acid composition of shelled walnuts. Overall, current study suggests equal effectiveness of low energy irradiation and potentially safe method for enhancing the safety and quality of walnut kernels.





Graphical Abstract: Effects of Gamma and Low Energy X-rays Irradiation on the Decontamination of Aflatoxins, Physiochemical and Sensory Properties of Walnut Kernels

1. Introduction

Nuts are widely consumed around the globe due to their appealing sensory qualities, nutritional value, and health promoting characteristics. They serve as a significant source of bioactive compounds, including dietary fiber, folic acid, and antioxidants i.e. tocopherol-an antioxidant associated with alleviating the risk of coronary artery disease (Gonçalves *et al*., 2023). Also, nuts contain substantial amounts of L-arginine, an amino acid precursor to the endogenous vasodilator nitric oxide (Ros, 2010). Among nuts, walnuts stand out for their higher concentration of unsaturated fatty acids, especially linoleic and alpha-linoleic acids (Spence *et al*., 2023). The latter is recognized for its anti-atherogenic properties (Bertoni *et al*., 2023). Diets rich in linoleic acid have been associated with weight loss (den Hartigh, 2019) and reduced levels of lipoprotein (a) (Froyen & Burns-Whitmore, 2020). Walnuts also rank second-highest among food items with most antioxidants *(Blomhoff et al., 2006; Pandareesh et al.*, 2018).

The safety and quality of walnuts are closely associated with the development of AFs (Buranasompob *et al*., 2007). They are potent toxins produced by Aspergillus flavus and Aspergillus parasiticus. They are contaminating a diverse array of food products i.e. nuts and presenting global food safety challenges. They exhibit carcinogenic, teratogenic and, mutagenic properties. These are causing substantial health hazards to both humans and animals. Aflatoxin B1 is the most potent among all forms and is closely linked with the development of hepatocellular carcinoma *(Loi et al*., 2023; Qian, 2019). European Commission Regulations have enforced restrictions on aflatoxins B1 and total aflatoxins since 1998. These limits have been set at 2 and 4 µg/kg, respectively, for groundnuts, nuts, dried fruit, and cereals (EC, 2006).

Conventional decontamination methods i.e. roasting involve thermal processing have limitations and are likely to alter the physicochemical and sensory properties of the nuts. AFs are also stable at high temperatures, rendering these methods less effective (Qian, 2019; Sánchez-Bravo *et al*., 2022). In contrast, food irradiation, a nonthermal, nonchemical, emerges as an efficient and safe technology for ensuring food safety without compromising food quality (FDA, 2016). Irradiation has also been used to decontaminate dry nuts (Song *et al*., 2016). Traditional γ-irradiation presents issues i.e. hazardous waste and continuous radiation emission. It is now essential to adopt switch-on/off technologies to avoid environmental pollution. X-rays and Electron Beam (EB) are emerging as a viable, non-thermal, environment-friendly, alternatives to traditional γ irradiation in food processing industries (AEP, 2003; FDA, 2016; Suresh D. Pillai & Bhatia, 2018). EB and X-Ray are switch-on/off technologies that can be adapted for various food industries (Song *et al*., 2016). The current study aimed to evaluate the potential of low-energy X-ray irradiation as a substitute for γ radiation in the decontamination of aflatoxins in walnut kernels, while examining its effects on the physicochemical properties of the walnuts.

2. Materials and methods

2.1. Procurement & Preparation of Samples:

Fresh shelled walnut kernels indigenously produced in district Chitral were bought from local market of Peshawar, Pakistan and brought to Food Irradiation Laboratory, Nuclear Institute for Food and Agriculture (NIFA). The samples were sorted, labeled, packed, and sealed in airtight plastic bags.

2.2. Irradiation of Samples

The walnut samples were irradiated with both γ-rays and X-rays at doses of 1, 1.5, 3.5, and 5 kGy/ A Hungarian-made ISSO-GAMMA-LL was used for γ irradiation at a dosage rate of 2.17 kGy/hr, while RAD-2400 was used for X-ray irradiation with a dose rate of 2 kGy/hr at 150 kV and 45 mA. The PMMA Dosimetry System was employed for routine dosimetry for γ-rays, and the GEX Corporation USA dosimetry system (B6002, 150 kV, polystyrene) was used for X-rays.

2.3. Determination of Aflatoxins:

The quantification of aflatoxins B1, B2, G1, and G2 in walnut samples was performed using Thin Layer Chromatography (TLC), as outlined in the Official Method of Analysis (Horwitz & Latimer, 2000).

2.4. Determination of Peroxide Value (POV):

Oil was extracted from walnuts using the Welmann method. Peroxide value was determined by reacting oil with a potassium iodide solution, followed by titration against sodium thiosulfate with starch as an indicator as outlined in official method of AOAC (Horwitz & Latimer, 2000).

2.5. Determination of Free Fatty Acids (FFA):

FFA was determined through titration of an ethanol-oil mixture with NaOH using phenolphthalein as an indicator as outlined in official method of AOAC (Horwitz & Latimer, 2000).

2.6. Sensory Evaluation of Selected Samples:

To assess the quality and acceptability, the samples were evaluated for sensory parameters using a hedonic scale according to method described by Meilgaard *et al*. (2007).

2.7. Determination of Fatty Acid (FA) Profiles:

Fatty acid profiles of the samples were obtained using GC-MS as outlined in official method of AOAC (Horwitz & Latimer, 2000).

2.8. Proximate Composition Analysis:

Proximate Composition analysis including percent crude fat, protein and moisture were determined by AOAC (Horwitz & Latimer, 2000).

2.9. Statistical Analysis

The obtained data from were statistically analyzed, following the method described by Steel *et al.* (1997).

3. Results and discussions

3.1. Effect of γ and X-Ray Irradiation on Aflatoxins of Walnut Kernels

Aflatoxins contamination of food poses a significant risk in countries with high temperatures and humidity, affecting people across the globe. The current study investigated the effects of γ and X-Ray Irradiation at different doses (1, 1.5, 3.5 and 5) on walnut kernels. It was found a significant decrease in AFs content in walnuts with increasing irradiation dosage **(Table 1)**. Both irradiation technologies effectively reduced AFs content at doses of 3.5 and 5 kGy. AFB1 content was found to be 4.89 ppb in the non-irradiated (control) sample and decreased to 2.32 ppb and 3.53 ppb after irradiation at a dose of 5 kGy with X-rays and γ rays, respectively. AFB2 was recorded 2.14 ppb in the control sample and was not detected after irradiation at 5 kGy with either X-rays or γ rays. AFG1 (1.3 ppb) was detected in the control sample and was not detected after at any irradiation dose for both X-rays and γ rays. Similarly, AFG2 (1.23 ppb) was only found in the control sample and not detected after irradiation at any dose for both X-rays and γ rays. The total AFs content in the control sample was 9.56 ppb. After irradiation, the total AFs content was reduced to 2.32 ppb with X-ray treatment and 3.53 ppb with γ ray treatment at doses of 5 kGy.

Patras *et al.* (2017) has observed that UV treatment degrades AFs into less toxic compounds and proposed that AFB2a (hydroxy AFB1) is formed from AFB1 through free radical attack under UV irradiation, where a H^+ atom at the C8 position is oxidized to a hydroxyl group AFB2a has been described as less poisonous than AFB1 in duckling feeding tests (Albores & Río-García, 2007). However, it has also been reported that AFB2a can revert back to AFB1 di-aldehyde (Rushing & Selim, 2018). Nevertheless, AFB1 di-aldehyde may react with amino groups within the food matrix to form a Schiff base, ultimately reducing its bioavailability, potentially explaining the observed lower harmfulness of AFB2a in duckling feeding tests. Lower cytotoxicity of AFs degradation products has been reported after irradiation (Patras *et al.*, 2017). Ghanem *et al.* (2008) found γ irradiation to be effective in degrading AFB1 in peanut samples.

Meanwhile Di Stefano and Pitonzo (2014) reported that γ irradiation at doses ranging from 0.5 to 15 kGy reduced AFs (B1, B2, G1, G2) in almond samples by 0.25% to 21%. Additionally, Assunção *et al.* (2015b) observed 70.61% and 84.15% reduction in Brazil nuts with irradiation doses ranges of 5 and 10 kGy. Furthermore, Assunção *et al.* (2015a) *et al.*, 2015a have achieved 53.32% and 65.66% reduction in AFB1 contents with EB irradiation at doses of 5 and 10 kGy, respectively.

Table 1. Effect of γ and X-Ray Irradiation on AFs Levels in Walnuts

Parameters	**Control**	**X-Rays**				**γ Rays**			
		1	1.5	3.5	5	1	1.5	3.5	5
Aflatoxins B1	4.89	4.1	3.83	2.78	2.32	4.18	3.98	3.72	3.53
Aflatoxins B2	2.14	1.68	1.52	1.5	∗N.D	1.74	1.64	1.48	∗N.D
Aflatoxins G1	1.3	∗N.D	∗N.D	∗N.D	∗N.D	∗N.D	∗N.D	∗N.D	∗N.D
Aflatoxins G2	1.23	∗N .D	∗N.D	∗N.D	∗N.D	∗N.D	∗N.D	∗N.D	∗N.D
T. Aflatoxins(ppb)	9.56	5.78	5.35	4.28	2.32	5.92	5.62	5.2	3.53

∗N.D= Not Detected

3.2. Effect of γ and X Rays Irradiation on FFA and POV of Walnut Kernels

The effect of γ-ray and X-ray irradiation on the free fatty acid (FFA) content in walnut kernels is presented in **Table 2**. The FFA content was significantly affected by both the irradiation source and dose. The control samples (0 kGy) showed an FFA value of 0.66. Irradiation with X-rays and γ-rays resulted in higher FFA levels compared to the control. For X-ray irradiation, the FFA content was observed to increase with higher doses, rising from 0.95 at 1 kGy to 1.25 at 5 kGy. Similarly, γ-ray irradiation also caused an increase in FFA content. The FFA content increased from 0.96 at 1 kGy to 1.26 at 5 kGy. Overall, both X-ray and γ-ray irradiation were found to increase FFA levels in a dose-dependent manner. Statistical analysis also revealed significant differences ($p < 0.05$) between the treatment groups. These results are in accordance with the findings of Al-Bachir (2004) and Mexis, Badeka, Riganakos*, et al.* (2009), who also reported an increase in free fatty acids (FFAs) as a result of irradiation. They inferred that breakdown of lipids leads to the production of smaller molecules, which contribute to the observed rise in FFA content in the irradiated walnut kernels. This increase is likely due to the oxidative processes triggered by irradiation, which cause the degradation of lipids into free fatty acids.

The current study also evaluated the effect of γ-ray and X-ray irradiation on the POV of walnut kernels, as presented in Table 2. It was found that there were no considerable variations in peroxide values between irradiated and non-irradiated walnuts after irradiation. However, the POV of the control sample was 9.65, with a minor increase observed in X-ray-irradiated walnuts: 10.15 at 1 kGy and 10.89 at 5 kGy. Similarly, for γ-ray-irradiated walnuts, the POV values were 10.19 at 1 kGy and 10.91 at 5 kGy.

These findings align with Masoodi *et al.* (2023), who examined lipid oxidation in walnuts at irradiation doses of 0.5 and 1.0 KGy. These are also consistent with the findings of Jan *et al.* (1988), who reported no effects on lipid oxidation in shelled walnuts at 0.5 and 1.0 kGy irradiation doses. Purwanto *et al.* (1985) also reported no effect on POV in ground nutmeg up to 10 kGy irradiation. Byun *et al.* (1995) also found no significant changes in POV of soybeans irradiated with γ-irradiation at different doses. While, Inayatullah *et al.* (1987) reported significant increase in the POV of soybeans irradiated at doses of 0.25, 0.5, 1.0, 2.5, and 5 kGy. Similarly, Chun (2002) reported increased in the POV of peanut oils extracted after irradiation of peanuts.

Table 2. Effect of γ and X Rays Irradiation on FFA and POV of Walnut Kernels

Treatments	**Doses (kGy)**	**FFA**	**POV**
Control	0	0.66^{e}	9.65^{b}
X-ray	1	0.95^{d}	10.15^{ab}
	1.5	1.05^{b}	10.55^{a}
	3.5	1.08^{b}	10.45^{ab}
	5	1.25^{a}	10.89^{a}
γ-ray	1	0.96^{cd}	10.19^{ab}
	1.5	1.04^{bc}	10.44^{ab}
	3.5	1.06^{b}	10.51^{ab}
	5	1.26^{a}	10.91^{a}

3.3. Sensory Evaluation

The effect of γ and X-ray irradiation on the sensory characteristics (taste, texture, appearance, and odor) of walnut kernels is presented in **Table 3**. The texture of walnut kernels was not significantly affected ($p > 0.05$) by irradiation with either γ-rays or X-rays. The sensory scores for γ-ray-irradiated samples ranged from 6.24 to 6.35 showed minimal variation across all doses. Similarly, X-ray-irradiated samples maintained relatively stable sensory scores, with values ranging from 6.79 to 6.97. Overall, X-ray treatment showed slightly higher scores compared to γ-ray treatment, indicating better retention of texture quality. Sensory scores for Taste of γ-ray-irradiated samples ranged from 6.75 to 6.89, with the highest score observed at the 1 kGy dose. In contrast, X-ray-irradiated samples exhibited scores ranging from 6.73 to 6.99, with the best score achieved at 1 kGy. Although there were some minor variations across doses, there was no statistically significant difference ($p > 0.05$) in taste due to either irradiation type or dose. The X-ray treatment at lower doses (1 kGy) demonstrated a marginally better score compared to γ-rays, suggesting a slightly more favorable impact on taste. The mean sensory scores for appearance were consistent across all doses for both γ-ray and X-ray irradiation. However, X-ray-irradiated samples performed slightly better in sensory score for appearance compared to γ-ray-irradiated samples.

Table 3. Effect of γ and X-Ray Irradiation on the Sensory Characteristics of Walnut Kernels

Parameters	γ-rays (kGy)				X-rays (kGy)			
	1	**1.5**	**3.5**	**5**	**1**	**1.5**	**3.5**	**5**
Appearance	6.21^{d}	6.18^{d}	6.19^{d}	6.15^{c}	6.95^{b}	6.91^{b}	6.75^{b}	6.69^{b}
Texture	6.35^{a}	6.28^{a}	6.26^{a}	6.24^{a}	6.97^{b}	6.93^{a}	6.79^{a}	6.82^{a}
Taste	6.89^{d}	6.87^{ac}	6.85^{ab}	6.75^{a}	6.99^{b}	6.73^{a}	6.78^{a}	6.75^{a}
Odor	6.80^{c}	6.78^{ab}	6.75^{ab}	6.75^{ab}	6.90^{b}	6.80^{a}	6.75^{ab}	6.73^{b}

$^{a-f}$ Means in the same row with dissimilar letters are significantly different ($p \leq 0.05$).

The Sensory scores for odor of walnut kernels showed minimal variation across irradiation treatments. The scores for γ-ray-irradiated samples ranged from 6.75 to 6.80, whereas X-ray-irradiated samples had scores ranging from 6.73 to 6.90. Statistical analysis showed no significant effect ($p > 0.05$) of irradiation type or dose on the odor of the samples. However, X-ray irradiation consistently resulted in marginally higher scores at lower doses, with the highest score observed at 1 kGy (6.90).

Irradiation by γ-rays or X-rays did not significantly impact the sensory quality of walnut kernels ($p > 0.05$). X-rays provided marginally better performance indicating both methods are effective for processing without compromising sensory attributes. These results are in accordance with Sajilata and Singhal (2006) and Kashani and Valadon (1984) who also reported similar findings.

Table 3: Effect of γ and X-Ray Irradiation on the Sensory Characteristics of Walnut Kernels

3.4. Fatty Acid Composition of Walnut Kernels

Table-4 highlights some major fatty acids found in walnut oil including Saturated fatty acids (SFA) like Palmitic and Stearic acids, Mono-Unsaturated fatty acids (MUFA) e.g. Oleic and Eicosanoic acids and Poly unsaturated fatty acids (PUFA) i.e. Linoleic and Linolenic acids. In addition to these, minor fatty acids (less than 0.01%) like 12:0, 14:0, 17:0, 20:0 and 22:1 are also present in walnuts but are not discussed here. Predominantly, PUFAs were quantified at highest percentage (72.64%) among non-irradiated samples and 76.12 % & 74.14 % in samples irradiated with 5 kGy dose of X-rays and γ-rays respectively. PUFAs are valuable fatty acids for human health and walnut oil is such kind of edible oil with a high nutritive value from the perspective of fatty-acid intake. Likewise, same behavior was observed among MUFAs in control and irradiated samples. The linkage between the increments in PUFAs/ MUFAs percentages with the increasing dose rates (1, 1.5, 3.5 & 5) of irradiation sources lies in the fact that higher dose rates produce more un-saturation due to cleavage of ester single bonds in triglycerides (TGs) at various attacking sites on fatty acids molecules and yield 1, 2 or 3 double bonds among treated walnuts. This phenomena leads to an upsurge in the concentrations of MUFAs & PUFAs as compared to untreated samples. On the contrary, highest percentages of SFAs (8.31%) were found in non-irradiated samples while a downwards trend in SFAs contents with respect to increasing dose rates was viewed among irradiated samples with lowest recorded value of 8.20% & 8.23% for X-rays and γ -rays respectively. The output infers to the former discussion about MUFAs & PUFAs and further cements the fact about radiations altering the original molecular structures resulting in unsaturation.

Table 4. Fatty-acid composition (%) of the lipid fraction extracted from the walnut samples

Walnut Oil Fatty Acids (%)	**Non-Irradiated**	**X Rays (kGy) 1**	**1.5**	**3.5**	**5**	**Γ (γ) Rays (kGy) 1**	**1.5**	**3.5**	**5**
Palmitic acid (16:00)	5.84 ± 0.00e	5.83 ± 0.01ef	5.82 ± 0.01ef	5.80 ± 0.01efg	5.77 ± 0.02efg	5.84 ± 0.00e	5.83 ± 0.01ef	5.81 ± 0.01ef	5.79 ± 0.02efg
Stearic acid (18:00)	2.47 ± 0.01a	2.45 ± 0.01ab	2.45 ± 0.01ab	2.44 ± 0.01abc	2.43 ± 0.02abcd	2.46 ± 0.01a	2.46 ± 0.01a	2.45 ± 0.01ab	2.44 ± 0.01ab
Oleic acid (18:01)	18.29 ± 0.01c	18.30 ± 0.01c	18.30 ± 0.01c	18.32 ± 0.01cd	18.33 ± 0.02cd	18.29 ± 0.00c	18.30 ± 0.01c	18.31 ± 0.01cd	18.32 ± 0.02cd
Eicosanoic acid (20:01)	0.23 ± 0.00k	0.23 ± 0.00k	0.23 ± 0.00k	0.24 ± 0.01kl	0.24 ± 0.01kl	0.23 ± 0.00k	0.23 ± 0.00k	0.232 ± 0.00k	0.237 ± 0.00kl
Linoleic acid (18:02)	63.27 ± 0.02g	63.37 ± 0.01g	63.89 ± 0.00g	64.23 ± 0.01gh	65.58 ± 0.02gh	63.27 ± 0.01g	63.40 ± 0.02g	63.78 ± 0.03g	64.02 ± 0.01gh
Linolenic acid (18:03)	9.37 ± 0.01b	9.54 ± 0.00b	9.69 ± 0.00b	10.13 ± 0.01bc	10.54 ± 0.00bc	9.46 ± 0.00b	9.61 ± 0.00b	9.86 ± 0.00b	10.12 ± 0.01bc
SFA	8.31 ± 0.01d	8.28 ± 0.01d	8.27 ± 0.01de	8.24 ± 0.01e	8.20 ± 0.02f	8.30 ± 0.00d	8.29 ± 0.01de	8.26 ± 0.01e	8.23 ± 0.01ef
MUFA	18.52 ± 0.02f	18.53 ± 0.01ef	18.53 ± 0.01ef	18.56 ± 0.02g	18.57 ± 0.03h	18.52 ± 0.01ef	18.53 ± 0.01h	18.542 ± 0.02hi	18.557 ± 0.02ghi
PUFA	72.64 ± 0.03a	72.91 ± 0.02b	73.58 ± 0.01bc	74.36 ± 0.02c	76.12 ± 0.02d	72.73 ± 0.01a	73.01 ± 0.01ab	73.64 ± 0.02ab	74.14 ± 0.02b

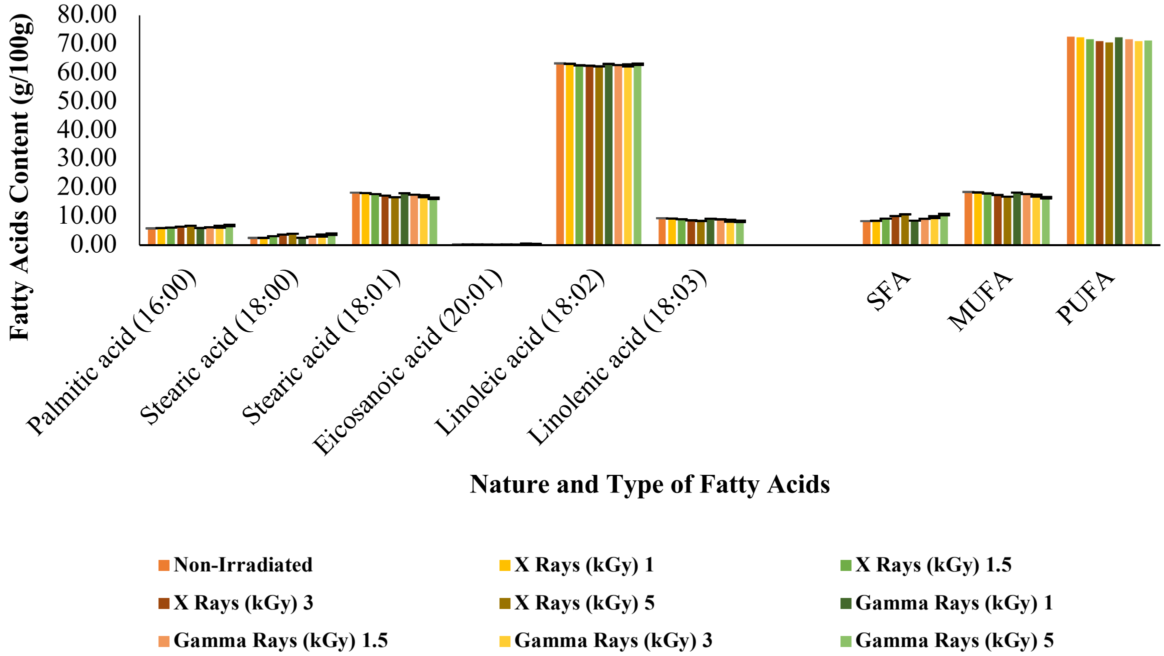


Figure 1. Fatty acid composition of non-irradiated and irradiated walnuts kernels

Outcomes of the current study aligned well to those of Gao *et al.* (2018) who investigated chemical composition of walnut oils from different regions in China and found similar findings. Furthermore, Bhatti *et al.* (2013) reported an increasing trend in concentrations of monoenoic acids during his study to check the safety and quality of almonds oils extracted from γ irradiated almond seeds. While decreasing shift towards generation of unsaturation was documented by Mexis, Badeka, Chouliara, *et al.* (2009) when revealing the effect of γ-irradiation on physicochemical & sensory properties of raw unpeeled almond kernels. Another school of thought was also noted by Di Stefano and Pitonzo (2014) who saw no changes or alterations in fatty acids content and α-tocopherol of γ irradiated raw almond kernels.

Table 4: Fatty-acid composition (%) of the lipid fraction extracted from the walnut sample

3.5. Proximate Compositional Analysis

The effect of γ and X-ray irradiation on the Proximate Compositional Analysis in walnut kernels is presented in **(Table 5)**. The crude protein content of walnut kernels was not majorly influenced by either irradiation type or dose. Across all storage durations, crude protein values ranged from 11.66 to 14.16%. For γ-ray-irradiated samples, the protein content ranged between 11.90 and 14.16%, whereas for X-ray-irradiated samples, it was slightly narrower ranging between 12.99 to 13.50%. The observed minor statistical differences might be attributed to natural variability in kernel composition, minor experimental variations during irradiation, or slight differences in the energy transfer mechanisms between the two irradiation types. These factors could have led to subtle changes in protein measurements without significantly affecting the overall trend. The crude fat content of walnut kernels was shown same behaviour. Across all storage durations, crude fat values ranged from 45.55 to 54.97%. For γ-ray-irradiated samples, the fat content ranged between 48.78 and 54.97%, while for X-ray-irradiated samples, it ranged from 49.15 to 52.30%. These findings concur with earlier research of Ma *et al.* (2013)observed similar changes in, fat, and crude protein after irradiation of fresh walnuts with doses of 0.1, 0.5, 1.0 and 5kGy respectively.

Table 5 . Proximate composition of control and irradiated walnuts kernels

Parameters	Storage Duration	Control	X -ray (kGy)				γ -ray (kGy)				Means
			1	1.5	3.5	5	1	1.5	3.5	5	
Crude Protein	1st Month	13.10±0.655^{h}	11.90±0.59^{m}	12.04±0.60^{l}	14.08±0.70^{b}	14.16±0.70^{a}	13.00±0.65^{i}	13.30±0.66^{g}	13.10±0.65^{h}	13.50±0.68^{e}	13.13^{b}
	2nd Month	12.90±0.65^{j}	13.45±0.67^{ef}	13.49±0.67^{e}	11.66±0.58^{n}	13.98±0.70^{c}	13.50±0.70^{e}	13.40±0.67^{f}	13.10±0.65^{h}	13.30±0.66^{g}	13.19^{a}
	3rd Month	13.32±0.67^{g}	12.45±0.62^{k}	13.87±0.69^{d}	12.86±0.64^{j}	12.00±0.60^{l}	13.30±0.66^{g}	12.98±0.65^{i}	13.10±0.65^{h}	12.99±0.65^{i}	12.98^{c}
	Means	13.10^{de}	12.60^{g}	13.13^{d}	12.86^{f}	13.38^{a}	13.26^{b}	13.22^{c}	13.10e	13.26^{b}	
Crude Fat	1st Month	50.45±2.52^{ij}	50.35± 2.52^{j}	49.41±2.54^{m}	51.39±2.47^{d}	51.07±2.57^{ef}	51.37±2.55^{d}	50.67±2.57^{gh}	50.78±2.53^{g}	51.09±2.54^{e}	50.73^{b}
	2nd Month	50.34±2.55^{j}	50.96±2.52^{f}	49.89±2.55^{l}	48.78±2.49^{o}	50.56±2.44^{hi}	50.20±2.53^{k}	52.30±2.51^{b}	52.11±2.62^{c}	54.97±2.61^{a}	51.12^{a}
	3rd Month	45.55±2.75^{p}	50.67±2.28^{gh}	50.99±2.53^{ef}	49.19±2.55^{n}	50.45±2.46^{ij}	50.65±2.52^{gh}	50.97±2.53^{ef}	49.15±2.55^{n}	50.43±2.46^{j}	49.78^{c}
	Means	48.78^{g}	50.66^{d}	50.09^{e}	49.79^{f}	50.69^{cd}	50.74c	51.31^{b}	50.68^{cd}	52.16^{a}	
Moisture	1st Month	5.20±0.26^{b}	5.20±0.26^{b}	5.40±0.27^{a}	4.90±0.25^{e}	5.00±0.25^{d}	5.00±0.26^{d}	5.10±0.25^{c}	5.20±0.26^{b}	5.10±0.26^{c}	5.12^{a}
	2nd Month	5.00±0.25^{d}	5.40±0.27^{a}	4.90±0.25^{e}	5.10±0.26^{c}	5.20±0.26^{b}	4.70±0.24^{g}	4.80±0.24^{f}	4.90±0.25^{e}	5.20±0.26^{b}	5.02^{b}
	3rd Month	5.10±0.26^{c}	4.40±0.22^{i}	4.90±0.25^{e}	4.80±0.24^{f}	4.60±0.23^{h}	4.30±0.22^{j}	4.70±0.24^{g}	4.90±0.25^{e}	4.80±0.24^{f}	4.72^{c}
	Means	5.1^{c}	5.00^{d}	5.06^{b}	4.93^{e}	4.93^{e}	4.66^{g}	4.86^{f}	5.00^{d}	5.03^{c}	

The moisture content of walnut kernels was also not significantly affected by either irradiation type or dose. Across all storage durations, moisture content ranged from 4.30 to 5.40%. For γ-ray-irradiated samples, the values ranged between 4.30 and 5.20%, whereas for X-ray-irradiated samples, they were slightly narrower, ranging from 4.40 to 5.40%. The results align with Inayatullah *et al*. (1987) who reported no significant effect on the moisture content in soybean at different irradiation doses. Similarly, as Akingbohungbe (1994) clarify that 0.2 kGy dose of irradiation didn't cause any major change in the percent crude moisture of kola nuts.

Table 5: Proximate composition of control and irradiated walnuts kernels

4. Conclusion

The current study found a significant decrease in AFs content with increasing irradiation doses while preserving nutritional quality. However, PoV and FFA increased slightly but remained within non-hazardous levels. The overall fatty acid composition was minimally affected; SFAs slightly increased, MUFAs slightly decreased, while PUFAs remained unchanged by irradiation. Additionally, color and texture were not affected by irradiation. Overall, the study suggests that X-rays and γ-irradiation are effective methods for reducing aflatoxin contamination without compromising the physicochemical and sensory properties of walnut kernels.

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