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Original article

Validation of low dosages of γ-radiation and their effect on red beetle mortality, storability characteristics, and nutritional value of sorghum (*Sorghum bicolor* L. Moench) grain

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ABSTRACT

This research was undertaken to validate the low dosages of γ-radiation of sorghum to examine the efficiency of gamma irradiation doses in quality attributes and storability of sorghum grain. Infested sorghum grains with the red flour beetle at the adult stage were irradiated at 0.25, 0.5, 0.75, 1.0, and 2.0 kGy emitted by ^{60}CO. Subsequently, the mortality rate of the red flour beetle as affected by gamma doses was estimated and the storability characteristics and nutritional value of sorghum grains were measured. Eventually, the Partial Least Squares regression (PLS) analysis was executed to confirm the optimum dose of gamma which eliminate the red flour beetle and enhanced the grain quality. Results provide that the storability characteristics were enhanced after treatments. However, the changes in the germination rate of the grains were not different significantly after radiation. On the other hand, the radiation process enhanced sorghum grins' nutritional quality. Both tannins and phytic acid content dropped significantly and the digestibility and solubility of protein were gradually incremented in the grains. The PLS results indicated that using 1 and 2 kGy reflect the utmost effective dosage for sorghum. It can be concluded that this method is a potent rapid and operative preservation process to the alternate smoking chemical procedure for improving sorghum's nutritional and functional quality and prolong its shelf life. Possibility of providing effective and rapid quarantine security as an alternative to chemical fumigation protocol to extend shelf life and enhance the nutritional and functional quality of sorghum.

1. Introduction

The grain crop of sorghum (*Sorghum bicolor* L. Moench) has several unique properties and is an essential cereal product in Africa and Asia (Hariprasanna and Patil 2015), For poor Asian and African peoples, sorghum is an essential macro and micronutrient (protein, carbohydrates, vitamins and minerals) as well as an antioxidants' source, it also constitutes a gluten-free diet (Ratnavathi et al., 2016). In Sudan, as the utmost widespread foodstuff, sorghum is extensively cultivated in regions with adequate rainfall or those with irrigation (Abdalla and Abdelbagi 2015). However, during the year, sorghum is stored traditionally at the farm level in different local storage modes, which are poor-quality constructions that generate suitable conditions for the growth of fungi and contamination of stored commodities with mycotoxins (Abdalla et al., 2002). The fungal incidence in stored grains was observed in several studies (Mahmoud et al., 2016; Ahmed et al., 2018). These factors provide an optimal situation for insect infestation and fungi growth, which leads to quantitative and qualitative deterioration of grains.

Among store insects, *Tribolium castaneum* the red beetle of the flour is considered one of the supreme economically severe pests of cereal grains and its flours (Rees 2004). Currently, control of store pests using chemical fumigants is highly discouraged. Apply-

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ing chemical fumigants does not eradicate the eggs of the insect and can potentially be left harmful residues in the grains after treatment and their environmental problems (Cherry et al. 2005). Hence, the compulsory need to discover non-chemical methods in the industry. One potential substitute preservation technique is the process of applying gamma radiation. Recently several works have been carried out on applying gamma irradiation to manage stored pests of cereal grains (Hallman 2013). Hallman (2012), reported that applying gamma radiation with high doses (0.4 kGy) and low doses (0.05 kGy) prevented the reproduction of many species of Coleoptera.

Moreover, it has been stated that gamma radiation is approved to control stored product insects of cereal grains in>30 countries. Of these countries, about 45% have permitted radiation treatment for each of their stowed crops. However, limited nations have irradiated stored goods commercially (Hallman 2013).

In addition to the fumigation principles, the gamma radiation improved the nutritive quality of cereals and their flours' functional characteristics such as protein digestibility and solubility (Mahmoud et al., 2016; Ahmed et al., 2018; Mohamed et al., 2022). Likewise, it was stated that gamma radiation red reduces antinutrients, increases the grains' globulin and albumin fractions of sesame protein significantly, and decreased the tannins and phytic acid content of the millet grains, as well as enhances the useful possessions of the sesame seeds (Hassan et al., 2009; Mahmoud et al., 2016).

Despite several reports concerning the contamination of stored sorghum by several types of insect pests in Sudan, few types of research have been conducted on applying postharvest treatments to control store pests. Hence, this research investigates the minimum effective, most valid, and optimum low dose of gamma radiation that eliminates store pests and maintains sorghum grain quality.

2. Material and methods

2.1. Preparation of grain samples and grain infestation

Sorghum grains (Wad Ahmed cultivar) utilized in this work were meticulously cleansed, freed from foreign substances, and stored under ambient temperature during the study. The chemicals utilized in this research were of analytical grade.

2.2. Radiation treatments

Sorghum grains (250 g) were treated by irradiation using 3.89 KCi and ^{60}Co source at 0.25, 0.5, 0.75, 1.0, and 2.0 (kGy) with a 33 Gy/min dose rate. Radiation processing was applied at (25 °C) the ambient temperature at the unit Kaila irradiation processing, Sudanese Atomic Energy Corporation (SAEC). Gamma rays were exposed to both sides of the sample through the radiation process to minimize the variations. As a control, non-irradiated grains (0 kGy) were used. The control and treated grains were ground and sieved (mesh diameter 0.4 mm) and kept at 4 °C for further analysis.

2.3. Assessment of insect mortality

The mortality of the red flour beetle adults was calculated in control and treated samples as described by Zhao et al., (2007a) by the dead insects counting, calculated by the following equation:

$$\boldsymbol{M_a}\% = (\boldsymbol{N_d}/\boldsymbol{N_s})100$$

Where: M_a is the adult mortality percent, N_d is the number of deceased insects for all experiments, and N_s represent the summation of both dead and living adult insects of every experiment.

2.4. Fungal culture and growth

The AOAC (2005) standard methods were performed to estimate the fungal growth on control and radiated sorghum samples. Fungal growth (log cfu/g) was determined after five days of incubation at 25 °C in twofold-strength media culture Sabaroud Dextrose Agar SDS.

2.5. Free fatty acids measurement

The amount of free fatty acids FFAs in both gamma-radiated sorghum and control grains samples were assessed using the technique defined by Zhao et al., (2007b). The FFAs contents were determined by counting the mg of the alkaline that was consumed in the neutralization (mg KOH / 1 g of dry matter).

2.6. Evaluation of the grain germination rate

The rate of Germination of the control and radiated sorghum samples was evaluated using the technique described by International Seed Testing Association ISTA (ISTA 2006). First, a hundred sorghum grains have been platted and incubated at 25 ± 2 °C for seven days. The germinated grain was calculated on the seventh day, and then the sprouting ratio was calculated.

2.7. Total digestible and soluble proteins assessment

Kjeldahl's method of AOAC was C used to assess the content of total proteins in the samples (2005). The digestibility of proteins in vitro of treated and controlled sorghum grains was measured using a pepsin digestion assay according to Monjula and John (1991). The solubility of protein was accomplished as stated by Elkhalifa and Bernhardt (2010).

2.8. Tannins content and phytic acid determination

The contents of total tannins in samples were analyzed by utilizing the vanillin–HCl method in the methanol according to Price et al., (1978). Diverse concentrations of catechin were made based on the generated standard curve, and the amounts tannins in the grains were expressed as milliequivalents' of catechin. The procedures prescribed by Latta and Eskin (1980) were applied to measure the phytic acid concentration in control and gamma-radiated sorghum grain. A standard curve was made by means of $Fe(NO_3)_3$ concentrations series.

2.9. Determination of P, Ca, and Fe

The determination of Phosphor (P), Calcium (Ca), and Iron (Fe) was measured according to Chauhan and Mahjan (1988). Minerals were extracted by using 10 mL of HCl (0.03 M) and then burned in a muffle furnace at 550 °C, and then the mineral extracts were resuspended by five ml HCl 5 N.

2.10. Holding capacity of water and oil

The capacity to hold oil (OHC) and water (WHC) by sorghum samples haven estimated using Sudha et al. (2007) method. The quantities of oil and water retained by sorghum flour were expressed as the WHC and OHC (ml/g dm).

2.11. Statistical analysis

The mean ± standard divination St.D. were recorded for 3 values. One-way ANOVA, LSD (at P ≤ 0.05 level), and HJ-Biplot PCA algorisms tests were used for analyzing the experimental results using the software XLSTAT(Vidal et al., 2020). By the same software, the validation and optimization of gamma dose were calculated by Linear Partial Least Squares Regression (PLS) (Tenenhaus et al., 2005).

3. The results

3.1. Effects of irradiation on the storability characteristic of the sorghum grain

The storability characteristic changes by the gamma radiation process were exposed in terms of red beetle mortality rate, fungal growth, flour acidity, and germination rate of sorghum flour. Before radiation treatment, the mortality rate of the red flour beetle was found to be 1.5% (Table 1). It revealed that the beetle rate of mortality was significantly increased as the gamma dose increases at (P ≤ 0.05) level. It was found to be 21.1 at 0.25, 46.7 at 0.50, 72.0 at 0.75, 83.3 at 1.0, and 100% at 2.0 kGy of the gamma doses. There are no death states were noted among non-treated samples (control). Also, the 2.0 kGy dose resulted in the eradication of the insect adults.

The results of the growth of fungi in Table 1 showed that no significant differences appeared among the growth rate of fungi at each of the doses 0.0, 0.25, and 0.50 (KGy), while it was reduced significantly at the doses 0.75, 1.0, and 2.0(KGy) as the dose augmented respectively at level P ≤ 0.05.

FFAs quantities in the flour of sorghum ranged from 18.6 ± 0.00 to 12.4 ± 0.00 (mg/g) at the doses 0.0 and 2(kGy) respectively, FFA levels did not differ significantly among the control sample and the low radiation doses 0.25 (kGy), but, the flour acidity was dropped significantly as the dosses increasing.

The germination rate of the grains treated with the gamma radiation in Table 1 showed that, up to 0.75 kGy remained in the range of 97.8 to 97.4%, increasing the gamma dose to 1.0 and 2.0 kGy reduced the germination rate to 96.7 and 94.9%, respectively. Nevertheless, there no significant differences appeared at the level (P ≤ 0.05) in the change of grain germination rate after the irradiation.

3.2. Total proteins, protein solubility, and in-vitro proteins digestibility (IVPD) of the sorghum cereals

The rates of crude protein (CP) ranged from 8.1 ± 0.01–8.6 ± 0. 11% for 0.50 dose (kGy) and control respectively, without any significant variances amongst all cures at P ≤ 0.05 (Table 2), protein solubility (PS)% were lowest 8.2 ± 0.88 significantly in control grains and highest 11.8 ± 0.74 significantly at (P ≤ 0.05) in the grains that treated with the dose 2 (kGy), while the IVPD of the control sample was found to be 17.9%, it augmented in paralleled with doses increasing to be 19.6, 19.6, 20.3 and 22.4% at 2 (kGy) for the doses of radiation 0.5, 0.75, 1.0 and 2 kGy correspondingly, with significant differences at P ≤ 0.05 (Table 2).

Table 2
Effect of gamma irradiation on the crud protein (CP), in vitro protein digestibility (IVPD), and protein solubility (PS) of sorghum grain.

Gamma dose (kGy)	CP (%)	IVPD (%)	PS (%)
0.0	8.6 ± 0.11a	17.9 ± 0.56d	8.2 ± 0.88d
0.25	8.2 ± 0.15a	17.5 ± 0.75d	8.5 ± 0.24c
0.50	8.1 ± 0.01a	19.6 ± 0.06c	8.8 ± 0.93b
0.75	8.1 ± 0.12a	19.6 ± 0.00c	9.0 ± 0.00b
1.0	8.1 ± 0.91a	20.3 ± 0.00b	9.2 ± 0.12b
2.0	8.4 ± 0.12a	22.4 ± 0.61a	11.8 ± 0.74a
***F*-test**	–	**	**
LSD 0.05	**NS**	**0.442**	**0.586**

Values are means (±SD) of triplicate samples. Values with the same letter in one column are not significantly different (*P* > 0.05) as assessed by LSD.

3.3. Tannins and phytic acid values of irradiated sorghum grain

Tannins concentrations of sorghum were 3.39(mg/g) and 4.01 (mg/g) at 0.50(kGy) and both 0 and 0.50(kGy) respectively. There are highly significant differences in Tannins decreasing were recorded for the doses 2 and 1(kGy) followed by both 0.75 and 0.50 (kGy) and both 0.25 and 0.00 (kGy) respectively at P ≤ 0.05 (Table 3).

Sorghum composition of phytic acid (PA) was high at 1.87 mg/g in control grains, and it was diminished gradually by irradiation to arrive at 1.09(mg/g) at the highest dose of 2 (kGy), with notable significant differences at P ≤ 0.05 (Table 3).

3.4. The minerals determination of irradiated sorghum grain

The determination of P, Fe, and Ca% on sorghum grains is exposed in Table 4. Before radiation treatment, the determination of P, Fe, and, Ca was 47.0, 49.6 and 66.7%, respectively. The increment of P, Fe, and Ca determination shows radiation dose-dependent. It was augmented by the increase in gamma doses. Gamma radiation treatment of sorghum enhanced the determination of these elements particularly at 0.5 kGy or higher with significant differences at P ≤ 0.05.

3.5. The sorghum flour WHC and OHC

The results of the capacities of sorghum flour to holding water and Oils (WHC) and (OHC) in Table 5, revealed that WHC and OHC of the control were 1 and 2.8(ml/g) respectively, both of these holding capacities were enhanced by gamma radiation treatment

Table 1
Effect of gamma irradiation on the storability characteristics of sorghum grain.

Gamma dose (kGy)	Mortality (%)	Fungal growth (log cfu/g)	Flour acidity (mg/g)	Germination (%)
0.0	1.5 ± 0.77 [g]	4.72 ± 0.56[a]	18.6 ± 0.00[a]	97.8 ± 2.04[a]
0.25	21.1 ± 1.77[d]	4.32 ± 0.75[a]	17.7 ± 1.07[a]	97.8 ± 1.56[a]
0.50	46.7 ± 0.77[d]	4.32 ± 0.36[a]	15.4 ± 0.80[b]	97.4 ± 0.12[a]
0.75	72.0 ± 1.32[c]	2.60 ± 0.31[b]	12.4 ± 0.00[c]	97.4 ± 0.17[a]
1.0	83.3 ± 1.92[b]	2.48 ± 0.00[c]	12.4 ± 0.00[c]	96.7 ± 1.27[a]
2.0	100 ± 0.00[a]	1.48 ± 0.62[c]	12.4 ± 0.00[c]	94.9 ± 2.54[a]
***F*-test**	**	**	**	–
LSD 0.05	**6.263**	**5.036**	**0.971**	**NS**

Values are means (±SD) of triplicate samples. Values with the same letter in one column are not significantly different (*P* ≤ 0.05) as assessed by LSD. **.

Table 3
Tannin and Phytic acid contents of irradiated sorghum grain.

Gamma dose (kGy)	Tannin (mg/g)	Phytic acid (mg/g)
0	4.01 ± 0.07a	1.87 ± 0.01a
0.25	4.01 ± 0.03a	1.83 ± 0.04a
0.50	3.39 ± 0.09b	1.69 ± 0.08b
0.75	3.85 ± 0.03b	1.62 ± 0.10b
1.0	3.66 ± 0.04c	1.43 ± 0.05c
2.0	3.64 ± 0.00c	1.09 ± 0.04d
***F*-test**	**	**
LSD 0.05	**0.044**	**0.107**

Values are means (±SD) of triplicate samples. Values with the same letter in one column are not significantly different ($P > 0.05$) as assessed by LSD.

Table 4
Gamma irradiation effects on the P, Fe, and Ca determination of sorghum grain.

Gamma dose (kGy)	P (% DM)	Fe (% DM)	Ca (% DM)
0.0	47.0 ± 1.47d	49.6 ± 0.00d	66.7 ± 0.88c
0.25	49.5 ± 1.75 cd	55.9 ± 0.02c	67.9 ± 2.14c
0.50	51.1 ± 1.91bc	59.0 ± 0.18b	72.2 ± 0.93b
0.75	53.1 ± 0.40b	58.7 ± 0.28b	75.3 ± 2.14a
1.0	57.7 ± 1.62a	61.8 ± 2.15a	76.1 ± 0.35a
2.0	58.7 ± 1.25a	64.4 ± 2.77a	76.6 ± 0.98a
***F*-test**	**	**	**
LSD 0.05	**2.639**	**2.558**	**2.321**

Values are means (±SD) of triplicate samples. Values with the same letter in one column are not significantly different ($P > 0.05$) as assessed by LSD. Phosphor (P), Iron (Fe), and Calcium (Ca).

Table 5
Effect of gamma irradiation on the water holding capacity (WHC) and oil holding capacity (OHC) of sorghum grain.

Gamma dose (kGy)	WHC (ml/g)	OHC (ml/g)
0.0	1.0 ± 0.07c	2.8 ± 0.29a
0.25	1.7 ± 0.29b	3.0 ± 0.87a
0.50	1.7 ± 0.29b	3.3 ± 0.58a
0.75	1.8 ± 0.06b	3.3 ± 0.58a
1.0	1.9 ± 0.12b	3.5 ± 0.87a
2.0	2.5 ± 0.12a	3.8 ± 0.29a
***F*-test**	**	–
LSD 0.05	**0.311**	**NS**

Values are means (±SD) of triplicate samples. Values with the same letter on one column are not significantly different ($P > 0.05$) as assessed by LSD.

to reach 2.5 and 3.8 (ml/g) respectively at the highest doses 2 Gy. The statistical analysis results displayed that the amounts of water that holds by sorghum flour were improved significantly by all irradiation doses in comparison to control at $P \leq 0.05$, while no statistical significant in the OHC among all grain samples at the same level.

3.6. The results of the analysis of principal components

Fig. 1 the results of the Analysis of the Principal Components PCA of the mortality rate of red flour beetle, fungal growth, flour acidity, germination, tannin, phytic acid, P, Fe & Ca content. Protein solubility (PS), IVPD, WHC, and OHC. It revealed mutual correlations between the doses of irradiation and all the properties of the quality of sorghum grain and its storage capacity.

3.7. The results of regression analysis by PLS

The PLS outcomes in Fig. 2, revealed that there are interactions and influences were exhibited on the examined indicators of sorghum grains by gamma radiation treatments in (x variables) and (y variables) respectively.

4. Discussions

The main objective of the current study was to determine the potential application of low doses of gamma radiation for controlling the red flour beetle (*Tribolium castaneum*) in sorghum grains without adverse damage to their quality. Generally, the radiation treatments for grain disinfestation strategies require an optimum dose that will cause 100% mortality of a target insect and maintain commodity quality. In many previous studies, the safe recommended gamma dose for disinfestation of commodities as well as to maintain the quality of the products, should not exceed the low gamma dose level (Hallman, 2013; Ahmed et al., 2018). Therefore, in this study, the gamma radiation experiments were designed for a maximum of 2 kGy to determine the lethal dose for the red flour beetle. On the other hand, improving the functional properties such as water and holding capacity and protein solubility of agricultural commodities is expected due to the radiation treatment. Changing the functionality of sorghum grains due to physical, chemical and biological changes might affect their nutritional value (Ahmed et al., 2018).

4.1. Effects of gamma radiation treatment on the storability characteristic of the sorghum grain

The findings of this work revealed that the beetle rate of mortality was significantly increased as the gamma dose increases to 100% at 2.0 kGy of the gamma doses. The high mortality rate of the insects might be due to radiation affecting insects at the cellular level, and it causes damage to their DNA molecules (Wang and Tang 2001).

Similarly, the results are compared with those conducted by many researchers (Tandon et al., 2009, El-Naggar and Mikhaiel 2011), that concluded that death of the adult *T. castaneum* has been induced significantly by gamma radiation of dose not>1.0 kGy. It was stated that many factors influenced gamma irradiation's impacts on insect mortality. These factors could conduct a momentous function on variations in the reaction of the insect to the irradiation Hallman et al., (2010).

The data of the current work revealed significant decrease in the rate of fungal growth at the upper dosages of 0.75, 1.0, and 2.0 (KGy) of radiation as the dosage was increasing respectively. Likewise, Mahmoud et al.,(2016) stated that the gamma radiation (2 kGy) reduced fungal incidence in the millet granules. As reported by McNamara et al., (2003), fungal development inhibition in the treated sorghum seeds may attribute to the damage of the fungal DNAs which are susceptible to gamma radiation. Hence, gamma radiation might be applied as a defensive technique to hinder the growth of the fungi as well as to obstruct the manufacturing of their mycotoxins.

The sorghum flour acidity (FFA) in this study dropped significantly as the doses increased. The reduction in the FFA content might result from the decrease in the activity of lipase, leading to FFA formation diminishing. As demonstrated by Pankaj et al., (2013), the irradiation process sharply lowered lipase activity in the wheat. Hence, the obtained findings revealed that radiation (gamma) can be considered an excellent active practice in stabilizing grain shelf life since FFAs concentration is an indicator of the lipid oxidation (rancidity) occurring and leads to off-odors and off-flavor progress in the oils throughout the stowage.

A germination examination is reasonably evaluating the decreasing the grain quality next to the irradiation process. It is linked straight to numerous features of the quality of the grain (Beckett and Morton 2003). The germination rate of the grains treated with the gamma radiation in this study lowered the germination rate by a rate of 2.9% at the high dose 2.0 (KGy) of radiation.

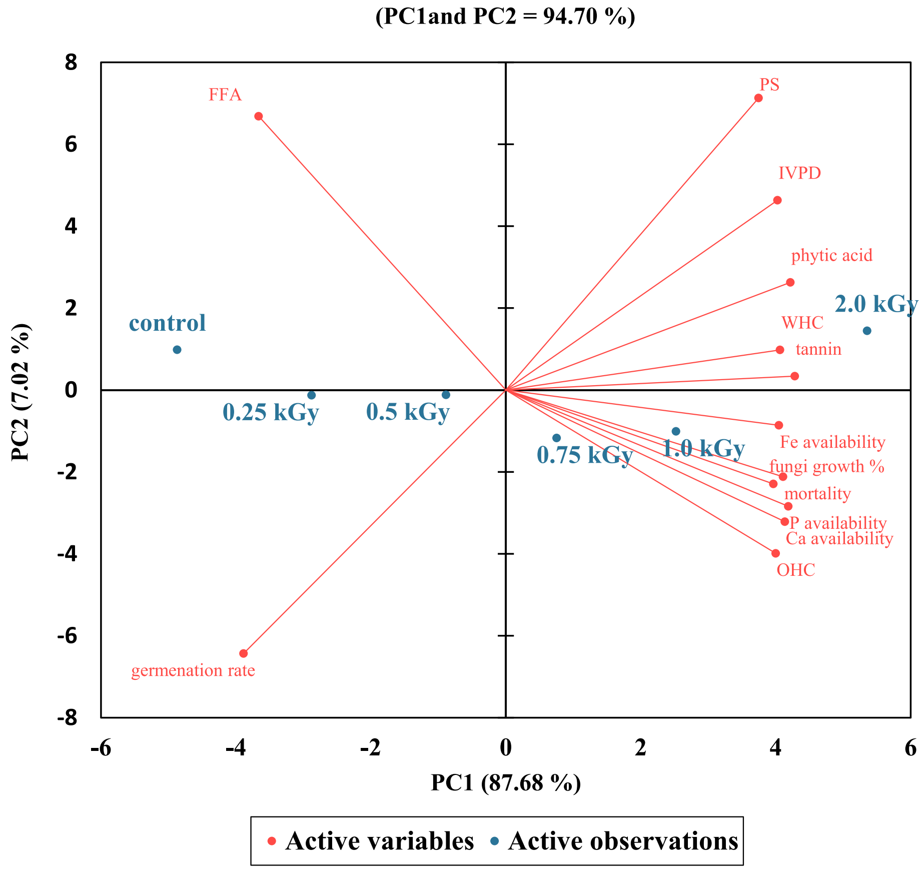

Fig. 1. Principal Component Analysis (PCA) of the mortality rate of red flour beetle, fungal growth, flour acidity, germination, tannin, phytic acid, P, Fe & Ca determination, Protein solubility (PS), *in-vitro proteins digestibility* IVPD WHC, and OHC.

El-Nagar and Mikhaiel (2011) also reported similar findings, who stated that gamma doses of 1 kGy have not caused a change in the germination rate in the wheat grains.

4.2. Total proteins, protein solubility, and in-vitro proteins digestibility (IVPD) of sorghum grains

Protein solubility (PS)% and IVPD were significantly increased in the grains treated with the dose 2 (kGy), Gamma radiation, particularly with low doses, has increased the IVPD of many food resources. It was established that the IVPD of pigeon peas and beans was significantly increased by gamma radiation (Bamidele and Akanbi 2013; Bhat, Sridhar, and Seena 2008). The increment of the IVPD after gamma radiation treatments of sorghum might be attributed to the fact that the free radicals that are created after exposure to gamma rays react with the protein molecules thus, it loses its conformational or structure, resulting in enhanced digestibility of protein and improves the proteolysis (Hassan et al., 2018).

Gamma radiation, particularly with low doses, has increased the IVPD of many food resources. it found that gamma radiation significantly increased the IVPD of pigeon peas and beans (Bamidele and Akanbi 2013; Bhat, Sridhar, and Seena 2008). The increment of the IVPD after gamma radiation treatments of sorghum might be attributed to the fact that the free radicals that are created after exposure to gamma rays react with the protein molecules thus, it loses its conformational or structure, resulting in enhanced digestibility of protein and improves the proteolysis (Hassan et al., 2018).

Protein solubility considers the essential characteristics of the protein. Enhancing the protein solubility was affected by several factors, mainly the denaturing of the protein molecules. A similar increment in protein solubility due to radiation was also stated by Abu et al., (2006), Bhat et al., (2008), and Hassan et al., (2018). Regarding the obtained results, gamma radiation of sorghum grain at 0.25, 0.50, 0.75, 1.0, and 2.0 kGy improved both its IVPD and protein solubility, which may enhance its nutritional and functional characteristics.

4.3. Tannins and phytic acid values of irradiated sorghum grain

The decrease in Tannins values in treated sorghum was dose-dependent. The decrease of tannin content during irradiation treatment mainly referred to the chemical destruction of the molecules caused by reactive molecules effects generated as a result of radiation action. Several studies also state these findings. Hassan et al., (2009), and Lima et al., (2019) reported sharply reducing in tannin amounts in maize and different kinds of legume seeds. Decreasing tannin content due to the radiation process is also associated with the increment of the Bioavailability of some nutrients, particularly protein (Lima et al., 2019).

Distinguished significant differences were appeared in the diminishing of phytic acid (PA) at the highest dose of 2 (kGy), the dropping of PA amount in the treated grains may be associated with free radical action that is generated during the grains' radiation process. These free radicals could aid in the disruption of links between the macro and micronutrients and phytate (Lima et al., 2019). The obtained results are approved by that described in for-

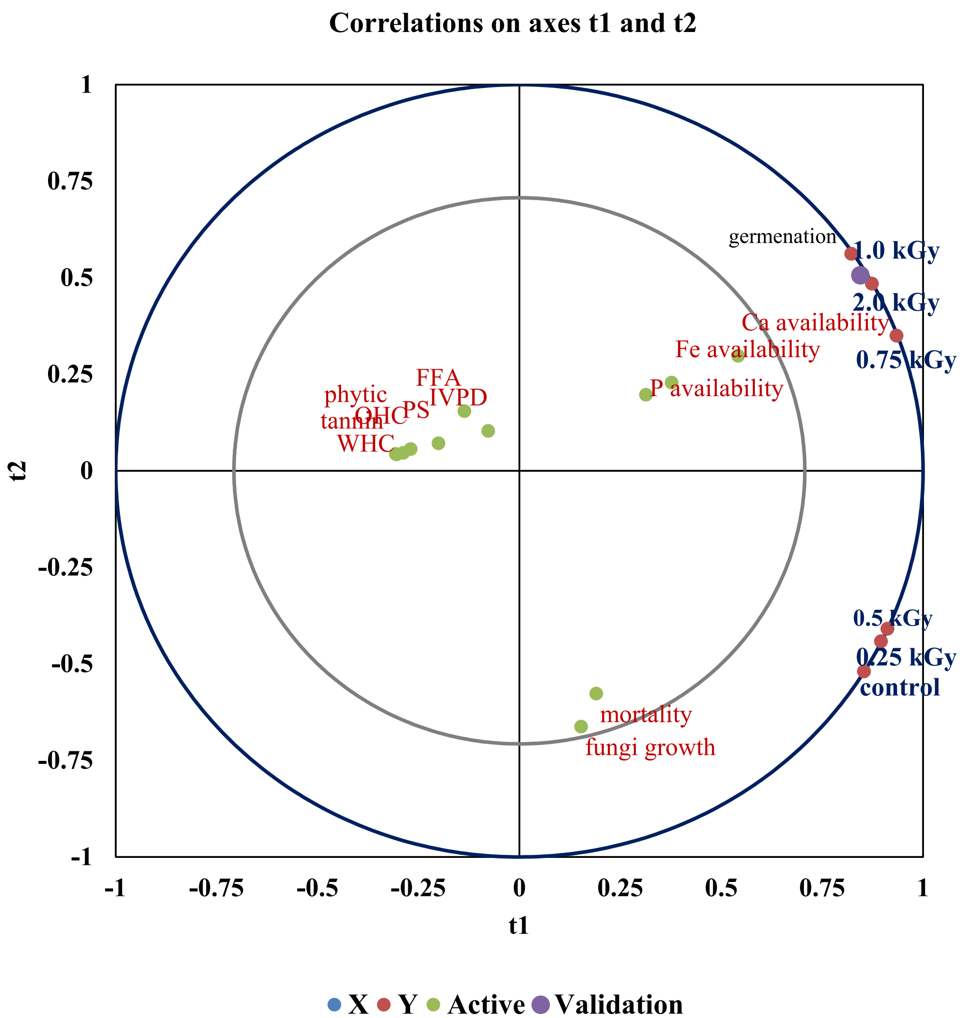

Fig. 2. Partial Least Squares regression analysis (PLS) of the mortality rate of red flour beetle, fungal growth, flour acidity, germination, tannin, phytic acid, P, Fe & Ca determination, protein solubility (PS), in-vitro proteins digestibility (IVPD) capacity to hold Water (WHC), and capacity to hold oil(OHC).

mer research (Hassan et al., 2009; Lima et al., 2019) in cereal grains and legumes.

4.4. The minerals determination of irradiated sorghum grain

The increment of P, Fe, and Ca determination shows radiation dose-dependent, it began from 0.5 kGy or higher. The increment of mineral content after the radiation process might be associated with reducing the phytic acid content. It has been stated by Lima et al., (2019) that the free radical could destroy the bond between phytate molecules and the minerals, hence increasing their Bioavailability.

4.5. The sorghum flour WHC and OHC

Both WHC and OHC reflected an essential property in food manufacturing. They mainly manufacture different kinds of food such as cake batters and sausages. These properties provide the manufactured products with harder and crisp textures. Moreover, they play an essential role in processing sticky and glutinous foods. Consequently, they are considered suitable possessions to change the texture and develop stabilize emulsion phases (Elleuch et al., 2011).

4.6. Principal components analysis results

The principal components analysis results in this study revealed mutual correlations between the doses of irradiation and all the properties of the quality of sorghum grain and its storage capacity. The influence of the PC1 and PC2 axes were described as 87.68% and 7.02%, Consequently, the plotted components were in high variability (94.70%). Furthermore, a strong affirmative association between radiation doses 0.75, 1.0, and 2.0(kGy) and grain quality parameters were also observed. Yan and Fregeau-Reid (2008) reported that the eccentric mutable and remark which form an angle $\leq 90^{\circ}$ are interrelated in a positive manner, whereas negatively correlated ones form > 90° angles which is equal to 90° when there is no relationship.

The PCA factor expressed that the insect mortality rate, fungal growth, Fe availability, P availability, Ca availability, protein solubility, IVPD, tannin content, phytic acid, water holding capacity, and oil holding capacity were highly correlated with PC1. In contrast, the FFA and germination rate were greatly associated with PC2 (Fig. 1).

Accordingly, the doses of radiation were congregated in the biplot in two main clusters of 3 treatments. The first includes the control, 0.25, and 0.5 kGy treatment, which possesses superior levels of the germination rate, a load of fungi, and FFAs contents, whereas the rest measured includes 0.75, 1.0, and 2.0 kGy. These observations exposed that the treatments of gamma irradiation of sorghum grain by doses of 0.75, 1.0, and 2.0 kGy might develop its nutritional value, storage capability, as well as functional features.

4.7. The results of regression analysis by Partial Least Squares (PLS)

Accordingly, the radiation treatments doses have been divided into two clusters concerning their actions on the mortality rate of red flour beetle, fungal growth, flour acidity, germination, tannin, phytic acid, P, Fe & Ca determination, PS, IVPD WHC, and OHC. The results of PLS exhibited a progressive validation score for the treatments of sorghum grain with gamma radiation mainly by the doses 1.0 and 2.0 kGy, on the majority of those indicators evaluated in this study. Thus, PLS specified that the application of 1.0 and 2.0 kGy reflect the greatest appropriate processing for useful food manufacturing tenders, this makes it interesting in several important applications in the food industry.

5. Conclusion

The findings of this work validated the optimizing low dosages of γ-radiation to elevate the storage abilities of sorghum grains and raise their quality traits. Accordingly, the gamma radiation usages provided control of red flour beetle and fungal growth in sorghum grain and enhanced the sorghum grins' nutritional quality. Additionally, it produced a lessening in antinutritional factors and a gradual increment in IVPD and solubility of protein in the cereals. treatment with 1.0 and 2.0 kGy shows a high perspective to its applications in the field of food manufacturing and might develop a new operative technique in preserving systems of foods. Nevertheless, supplementary investigations in the effects of processing of foods by radiation on further quality properties and the storage and handling possessions of the sorghum grains and flour are recommended for develop its effectiveness to the application degree in the practice of operative alternate non-chemical additives in the field of food productions methods and cereals technologies.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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