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Irradiated sorghum grain: Phytochemical, physicochemical, and functional properties

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Abstract:
Sorghum (*Sorghum bicolor* L. Moench) grain is prone to microbial and insect infestation. This study evaluated some quality properties of sorghum grain irradiated with low energy electron beam (LEEB), high energy electron beam (HEEB), and gamma rays.

The experimental samples were sorghum grain irradiated at 2, 4, 6, 8, and 10 kGy, while the unirradiated sample served as a control. The experiments with LEEB and HEEB involved accelerators ILU-6 (250 keV) and ELEKTRONIKA 10-10 (9 MeV), respectively. A Chamber 5000 Co-60 device provided gamma irradiation. The phytochemical, physicochemical, and functional properties were defined by standard methods.

The study revealed significant ($p \leq 0.05$) reductions in the total phenolic, flavonoid, and tannin contents, although they were not dose-dependent. The total phenolic contents reduced from 6.15 (control) to 3.13 GAE/g (gamma rays), 2.74 (HEEB), and 3.47 GAE/g (LEEB). The total flavonoid content reduced from 3.55 (control) to 1.83 QE/g (gamma), 1.78 (HEEB), and 1.59 QE/g (LEEB). The tannin content reduced from 11.96 (control) to 5.19 TAE/g (gamma rays), 2.58 (HEEB), and 6.17 TAE/g (LEEB). The HEEB treatment and gamma rays reduced the pasting properties whereas the LEEB method caused no significant changes. Irradiation did not change the A-type starch crystals but affected its relative crystallinity. The bulk density, oil absorption capacity, solubility index, and swelling power changed significantly after irradiation.

The low energy electron beam treatment demonstrated a good potential as an alternative irradiation source for sorghum grain because it had no adverse effect on its physicochemical and functional properties.

Keywords: High energy electron beam, low energy electron beam, gamma rays, phytochemical profile, physicochemical profile, X-ray diffraction

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INTRODUCTION

Sorghum (*Sorghum bicolor* L. Moench) is an ancient cereal grain that originated over 8000 years ago in Northern Africa [1]. Sorghum grain is stored in many different ways to reduce its susceptibility to microbial and insect-pest infestation. Chemicals are the most common disinfesting method. However, chemicals are expensive and unsustainable. Physical techniques offer a greener alternative. They include low gamma radiation, electron beams, and X-rays [2].

As a physical method of food decontamination, ionizing radiation has been accepted by *The Codex Alimentarius* and many countries globally [3]. The method relies on gamma rays from radionuclide sources rather than on electron beams or X-rays because gamma rays possess a higher penetration power [4]. However, the use

of gamma rays may become problematic in the future due to the increasing cobalt-60 prices, transportation risk, and license issues [4]. The food industry is looking for more sustainable solutions to enhance the safety and quality of food while reducing the environmental impact, i.e., carbon footprint, high energy consumption, inefficient use of water, chemical waste, etc. [5]. This approach results in a new method of food irradiation that involves low-energy beams. It requires relatively small devices that generate ionizing radiation with energies of hundreds keV [5]. This technology also makes it possible to relocate food irradiation processes to the production line in food factories or packing facilities because low-energy beams do not require heavy shielding [5].

Sugar content in Fuji apples and Niitaka pears was not affected by gamma ray and electron beam irradiation at a 0.2–1 kGy [6]. Gamma ray and electron beam irradiation (2–10 kGy) had no effect on the capsaicinoid content of pepper [7]. The extraction yield of polysaccharides from tamarind seed increased after gamma (0.5 kGy) and electron (10 kGy) irradiation [8]. Dried apricot and quince irradiated with gamma ray and electron beam maintained most of their physicochemical qualities and even enhanced their antioxidant potential [4].

One of our previous studies featured the effects of low energy electron beams, high energy electron beams, and gamma rays on the microbial load and aflatoxin levels in sorghum grain. The irradiation either significantly reduced or totally eliminated the microbial loads on sorghum grain [9]. However, the research did not cover the effects of these radiation sources on the physicochemical and functional properties of sorghum grain and powder. This study, therefore, sought to evaluate some quality properties of sorghum grain as affected by low and high energy electron irradiation in comparison with gamma rays (cobalt-60).

STUDY OBJECTS AND METHODS

Preparing the samples and irradiating the sorghum grain. Red sorghum grain (*Sorghum bicolor* L. Moench) was purchased on a local market in Ghana. The grain was thoroughly sorted to remove foreign materials and then kept in 13×21 cm zip-lock bags. The samples underwent standard irradiation at the Institute of Nuclear Chemistry and Technology, Warsaw, Poland [9]. The samples were separately irradiated with low energy electron beam, high energy electron beam, and gamma rays. The irradiation doses were 2, 4, 6, 8, and 10 kGy. Unirradiated sorghum grain served as a control.

The high energy electron beam irradiation experiment involved 300 g of sorghum grain and an ELEKTRONIKA 10-10 accelerator (9 MeV) with a dose rate of 10^3 Gy/s. The gamma irradiation was performed using a Gamma Chamber 5000 Co-60 at a dose rate of about 2 kGy/h. Alanine pellets (Aerial) were used to determine the delivered doses for the samples irradiated with high energy electron beam and gamma rays. They were measured at the INCT Laboratory for Measurements of Technological Doses, Poland (5% uncertainty). All the dose measurements were traceable to the NPL standard. The dose uniformity ratio (DUR) was evaluated as the ratio of maximal and minimal dose in the sample and equaled 1.1.

The low energy electron beam irradiation experiment involved 150 g of sorghum grain irradiated in a cylinder with an ILU-6 accelerator. The system for loose sample irradiation with low energy electron beam [10] provided a uniform dose distribution on each grain surface and made it possible to control the dose by the irradiation time. The dose rate to the grain surface was 2.5 kGy/min. The electrons had 250 keV energy; the layer under the surface of each grain was 150 μm thick. B3 dosimetric foil and the RISOSCAN software made it possible to determine the dose and penetration ability of electrons. The dose variability was 15% because of the irradiation conditions and the approximated dose measurements. All the experiments were triplicated, and the irradiated samples were sent back to Ghana for further analysis.

Powdering the irradiated and unirradiated sorghum grain. The irradiated and unirradiated sorghum samples were milled separately in a Waring CB15 blender (USA) and then sieved through a 500-μm sieve. The powder samples went to low-density zip-lock polyethylene bags to be analyzed within four weeks.

Determining the phytochemical properties. ***Preparing the extracts and determining the total phenolic content.*** The sorghum samples were subjected to extraction to measure the total phenolic content [11, 12]: 1 g of powder was extracted twice with water and methanol (40 mL) at a volume of 20:80 for 2 h. The supernatants were removed after centrifuging. The extracts were pooled, dried by evaporation at 50°C, and reconstituted in 10 mL of methanol to be refrigerated until further analysis.

The Folin-Ciocalteu spectrophotometric technique [13] made it possible to define the total phenolic content in the control and experimental sorghum grain. The test was conducted in triplicate using 10-mL test tubes. About 100 μL of diluted grain extract (1 mg/mL) was mixed with 50 μL of Folin-Ciocalteu's reagent (1M), followed by adding 1.85 mL of distilled water. After incubation in the dark at 25°C for 5 min, we added 1.0 mL of Na_2CO_3 (20% w/v) to the mix and shook it slowly with intermittent agitation. After 1 h, each seed extract underwent spectrophotometry using a Jasco V530 UV-VIS spectrophotometer (Japan) at a wavelength of 725 nm against the blank (without extracts) to check the absorbance value. The results were expressed as gallic acid equivalents (GAE) per 1 g of dry sample.

Preparing the extracts and determining the total flavonoid content. After adding 1 g of powder to the methanol/HCl (1%, v/v) solution, the mix was stirred in a water bath at 180 rpm for 120 min. The centrifugation of the supernatant lasted 5 min at 2790 g. Acidified methanol was added to the collected supernatants until a total volume of 20 mL. The extract was stored at –20°C until further use [14].

The colorimetric method [15] made it possible to quantify the total flavonoid content of the control and

irradiated sorghum grain. We mixed 250 µL of grain extract (1 mg/mL) with 100 µL of 10% $AlNO_3$ and 100 µL of potassium acetate (1M). After adding 4.3 mL of 80% ethanol to achieve a final volume of 5 mL, the mix was shaken and permitted to react for 10 min. A Jasco V530 UV-VIS spectrophotometer (Japan) measured the absorbance in triplicate at a wavelength of 410 nm. Quercetin served as the standard curve. The total flavonoid content of each extract was expressed in terms of quercetin equivalent (QE) per 1 g of dry sample.

Determining the tannin content. The tannin content was quantified as in [16]. Approximately 0.1 g of each sample was measured into Erlenmeyer flasks. After pipetting 10 mL of HCl (4%) in methanol, the flasks were sealed by parafilm, shaken for 20 min, and centrifuged at 4500 rpm for 10 min. The supernatants were transferred to 25-mL volumetric flasks, followed by the second extraction of residue using 1% HCl (5 mL) for 600 s. Both extracts (first and second) were combined and topped up to 25 mL using methanol.

The Folin-Denis reagent [17] made it possible to measure the tannin content. Using the standard calibration curve, we estimated the absorbance against the concentration of tannins at a specific wavelength as follows. Suitable aliquots of the tannin-containing extract (initially 0.05, 0.2, and 0.5 mL) were pipetted in test tubes. The volume was made up to 1.00 mL with distilled water, followed by adding 2.5 mL of sodium carbonate reagent. After shaking, the absorbance was read in a Jasco V530 UV-VIS spectrophotometer (Japan) at 725 nm after 40 min. Finally, we calculated the total phenolics as tannic acid equivalent from the standard curve and expressed it as mg/g.

Determining the physicochemical properties. ***Pasting profile.*** The pasting profile analysis involved a Brabender Viscograph-E (Germany). We prepared about 9.5% powder slurry by suspending 40 g (dry basis) powder in 420 mL of distilled water. The starch-containing suspension was thoroughly mixed and poured into a measuring bowl. The test mode had a 700 cmg measuring range at 75 rpm. The heating process started at 50°C at the rate of 3°C/min and continued until 92°C. After 15 min at 92°C, the samples were cooled down to 55°C at the rate of 3°C/min. This temperature remained constant for 15 min. The resulting pasting properties included time, temperature, and viscosity. The test was triplicated for each sample.

X-ray diffraction and relative crystallinity. The X-ray diffraction revealed the crystal patterns and the relative crystallinity of the sorghum grain in the sorghum powder. It involved a PAN analytical Empyrean diffractometer (Netherlands). The experimental conditions presupposed the 95% relative humidity and 22% glycerol solution [18]. The samples were equilibrated at 25°C for 5 days. The operating conditions were 45 kV, 40 m A, and Cu Kα1 (0.154 nm). The samples underwent scanning from 5° to 40° (2θ) at a step size of 0.20° and a step time of 10 s. By plotting relative intensity peaks against 2θ peaks, we calculated the relative crystallinity as the integrated area of crystalline peaks to the total integrated area above a straight baseline as a percentage [19].

pH. The pH test on sorghum powder was conducted in triplicate: 5 g of dry basis was mixed with 20 mL of distilled water, stirred for 5 min, and left to settle for 10 min. The pH of the water phase was measured using a calibrated Edge HI2002pH meter (Hanna Instruments) [20].

Titratable acidity. The procedure relied on the method described in [20]. We weighed 10 g of the powder sample in triplicate and mixed it with 100 mL of boiled distilled water at 25°C. The resulting suspension was stirred and allowed to digest for 30 min with frequent shaking. After 10 min of settling, the decanted supernatant was put in a 250-mL flask and immediately titrated with NaOH (0.1 N) using 0.3 mL of phenolphthalein. The lactic acid was calculated in %.

Functional properties. ***Bulk density.*** After weighing, an empty graduated tube was filled with powder to the 5-mL mark and tapped until the volume remained constant. After weighing the tube with its content, we divided the difference in weight (g) by the volume of the sample (5 mL) to obtain bulk density.

Water and oil absorption capacities. The water/oil absorption capacity of sorghum grain was determined as in [21, 22]. We mixed 1 g of powder with 10 mL of distilled water/oil in a centrifuge tube and allowed the mix to stand at ambient temperature (25 ± 2°C) for 1 h. After centrifuging in a Universal 320 centrifuge (Germany) at 2000 rpm for 30 min, we measured the volume of water/oil in the sediment. The water/oil absorption capacity was calculated as 1 mL of water/oil absorbed per 1 g of sorghum powder.

Solubility index and swelling power. The modified method described in [23] made it possible to estimate the solubility and swelling power of sorghum powder. We added 1 g of sorghum powder and 40 mL of distilled water into a centrifuge tube (50 mL) of pre-established weight. The suspension was gently stirred to prevent the starch granules in the powder from rapturing. An OLS200 Grant thermostatically controlled water bath (England) heated the suspension at 85°C for 30 min with constant stirring. Then, the tube was taken out of the water bath, wiped, and allowed to dry and cool to ambient temperature. After that, we poured the supernatant into a pre-weighed crucible and allowed it to dry at 105°C in a Gallenkamp oven (United Kingdom). The weight of the dried supernatant and the sediment paste measured after cooling made it possible to calculate the solubility and swelling power, respectively.

Data analysis. The mean values were compared using a one-way analysis of variance (ANOVA, Tukey-Kramer HSD, $p \leq 0.05$) and the Minitab 20 software.

RESULTS AND DISCUSSION

Phytochemical properties as affected by irradiation dose levels and radiation sources. Table 1 shows the total phenolic content. It decreased significantly ($p \leq 0.05$) after irradiation with gamma rays, low energy electron beam (LEEB), and high energy electron beam (HEEB).

Table 1 Effects of radiation source and dose on phytochemical properties of sorghum grain

Phytochemical property	Irradiation dose, kGy	Irradiation source		
		Gamma	High energy electron beam	Low energy electron beam
Total phenolic content, GAE/g	Control	6.15 ± 0.15^{Aa}	6.15 ± 0.15^{Aa}	6.15 ± 0.15^{Aa}
	2	3.13 ± 0.03^{Cb}	2.74 ± 0.04^{Dc}	5.96 ± 0.09^{Aa}
	4	4.61 ± 0.13^{Ba}	3.98 ± 0.01^{Cb}	4.60 ± 0.07^{Ca}
	6	4.42 ± 0.00^{Ba}	3.81 ± 0.01^{Cb}	3.47 ± 0.00^{Ec}
	8	3.28 ± 0.07^{Cb}	3.00 ± 0.03^{Dc}	3.96 ± 0.02^{Da}
	10	6.21 ± 0.21^{Aa}	4.29 ± 0.08^{Bc}	5.55 ± 0.09^{Bb}
Total flavonoid content, QE/g	Control	3.55 ± 0.05^{Aa}	3.55 ± 0.05^{Aa}	3.55 ± 0.05^{Aa}
	2	2.16 ± 0.04^{Eb}	1.78 ± 0.03^{Cc}	3.25 ± 0.02^{Ba}
	4	3.02 ± 0.04^{Ba}	2.35 ± 0.01^{Bb}	2.21 ± 0.01^{Dc}
	6	2.37 ± 0.05^{Da}	2.39 ± 0.02^{Ba}	1.82 ± 0.01^{Eb}
	8	2.61 ± 0.03^{Ca}	1.82 ± 0.02^{Cb}	1.59 ± 0.00^{Fc}
	10	1.83 ± 0.01^{Fc}	2.38 ± 0.01^{Bb}	2.81 ± 0.01^{Ca}
Tannin content, TAE/g	Control	11.96 ± 0.39^{Aa}	11.96 ± 0.39^{Aa}	11.96 ± 0.39^{Aa}
	2	11.74 ± 0.62^{Aa}	5.41 ± 0.08^{Bc}	9.07 ± 1.08^{Bb}
	4	8.36 ± 0.69^{Ba}	3.01 ± 0.62^{Cb}	7.48 ± 0.31^{BCDa}
	6	5.74 ± 0.39^{Ca}	4.54 ± 0.77^{BCa}	6.17 ± 0.23^{Da}
	8	5.19 ± 0.23^{Cb}	4.16 ± 0.46^{BCc}	6.39 ± 0.15^{CDa}
	10	5.58 ± 0.62^{Cb}	2.58 ± 0.62^{Cc}	8.41 ± 0.31^{BCa}

Means with different superscripts (lower case) in the same row that concern the irradiation source are significantly different ($p \leq 0.05$) from each other. Means with different superscript (upper case) in the same column that concern the dose of a particular irradiation type are significantly different ($p \leq 0.05$) from each other

The total phenolics reduced from 6.15 (control) to 3.13, 2.74, and 3.47 GAE/g for the samples treated with gamma rays, HEEB, and LEEB, respectively. However, at 10 kGy the total phenolic content was similar to that of the control for the gamma-irradiated sorghum grain. The reductions were not dose-dependent. The samples exposed to HEEB had the lowest values at each dose level in terms of total phenolics. The total phenolic content in the untreated samples exceeded the values reported in [24]. However, they stayed below the values reported in [13], which ranged from 8 to over 500 mg/g (8000 to 500 000 mg/kg) of total phenolics in other varieties.

Table 1 also shows the total flavonoid content of the control and experimental (irradiated) samples. It decreased significantly ($p \leq 0.05$) with irradiation across the sources and doses. The total flavonoid content reduced from 3.55 QE/g in the control sample to 1.83, 1.78, and 1.59 QE/g in the samples treated with gamma rays, HEEB, and LEEB, respectively. The decrease was not dose-dependent. Flavonoids are one of the several sources of natural antioxidants needed by humans and are mostly consumed as supplements [13]. In our case, the total flavonoid content was higher than the values reported in [13]. However, our total flavonoid content in the unirradiated sample (control) also exceeded some previous findings [25]. In addition, the values of some of the irradiated sorghum samples recorded in the present study compared favorably with those described in [25].

Table 1 summarizes the tannin (condensed tannin) contents of the unirradiated (control) and irradiated sorghum grain. Irradiation with gamma rays, LEEB, and HEEB reduced the tannin content in sorghum grain ($p \leq 0.05$) from 11.96 (control) to 5.19 (gamma rays), 2.58 (HEEB), and 6.17 TAE/g (LEEB). In terms of tannin content, the HEEB irradiated samples had the lowest values at each dose level. However, the reduction was not dose-dependent. The tannin contents recorded in the present study were lower than those reported in [25] but higher than in [26]. Tannins in food facilitate glucose uptake, as well as possess anticancer, anti-allergic, and anti-diabetic properties [27].

The total phenolic, flavonoid, and tannin contents that we observed in the unirradiated (control) sorghum samples differed from the values reported by other authors. The phenomenon could be attributed to the varietal differences, as well as some edaphic and climatic factors. Generally, irradiation dose and source had a significant effect on the phenolic, flavonoid, and tannin contents of sorghum grain. Some reports are quite conflicting, when it comes to the effect of gamma irradiation, as well as low and high energy electron beam treatments, on the total flavonoid, phenolic, and tannin contents of various crops [28]. Some authors reported that gamma irradiation increased the total flavonoid, phenolic, and tannin contents in some instances while reducing them under other conditions. In the present study, we observed a general reduction in the total flavonoid, phenolic, and tannin contents of sorghum grain, as previously reported in [29]. The reductions could be attributed to the degradation effect of gamma rays, LEEB, and HEEB on the components of total flavonoids, phenols, and tannins [29].

Physicochemical properties as affected by irradiation dose levels and radiation sources. ***Pasting profile.*** The pasting profile included such variables as pasting temperature, peak viscosity, viscosity at 92°C, setback

viscosity, and breakdown viscosity (Table 2). The general trend suggests that LEEB treatment did not alter the pasting parameters even at 10 kGy compared to the control. This observation was not different from those reported by other researchers: although the LEEB treatment was more energy efficient than HEEB or gamma rays, it was effective for surface decontamination without irradiating the bulk food [5, 10]. Gamma rays and HEEB irradiation caused significant changes in some pasting profiles ($p \leq 0.05$) (Table 2). With the exception of breakdown viscosity, which was not observed for both the irradiated and unirradiated grain, the other variables demonstrated some changes. Unlike LEEB, HEEB and gamma rays irradiated the bulk food [5], thus causing the abovementioned changes.

Below 6 kGy, gamma rays and HEEB treatment had no effect on the pasting temperature. However, the pasting temperature values decreased at 6–10 kGy, although not significantly. The pasting temperature of starch or flour is the temperature at which a sudden rise in viscosity first occurs with concurrent swelling. It indicates the minimal temperature for cooking starch [30]. High pasting temperature relates to a restricted swelling ability [30, 31]. The significant reduction in the pasting temperature of the sorghum grain irradiated at ≥ 6 kGy suggests that starch in the irradiated samples would cook faster than in the unirradiated samples. Kumar *et al*. [32] reported a decrease in the pasting temperature in gamma-irradiated brown rice starch.

In general, the peak viscosity and viscosity at 92°C for the sorghum grain powder decreased with increasing irradiation dose in the samples treated with gamma rays and HEEB. Despite the decreases, we recorded no significant ($p > 0.05$) changes in the peak viscosity and viscosity at 92°C across the samples exposed to doses ≥ 4 kGy. The effects of gamma rays and HEEB were not significant. Peak viscosity relates to the behavior of flour and starch paste under varying shear, temperature, and time [31]. The decrease in peak viscosity and viscosity at 92°C in the irradiated sorghum grain could be attributed to the depolymerization of sorghum starch molecules through chain scission [33]. Similar outcomes were reported for irradiated brown rice, lotus stem starch, and cowpeas [18, 32, 34].

At 4–10 kGy, gamma rays and HEEB affected the setback viscosity of sorghum grain, although both sources were not significantly different in effect. Gamma rays and HEEB treatments caused the setback viscosity to decrease at all the dose levels, especially at 4–10 kGy, where they had no significant differences. Setback viscosity indicates the inability of amylopectin to hold granules during water imbibition [18, 32]. It is mostly associated with polymerization of leached amylose and depolymerization of long linear amylopectin molecules [34]. They

Table 2 Effects of radiation source and dose on pasting properties of sorghum grain

Irradiation dose, kGy	Radiation source	pH	Titratable acidity, % lactic acid	Pasting parameters				
				Pasting temperature, °C	Peak viscosity, Brabender units	Viscosity at 92°C, Brabender units	Setback viscosity, Brabender units	Breakdown viscosity (Brabender units)
Control	Gamma	6.353 ± 0.006^{Ad}	0.021 ± 0.005^{Aa}	85.73 ± 2.40^{Aa}	122.33 ± 8.08^{Aa}	66.33 ± 11.59^{Aa}	195.00 ± 71.72^{Aa}	0
	LEEB	6.353 ± 0.006^{Ad}	0.021 ± 0.005^{Aa}	85.50 ± 0.86^{Aa}	124.50 ± 5.46^{Aa}	64.33 ± 10.58^{Aa}	151.67 ± 23.25^{Aa}	0
	HEEB	6.353 ± 0.006^{Ac}	0.021 ± 0.005^{Aa}	87.17 ± 1.67^{Aa}	100.00 ± 18.19^{Aa}	58.67 ± 2.16^{Aa}	152.33 ± 12.10^{Aa}	0
2	Gamma	6.433 ± 0.006^{ABa}	0.024 ± 0.005^{Aa}	86.53 ± 1.79^{Aa}	73.00 ± 36.59^{Bb}	44.00 ± 9.00^{Bb}	132.67 ± 129.00^{Ab}	0
	LEEB	6.437 ± 0.006^{Aab}	0.021 ± 0.005^{Aa}	85.33 ± 0.32^{Aa}	128.67 ± 7.23^{Aa}	60.67 ± 5.13^{Aa}	159.33 ± 7.51^{Aa}	0
	HEEB	6.423 ± 0.006^{Ba}	0.021 ± 0.005^{Aa}	87.27 ± 1.10^{Aa}	72.33 ± 32.62^{Bb}	46.33 ± 9.29^{Bb}	107.67 ± 35.01^{Ab}	0
4	Gamma	6.447 ± 0.012^{ABa}	0.018 ± 0.000^{Aa}	73.47 ± 20.38^{Aa}	31.00 ± 3.61^{Bc}	29.67 ± 3.78^{Bbc}	39.00 ± 12.29^{Bc}	0
	LEEB	6.443 ± 0.006^{Aab}	0.018 ± 0.000^{Aa}	85.60 ± 1.32^{Aa}	112.00 ± 12.49^{Aa}	57.33 ± 12.22^{Aa}	152.67 ± 8.08^{Aa}	0
	HEEB	6.420 ± 0.010^{Ba}	0.018 ± 0.000^{Aa}	88.47 ± 1.10^{Aa}	25.33 ± 7.23^{Bc}	24.33 ± 6.35^{Bc}	45.67 ± 14.15^{Bc}	0
6	Gamma	6.393 ± 0.006^{Bbc}	0.021 ± 0.005^{Aa}	50.17 ± 0.06^{Bb}	29.33 ± 0.58^{Bc}	24.00 ± 1.00^{Bc}	21.33 ± 0.58^{Bc}	0
	LEEB	6.437 ± 0.006^{Abc}	0.024 ± 0.005^{Aa}	86.03 ± 0.55^{Aa}	109.67 ± 15.89^{Aa}	60.00 ± 9.54^{Aa}	141.33 ± 22.37^{Aa}	0
	HEEB	6.380 ± 0.010^{Bb}	0.024 ± 0.005^{Aa}	50.17 ± 0.56^{Bb}	28.00 ± 1.00^{Bc}	24.33 ± 0.58^{Bc}	26.67 ± 3.79^{Bc}	0
8	Gamma	6.403 ± 0.006^{Bb}	0.024 ± 0.005^{Aa}	50.20 ± 0.00^{Bb}	30.33 ± 0.58^{Bc}	21.67 ± 0.58^{Bc}	15.33 ± 1.53^{Bc}	0
	LEEB	6.427 ± 0.006^{Ac}	0.024 ± 0.005^{Aa}	86.10 ± 0.79^{Aa}	91.33 ± 10.60^{Aa}	41.67 ± 14.57^{Aa}	135.00 ± 6.00^{Aa}	0
	HEEB	6.387 ± 0.006^{Cb}	0.021 ± 0.005^{Aa}	50.23 ± 0.06^{Bb}	28.00 ± 2.00^{Bc}	20.67 ± 1.16^{Bc}	14.67 ± 3.22^{Bc}	0
10	Gamma	6.380 ± 0.010^{Bc}	0.022 ± 0.000^{ABa}	50.23 ± 0.66^{Bb}	29.00 ± 0.00^{Bc}	19.00 ± 0.00^{Bc}	12.00 ± 1.00^{Bc}	0
	LEEB	6.457 ± 0.006^{Aa}	0.021 ± 0.005^{ABa}	85.60 ± 0.30^{Aa}	104.33 ± 6.11^{Aa}	55.33 ± 12.22^{Aa}	149.00 ± 7.21^{Aa}	0
	HEEB	6.377 ± 0.006^{Bb}	0.018 ± 0.000^{Ba}	52.30 ± 0.00^{Bb}	29.00 ± 1.00^{Bc}	20.00 ± 0.00^{Bc}	14.33 ± 0.58^{Bc}	0

Means with different superscripts (upper case) in the same column that concern the irradiation source are significantly different ($p \leq 0.05$) from each other. Means with different superscript (lower case) in the same column that concern the dose of a particular irradiation type are significantly different ($p \leq 0.05$) from each other

LEEB – low energy electron beam; HEEB – high energy electron beam

might have caused the decrease in the setback viscosity. The decrease in the setback viscosity at cooling might have resulted in a higher resistance to starch retrogradation [18], thus the inability of amylopectin to hold the granules during water imbibition. The current results agree with the earlier findings [18, 34] connected with irradiated cowpea and lotus stem starch, respectively.

Breakdown viscosity happens when the swelling granules rupture [34]. Zero breakdown viscosity indicates that the extent of swelling was extremely low before the disintegration. The breakdown viscosity value estimates the susceptibility of cooked starch to disintegration [35]; therefore, the zero values could be linked to the stability of the pastes during cooling [36].

pH and titratable acidity. Compared to the control, we detected a significant increase in pH values, although not in a dose-dependent manner, irrespective of the radiation sources at all the dose levels (Table 2). However, the titratable acidity values demonstrated no significant difference across the samples. Despite the appreciable increase in pH, the pH of the grain samples irradiated with gamma rays and HEEB, unlike those irradiated with LEEB, were significantly ($p \leq 0.05$) lower at all the dose levels, as compared to the control. At 6–10 kGy, gamma ray and HEEB treatments reduced the pH level but not significantly below that of the control. This trend of increased pH in the irradiated sorghum grain contradicts other findings. For instance, a certain reduction in pH after gamma irradiation was reported for chickpea starch [37] and exopolysaccharide [38]. The change in pH could be attributed to the formation of free radicals and the cleavage of large starch molecules during irradiation [39]. The reduction in pH in the samples irradiated with gamma rays and HEEB at 6–10 kGy could be associated with the cleavage of starch molecules, as well as with acetic, formic, glucuronic, and pyruvic acids formed during irradiation [38].

X-ray diffraction and relative crystallinity. Figure 1 and Table 3 illustrate the X-ray diffraction patterns and the relative crystallinity of powders obtained from sorghum grain irradiated with gamma, HEEB, and LEEB. Major diffraction peaks were observed at 2 Theta;

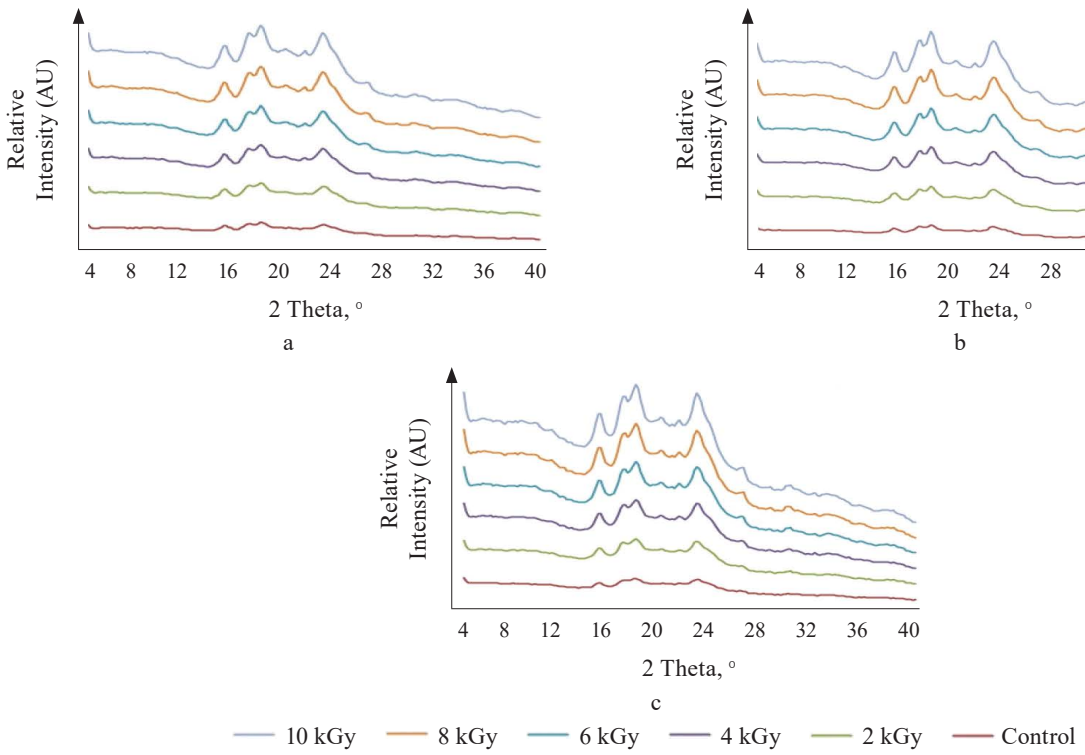

Figure 1 X-ray diffractograms of powder from sorghum grain irradiated with gamma rays (a), low energy electron beam (b), and high energy electron beam (c)

Table 3 Effects of radiation source and dose on relative crystallinity of sorghum grain

Irradiation source	Irradiation doses, kGy					
	0	2	4	6	8	10
Gamma rays	15.96 ± 0.00^{Ac}	16.31 ± 0.00^{Aa}	16.06 ± 0.00^{Bb}	15.93 ± 0.00^{Cd}	15.67 ± 0.00^{Ce}	14.69 ± 0.00^{Bf}
High energy electron beam	14.84 ± 0.05^{Ce}	15.43 ± 0.00^{Bd}	16.41 ± 0.00^{Ab}	18.28 ± 0.00^{Aa}	15.69 ± 0.00^{Bc}	14.55 ± 0.00^{Cf}
Low energy electron beam	15.64 ± 0.00^{Bc}	15.38 ± 0.00^{Ce}	14.95 ± 0.00^{Cf}	16.38 ± 0.00^{Ba}	16.11 ± 0.00^{Ab}	15.60 ± 0.00^{Ad}

Means with different superscripts (upper case) in the same column that concern the irradiation source are significantly different ($p \leq 0.05$) from each other. Means with different superscript (lower case) in the same row that concern the dose of a particular irradiation type are significantly different ($p \leq 0.05$) from each other

Table 4 Effects of radiation source and dose on some functional properties of sorghum grain

Parameters	Radiation source	Irradiation doses, kGy					
		0	2	4	6	8	10
Bulk density, g/mL	Gamma	0.841 ± 0.039^{Aa}	0.764 ± 0.042^{Aa}	0.812 ± 0.012^{Aa}	0.855 ± 0.037^{Aa}	0.776 ± 0.027^{Aa}	0.821 ± 0.041^{Aa}
	HEEB	0.806 ± 0.039^{Aa}	0.746 ± 0.024^{Aab}	0.682 ± 0.023^{Bb}	0.720 ± 0.057^{Bb}	0.703 ± 0.063^{Ab}	0.773 ± 0.004^{Aab}
	LEEB	0.841 ± 0.039^{Aa}	0.766 ± 0.048^{Aa}	0.759 ± 0.043^{Aa}	0.823 ± 0.017^{Aa}	0.775 ± 0.040^{Aa}	0.775 ± 0.009^{Aa}
Water absorption, mL/g	Gamma	1.720 ± 0.117^{Ab}	1.790 ± 0.007^{Aab}	1.794 ± 0.005^{Aab}	1.856 ± 0.110^{Aab}	1.924 ± 0.064^{Aab}	1.920 ± 0.114^{Aab}
	HEEB	1.720 ± 0.117^{Aa}	1.726 ± 0.111^{Aa}	1.860 ± 0.115^{Aa}	1.720 ± 0.114^{Aa}	1.918 ± 0.114^{Aa}	1.723 ± 0.111^{Aa}
	LEEB	1.720 ± 0.117^{Aa}	1.656 ± 0.120^{Aa}	1.728 ± 0.113^{Aa}	1.722 ± 0.110^{Aa}	1.721 ± 0.116^{Aa}	1.656 ± 0.116^{Aa}
Oil absorption, mL/g	Gamma	1.196 ± 0.002^{Ac}	1.592 ± 0.195^{Ab}	1.542 ± 0.115^{Ab}	1.660 ± 0.121^{Aa}	1.659 ± 0.121^{Aa}	1.661 ± 0.115^{Aa}
	HEEB	1.196 ± 0.002^{Ab}	1.658 ± 0.116^{Aa}	1.524 ± 0.117^{Aa}	1.726 ± 0.113^{Aa}	1.722 ± 0.112^{Aa}	1.723 ± 0.114^{Aa}
	LEEB	1.196 ± 0.002^{Ad}	1.388 ± 0.001^{Ac}	1.458 ± 0.115^{Abc}	1.488 ± 0.001^{Abc}	1.591 ± 0.002^{Aab}	1.720 ± 0.117^{Aa}
Solubility Index, %	Gamma	7.19 ± 0.08^{Af}	7.79 ± 0.02^{Ae}	8.35 ± 0.08^{Ad}	8.53 ± 0.31^{Bc}	9.40 ± 0.16^{Bb}	9.90 ± 0.31^{Ba}
	HEEB	7.21 ± 0.02^{Ac}	7.35 ± 0.01^{Bd}	7.16 ± 0.13^{Bf}	10.82 ± 0.18^{Ab}	10.77 ± 0.14^{Ac}	11.21 ± 0.33^{Aa}
	LEEB	7.28 ± 0.05^{Aa}	5.42 ± 0.02^{Cd}	6.22 ± 0.42^{Cc}	5.19 ± 0.12^{Cf}	6.53 ± 0.45^{Cb}	5.25 ± 0.65^{Ce}
Swelling power	Gamma	8.53 ± 0.01^{Aa}	7.03 ± 0.56^{Cb}	6.52 ± 0.08^{Cd}	5.59 ± 0.57^{Cf}	6.01 ± 0.39^{Ce}	6.62 ± 0.27^{Bc}
	HEEB	8.54 ± 0.01^{Aa}	7.58 ± 0.09^{Bb}	7.21 ± 0.05^{Bc}	5.86 ± 0.08^{Bf}	6.33 ± 0.32^{Be}	6.64 ± 0.41^{Bd}
	LEEB	8.53 ± 0.00^{Ac}	8.76 ± 0.15^{Ab}	8.51 ± 0.09^{Ac}	8.96 ± 0.06^{Aa}	8.13 ± 0.15^{Ad}	8.16 ± 0.05^{Ad}

Means with different superscripts (upper case) in the same column that concern the irradiation source are significantly different ($p \leq 0.05$) from each other. Means with different superscript (lower case) in the same row that concern the dose of a particular irradiation type are significantly different ($p \leq 0.05$) from each other

LEEB – low energy electron beam; HEEB – high energy electron beam

they approximately equaled 15, 17, 18, and 23° for both the unirradiated control sample and the powders from sorghum grain irradiated with gamma rays, LEEB, and HEEB (Fig. 1). These major peaks could be attributable to the presence of A-type crystal [33]. Similar patterns for sorghum powder from different sorghum hybrids cultivated in Argentina were reported in [40]. The X-ray diffraction patterns of the sorghum powder samples did not depend on the sources and doses. A similar finding was reported for rice [33].

The relative crystallinity values were significantly different across the samples (Table 3). Gamma irradiation doses from 6 to 10 kGy significantly decreased the relative crystallinity of the starch in the sorghum powder samples. However, a non-dose-dependent increase was recorded for 2 and 4 kGy. The effect of high and low energy electron irradiation had no pattern. Ocloo *et al.* [33] reported no significant difference in the relative crystallinity of some local rice cultivars after gamma irradiation doses of 0.25, 0.5, 0.75, 1.0, and 1.5 kGy.

Functional properties as affected by irradiation dose levels and radiation sources. Table 4 shows the bulk density, water absorption capacity, oil absorption capacity, solubility index, and swelling power of the sorghum grain samples under study. The bulk density decreased at 4 and 6 kGy in the samples subjected to high energy electron beam tretament. On the contrary, the samples irradiated with gamma ray and low energy electron beam retained the same bulk density from 2 to 10 kGy (Table 4). Compared with the control, gamma ray and LEEB did not significantly alter the bulk density. However, HEEB irradiation caused significant reductions in the bulk density at 4, 6, and 8 kGy. A previous study reported that gamma irradiation had no effect on the bulk density of cowpea flour [18]. Similarly, gamma irradiation had no significant effect on rice flour [33]. Bulk density is a function referred to the particle size of the samples. In the food industry, it is important for determining the packaging requirements, material handling, and application in wet processing [36]. The disparities in the bulk density values in the present study could be due to the differences in doses and radiation sources.

The water absorption capacity demonstrated no significant changes at all the dose levels across all irradiation sources (Table 4). Water absorption capacity explains the interaction between the product and water, with water being the limiting factor. Water absorption capacity helps preserve freshness and mouthfeel [41]. Other studies reported contrary findings. For instance, water absorption capacity increased in gamma-irradiated cowpea [18] and rice protein irradiated with high energy electron beam [41]. The fact that water absorption capacity remains the same after irradiation indicates that irradiation did not affect the freshness and mouthfeel.

The oil absorption capacity demonstrated no significant differences between the irradiation sources at 2–10 kGy (Table 4). However, oil absorption capacity increased in all the irradiated grain compared to the control. Greater increments in oil absorption capacity were observed at 6–10 kGy for the gamma-irradiated samples and at 10 kGy for the samples subjected to low energy electron beam treatment.

Oil absorption capacity is important in flavor retention, shelf-life improvement, and palatability [18]. Surface hydrophobicity, physical entrapment of oil, and macromolecule size could affect oil absorption capacity [41]. During irradiation, the partial unfolding of proteins causes the exposure of non-polar protein residues inside

the molecules, thus enhancing protein and oil interactions [41], which might result in the increment in oil absorption capacity. The outcomes of this study agree with a previous study that reported an increased oil absorption capacity of rice protein after irradiation with high energy electron beam [41]. Therefore, the increment in oil absorption capacity could improve shelf stability, palatability, and flavor.

The solubility index increased in the grain irradiated with gamma rays and HEEB. However, it decreased in the samples subjected to LEEB irradiation (Table 4). In the gamma-irradiated samples, the solubility index increased together with the dose. In the HEEB samples, the increase was not dose-dependent, and the highest solubility index was obtained at 10 kGy. In the LEEB samples, the decrease in solubility index did not depend on the dose either. The effect of radiation source on the solubility index was significant across the three sources, with LEEB being the lowest. At 2 and 4 kGy, the gamma-irradiated samples had a significantly higher solubility index than those irradiated with HEEB. However, a reverse trend was obtained at 6–10 kGy. Our results corresponded with the dose-dependent increase in solubility index reported for gamma-irradiated cowpea and potato starch [42].

An increase in the solubility of some rice cultivars with increasing irradiation dose was described in [33]. Solubility is mostly associated with the presence of soluble molecules, e.g., amylose, sugars, and albumins [35]. Irradiation could lead to depolymerization and breakdown of the polysaccharide (amylopectin), thus causing the formation of low molecular weight or shorter fragments [38], e.g., soluble molecules. The increase in solubility index could be related to the increased depolymerization of starch chains resulting in enhanced hydration of powder particles [2]. A comparative increase in solubility index renders irradiated sorghum grain the capabilities of a bio-thickener or stabilizing agent.

A reduction in the swelling power was observed in the grain samples irradiated with HEEB and gamma rays but it was not dose-dependent. In the LEEB irradiated grain, the swelling power increased at 2 and 6 kGy before decreasing at 8 and 10 kGy, as compared with the control. This trend shows the inconsistent effect of LEEB on swelling power. The three sources had significantly different effects on the swelling power.

At 2–8 kGy, the gamma-irradiated samples exhibited a lower swelling power followed by HEEB and then LEEB treatments, except at 10 kGy, where gamma rays and HEEB irradiation had a comparable effect. A similar decrease in swelling power was previously reported in the study of gamma-irradiated cowpea and potato starch [42]. Similarly, electronirradiated yam flour demonstrated a decrease in swelling power [43]. Ocloo *et al*. [33] also reported a decrease in the swelling power of some rice cultivars with increasing irradiation dose. Swelling is the ability of starch molecules (amylopectin) to trap and retain water within its structure [34]. In our case, the decrease in the swelling power in the irradiated samples could be linked to the reduced ability of starch (amylopectin) to imbibe water since the starch molecule might have been depolymerized by the irradiation.

CONCLUSION

In this study, the source of irradiation significantly ($p \leq 0.05$) affected the phytochemical parameters of sorghum grain. Irradiation with low energy electron beam (LEEB) had the least effect on most components, as compared with the other treatments. Except for LEEB, the irradiation sources had a different effect on most pasting parameters. The alteration (reduction) in the pasting parameters was not dose-dependent. The functional properties were significantly altered or remained unchanged after irradiation with gamma rays, high energy electron beam (HEEB), and LEEB. Different irradiation sources had different effects on some functional parameters, which usually depended on the increasing dose. The data obtained suggest that LEEB treatment proved to be an effective alternative to gamma rays and HEEB in sorghum grain production as the method had no significant effect on the physicochemical and functional properties of sorghum powder.

CONTRIBUTION

B. Darfour, J. Agyei-Amponsah, B.T. Odai, T. Mahami, J.O. Armah, E.A. Ayeh, I. Adjei, J. Basugilo, S. Asomaniwaa, and M.N.Y.H. Egblewogbe are responsible for the research, methodology, formal analysis, original draft, review, and proofreading. F.C.K. Ocloo developed the research concept and provided data curation and resources, as well as participated in the review and proofreading.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interests related to the publication of this article.

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REFERENCES

1. Dahlberg JA, Wasylikowa K. Image and statistical analyses of early sorghum remains (8000 B.P.) from the Nabta Playa archaeological site in the Western Desert, southern Egypt. Vegetation History and Archaeobotany. 1996;5: 293–299. https://doi.org/10.1007/BF00195297
2. Pan L, Xing J, Zhang H, Luo X, Chen Z. Electron beam irradiation as a tool for rice grain storage and its effects on the physicochemical properties of rice starch. International Journal of Biological Macromolecules. 2020;164:2915–2921. https://doi.org/10.1016/j.ijbiomac.2020.07.211

3. Chmielewski AG, Migdal W. Radiation decontamination of herbs and spices. Nukleonika. 2005;50(4):179–184.
4. Rather SA, Hussain PR, Suradkar PP, Ayob O, Sanyal B, Tillu A, *et al*. Comparison of gamma and electron beam irradiation for using phytosanitary treatment and improving physicochemical quality of dried apricot and quince. Journal of Radiation Research and Applied Sciences. 2019;12(1):245–259. https://doi.org/10.1080/16878507.2019.1650223
5. Innovation of irradiation technologies on surface treatment of food commodities. Report of a consultants meeting IAEA Headquarters, Vienna, Austria [Internet]. [cited 2024 July 3]. Available from: https://www-pub.iaea.org/MTCD/Publications/PDF/Newsletters/fep-23-1.pdf
6. Jung K, Go S-M, Moon B-G, Song B-S, Park J-H. Comparative study on the sensory properties of Fuji apples and Niitaka pears irradiated by gamma rays, electron beams or X-rays. Food Science and Technology Research. 2016;22(1):23–29. https://doi.org/10.3136/fstr.22.23
7. Jung K, Song B-S, Kim MJ, Moon B-G, Go S-M, Kim J-K, *et al*. Effect of X-ray, gamma ray and electron beam irradiation on the hygienic and physic-chemical qualities of red pepper powder. LWT – Food Science and Technology. 2015;63(2):846–851. https://doi.org/10.1016/j.lwt.2015.04.030
8. Choi J, Kim J-K, Srinivasan P, Kim J-H, Park H-J, Byun M-W, *et al*. Comparison of gamma ray and electron beam irradiation on extraction yield, morphological and antioxidant properties of polysaccharides from tamarind seed. Radiation Physics and Chemistry. 2009;78(7–8):605–609. https://doi.org/10.1016/j.radphyschem.2009.04.004
9. Ocloo FCK, Odai BT, Darfour B, Mahami T, Armah JO, Ayeh EA, *et al*. Microbial quality and aflatoxin levels of sorghum grains (*Sorghum bicolor*) irradiated with gamma rays, low energy electron beam (LEEB) and high energy electron beam (HEEB). Radiation Physics and Chemistry. 2024;216:111474. https://doi.org/10.1016/j.radphyschem.2023.111474
10. Gryczka U, Kamey H, Kimura K, Todoriki S, Migdała W, Bułka S. Efficacy of low energy electron beam on microbial decontamination of spices. Radiation Physics and Chemistry. 2020;170:108662. https://doi.org/10.1016/j.radphyschem.2019.108662
11. Wu L, Huang Z, Qin P, Ren G. Effects of processing on phytochemical profiles and biological activities for production of sorghum tea. Food Research International. 2013;53(2):678–685. https://doi.org/10.1016/j.foodres.2012.07.062
12. Van Hung P, Morita N. Distribution of phenolic compounds in the graded flours milled from whole buckwheat grains and their antioxidant capacities. Food Chemistry. 2008;109(2):325–331. https://doi.org/10.1016/j.foodchem.2007.12.060
13. Ghimire B-K, Seo J-W, Yu C-Y, Kim S-H, Chung I-M. Comparative study on seed characteristics, antioxidant activity, and total phenolic and flavonoid contents in accessions of *Sorghum bicolor* (L.) Moench. Molecules. 2021;26(13):3964. https://doi.org/10.3390/molecules26133964
14. Pinheiro SS, Anunciação PC, Cardoso LM, Della Lucia CM, de Carvalho CWP, Queiroz VAV, *et al.* Stability of B vitamins, vitamin E, xanthophylls and flavonoids during germination and maceration of sorghum (*Sorghum bicolor* L.). Food Chemistry. 2021;345:128775. https://doi.org/10.1016/j.foodchem.2020.128775
15. Moreno MIN, Isla MI, Sampietro AR, Vattuone MA. Comparison of the free radical-scavenging activity of propolis from several regions of Argentina. Journal of Ethnopharmacology. 2000;71(1–2):109–114. https://doi.org/10.1016/S0378-8741(99)00189-0
16. Dykes L, Rooney LW, Waniska RD, Rooney WL. Phenolic compounds and antioxidant activity of sorghum grains of varying genotypes. Journal of Agricultural and Food Chemistry. 2005;53(17):6813–6818. https://doi.org/10.1021/jf050419e
17. Makkar HPS, Blummel M, Borowy NK, Becker K. Gravimetric determination of tannins and their correlations with chemical and protein precipitation methods. Journal of the Science of Food and Agriculture. 1993;61(2):161–165. https://doi.org/10.1002/jsfa.2740610205
18. Darfour B, Wilson DD, Ofosu DO, Ocloo FCK. Physical, proximate, functional and pasting properties of flour produced from gamma-irradiated cowpea (*Vigna unguiculata, L.* Walp). Radiation Physics and Chemistry. 2012;81(4):450–457. https://doi.org/10.1016/j.radphyschem.2011.12.015
19. Cheetham NWH, Tao L. Variation in crystalline type with amylose content in maize starch granules: an X-ray powder diffraction study. Carbohydrate Polymers. 1998;36(4):277–284. https://doi.org/10.1016/S0144-8617(98)00007-1
20. Official methods of analysis. 15th Ed. Washington: Association of Official Analytical Chemists; 1990.
21. Sathe SK, Salunkhe DK. Functional properties of the great northern bean (*Phaseolus vulgaris* L.) proteins: emulsion, foaming, viscosity, and gelation properties. Journal of Food Science. 1981;46(1):71–81. https://doi.org/10.1111/j.1365-2621.1981.tb14533.x
22. Adebowale KO, Olu-Owolabi BI, Olawumi E, Lawal OS. Functional properties of native, physically, and chemically modified breadfruit (*Artocarpus artilis*) starch. Industrial Crops and Products. 2005;21(3):343–351. https://doi.org/10.1016/j.indcrop.2004.05.002

23. Leach HW, Mccowen LD, Schoch TJ. Structure of the starch granule. I. Swelling and solubility patterns of various starches. Cereal Chemistry. 1959;36(6):534–544.

24. Khalid W, Ali A, Arshad MS, Afzal F, Akram R, Siddeeg A, *et al*. Nutrients and bioactive compounds of *Sorghum bicolor* L. used to prepare functional foods: a review on the efficacy against different chronic disorders. International Journal of Food Properties. 2022;25(1):1045–1062. https://doi.org/10.1080/10942912.2022.2071293

25. Ofosu KF, Elahi F, Daliri EB-M, Yeon S-J, Ham HJ, Kim J-H, *et al*. Flavonoids in decorticated sorghum grains exert antioxidant, antidiabetic and antiobesity activities. Molecules. 2020;25(12):2854. https://doi.org/10.3390/molecules25122854

26. Pan L, Li W, Gu XM, Zhu WY. Comparative ileal digestibility of gross energy and amino acids in low and high tannin sorghum fed to growing pigs. Animal Feed Science and Technology. 2021;292:115419. https://doi.org/10.1016/j.anifeedsci.2022.115419

27. Sharma K, Kumar V, Kaur J, Tanwar B, Goyal A, Sharma R, *et al*. Health effects, sources and safety of tannins: a critical review. Toxin Reviews. 2019;40(4):432–444. https://doi.org/10.1080/15569543.2019.1662813

28. Gumul D, Berski W. The polyphenol profile and antioxidant potential of irradiated rye. International Journal of Food Science. 2021;2021(1):8870754. https://doi.org/10.1155/2021/8870754

29. Rodríguez-Núñez JR, Rodríguez-Félix A, Campa-Siqueiros PI, Val-Félix L, Madera-Santana TJ. Ionizing technology effects on bioactive compounds from food products. In: Shayanfar S, Pillai SD, editors. Ionizing radiation technologies: managing and extracting value from wastes. John Wiley & Sons Ltd; 2022. pp. 104–119. https://doi.org/10.1002/9781119488583.ch7

30. Hashimoto JM, Schmiele M, Nabeshima EH. Pasting properties of raw and extruded cowpea cotyledons flours. Brazilian Journal of Food Technology. 2020;23:e2019303. https://doi.org/10.1590/1981-6723.30319

31. Ayetigbo O, Latif S, Abass A, Müller J. Comparing characteristics of root, flour and starch of biofortified yellow-flesh and white-flesh cassava variants, and sustainability considerations: a review. Sustainability. 2018;10(9):3089. https://doi.org/10.3390/su10093089

32. Kumar P, Prakash KS, Jan K, Swer TL, Jan S, Verma R, *et al*. Effects of gamma irradiation on starch granule structure and physicochemical properties of brown rice starch. Journal of Cereal Science. 2017;77:194–200. https://doi.org/10.1016/j.jcs.2017.08.017

33. Ocloo FCK, Owureku-Asare M, Agyei-Amponsah J, Agbemavor WSK, Egblewogbe MNYH, Apea-Bah FB, *et al*. Effect of gamma irradiation on physicochemical, functional and pasting properties of some locally-produced rice (*Oryza* spp) cultivars in Ghana. Radiation Physics and Chemistry. 2017;130:196–201. https://doi.org/10.1016/j.radphyschem.2016.08.025

34. Gani A, Gazanfar T, Jan R, Wani SM, Masoodi FA. Effect of gamma irradiation on the physicochemical and morphological properties of starch extracted from lotus stem harvested from Dal Lake of Jammu and Kashmir, India. Journal of the Saudi Society of Agricultural Sciences. 2013;12(2):109–115. https://doi.org/10.1016/j.jssas.2012.08.004

35. Wani IA, Sogi DS, Gill BS. Physicochemical properties of acetylated starches from some Indian kidney bean (*Phaseolus vulgaris* L.) cultivars. International Journal of Food Science and Technology. 2012;47(9):1993–1999. https://doi.org/10.1111/j.1365-2621.2012.03062.x

36. Ocloo FCK, Bansa D, Boatin R, Adom T, Agbemavor WS. Physico-chemical, functional and pasting characteristics of flour produced from Jackfruits (*Artocarpus heterophyllus*) seeds. Agriculture and Biology Journal of North America. 2010;1(5):903–908. https://doi.org/10.5251/abjna.2010.1.5.903.908

37. Bashir M, Haripriya S. Physicochemical and structural evaluation of alkali extracted chickpea starch as affected by γ-irradiation. International Journal of Biological Macromolecules. 2016;89:279–286. https://doi.org/10.1016/j.ijbiomac.2016.04.080

38. Kavitake D, Techi M, Abid UK, Kandasamy S, Devi PB, Shetty PH. Effect of γ-irradiation on physico-chemical and antioxidant properties of galactan exopolysaccharide from *Weissella confusa* KR780676. Journal of Food Science and Technology. 2019;56:1766–1774. https://doi.org/10.1007/s13197-019-03608-w

39. Sabularse VC, Liuzzo JA, Rao RM, Grodner RM. Cooking quality of brown rice as influenced by gamma irradiation, variety and storage. Journal of Food Science. 1991;56(1):96–98. https://doi.org/10.1111/j.1365-2621.1991.tb07984.x

40. Palavecino PM, Penci MC, Calderón-Domínguez G, Ribotta PD. Chemical composition and physical properties of sorghum flour prepared from different sorghum hybrids grown in Argentina. Starch-Stärke. 2016;68(11–12):1055–1064. https://doi.org/10.1002/star.201600111

41. Zhang X, Wang L, Chen Z, Li Y, Luo X, Li Y. Effect of electron beam irradiation on the structural characteristics and functional properties of rice proteins. RSC Advances. 2019;9(24):13550–13560. https://doi.org/10.1039/C8RA10559F

42. Verma K, Jan K, Bashir K. γ irradiation of cowpea and potato starch: Effect on physicochemical functional and rheological properties. Journal of Food Processing and Technology. 2019;10(9):1000810. https://doi.org/10.35248/2157-7110.19.10.810

43. Wang G, Wang D, Qing C, Chen L, Gao P, Huang M. Impacts of electron-beam-irradiation on microstructure and physical properties of yam (*Dioscorea opposita Thunb.*) flour. LWT. 2022;163:113531. https://doi.org/10.1016/j.lwt.2022.113531

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