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Original Research

Effects of dehulling, irradiation, and cooking on nutritional quality, phytic acid, and protein digestibility of pearl millet cultivars during storage

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Abstract: Millet cultivars (Ashana and Dembi) were used in this study to investigate the effects of irradiation, dehulling, and cooking on energy sources, phytate, and protein digestibility during storage. Whole, irradiated, dehulled, and cooked flour of millet cultivars was stored for different periods (30 and 60 days). Energy source contents (protein, oil, and carbohydrates), phytate content, and protein digestibility were assayed for the cultivar flours before and after treatments. Chemical composition and total energy were assayed for all treatments. The effects of treatments varied across energy sources and the total energy of the whole flour and dehulled flour from both cultivars, with carbohydrate content increasing significantly ($P \leq 0.05$) after dehulling. The results showed that the storage period had no effect on phytate content for both cultivars. However, dehulling reduced phytate content by more than 50%. Moreover, cooking of the raw whole and dehulled flour significantly ($P \leq 0.05$) decreased phytate content for both cultivars. The radiation process alone had no effect on phytate content, but when followed by cooking, it significantly ($P \leq 0.05$) reduced the level of this antinutrient in the whole and dehulled flour of both cultivars. Dehulling alone significantly increased protein digestibility ($P \leq 0.05$). Radiation applied to whole or dehulled seeds had no effect on protein digestibility, but when followed by cooking, it significantly reduced protein digestibility ($P \leq 0.05$). The results indicated that a combination of different treatments applied to millet flour could improve nutritional quality and nutrient bioavailability.

Keywors: Millet, Irradiation, Dehulling, Cooking, Energy

1. Introduction

Pearl millet (*Pennisetum glaucum*), a traditional grain crop, is regarded as a vital staple in the dry and semi-arid regions of Africa [1]. Due to their enormous potential to solve serious issues like hunger and malnutrition, as well as the problems that climate change poses to agricultural productivity, millets are becoming more and more well-known worldwide [2]. These serve as an excellent alternative to other starchy grains. Furthermore, they are gluten-free, making them suitable for individuals with celiac disease, and they serve as a valuable source of minerals such as calcium, iron, and zinc. Millets are generally more nutritious than most cereal grains for minerals, vitamins, protein, fiber, slowly digested starch, and fatty acids. Nutrient-dense grains offer effective solutions to address malnutrition and metabolic disorders in the nation [3]. They have a calcium concentration two to three times that of rice. They provide several security benefits related to food, fodder, fiber, nutrients, the

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environment, health, and livelihood, while using minimal soil fertility and replenishing it.

Although millets have a substantial nutrient profile, caution is necessary when using them because of their elevated levels of anti-nutrients, including tannins, phenols, phytates, saponins, and trypsin inhibitors [4]. Both traditional and contemporary techniques can be utilized to reduce the antinutritional components in tiny grains. Milling, soaking, fermenting, debranning, and autoclaving are processes used to reduce antinutritional factors in small grains. Employing several strategies, either individually or in combination, can effectively diminish the concentration of antinutrients [5]. Various techniques have been used to enhance the nutritional profile of cereal grains, including fermentation. Fermentation has been utilized for food preservation since ancient times. It is cost-effective, supplies essential nutrients, promotes nutrient bioavailability, eliminates unwanted elements such as natural toxins and pathogenic microbes, and improves flavor [5]. Fermentation of millets may be helpful because during the process, various bioactive chemicals can be created, dangerous bacteria can be controlled, food safety is enhanced, and texture is improved [6].

Processing millet is challenging because of the grain's rigid outer husk. Dehulling is a fundamental processing stage that eliminates the outer layer of the grain and is the most critical phase in the entire millet processing sequence [7]. It is performed to eliminate 12%–30% of the grain; exceeding this range results in increased loss of ash, fat, and fiber [8]. The endosperm is pliable, while the pericarp is firmly affixed to the grain. The hull is nutritionally deficient and indigestible throughout the digestive system. The existence of anti-nutrients causes mineral shortages, disrupts protein digestion and nutrient absorption, and leads to gastrointestinal pain. Removing these hulls improves grain digestibility, nutritional value, organoleptic characteristics, and public acceptance, while reducing antinutritional factors [9]. The hulls are securely attached to the endosperm; thus, any external force applied to detach the hulls affects the endosperm, causing it to break. A specific dehuller is required for each millet type to improve dehulling efficiency and reduce grain loss [10]. Furthermore, the grain may undergo pretreatment to reduce hull hardness, facilitating hull extraction by the dehuller [11].

Recently, various advanced processing algorithms have been implemented to enhance consumption and storage. Irradiation is a sophisticated technology utilized in the food processing industry to extend the shelf life of products. Irradiation is a non-thermal food preservation technique that uses high-energy ionizing radiation, similar to thermal methods such as pasteurization and canning. Food irradiation is recognized as a viable method for reducing post-harvest food losses, ensuring food safety, and promoting broader food trade [12]. Furthermore, the safety of irradiated foods has been validated at an overall average dose of 10 kGy. Ionizing radiation is a widely used method to preserve food, extend its shelf life, and reduce the risk of foodborne diseases. The chemical structure of irradiated food is less altered than that of heat-treated food, and this method circumvents the employment of potentially hazardous chemicals [12]. Radiation (2 kGy) alone showed a negligible impact on the antinutrient content of both whole and dehulled millet flour cultivars. Nonetheless, when subjected to cooking, antinutrients were dramatically reduced [13]. Millet flour showed significant issues during storage, leading to off-flavors and a bitter taste. To reduce nutritional losses during the storage of millet flour, radiation offers a compelling and healthful alternative to standard chemical treatments. This study aimed to examine the effects of dehulling, irradiation, and cooking on energy sources and total energy, phytate, and protein digestibility of flour from a pearl millet cultivar.

2. Materials and methods

2.1 Sample preparation

Seeds from two Sudanese millet cultivars, Ashana and Dembi (*Pennisetum glaucum* L.), were acquired from the Nyala Agricultural Research Station in Southern Darfur State, Sudan. The seeds of each cultivar were purified of damaged seeds and extraneous materials, and then the grains were dehulled utilizing an MH200 dehuller (Kurima Agriculture Products, Zimbabwe).

2.2 Irradiation procedure

The flour with a moisture percentage of 5.45% was uniformly distributed and stored in polythene bags weighing 100 grams. The gamma radiation treatment was performed at the Kaila Irradiation Processing Unit of the Sudanese Atomic Energy Corporation (SAEC). The flour was subjected to gamma radiation with a medium dose of 2 kGy from a cobalt-60 source (Gammacell 220, MDS Nordion, Ottawa, Canada) in accordance with the protocols established by Codex [14], with a dose rate of approximately 2 Gy/min at 25 °C and standard relative humidity. Double-sided irradiation was conducted to ensure consistent dosage distribution. A dosimetry device was employed to quantify the dose absorbed by the batch utilizing Gafchromic HD-810 film (International Specialty Products, NJ, USA; FAO/IAEA/USDA, 2003). Each batch of flour comprised three dosimeters, which were analyzed post-irradiation using a Radiachromics reader (Far West Technology Inc., CA, USA). All studies were conducted thrice, with three replicates of each flour type subjected to irradiation.

2.3 Cooking of the flour

In a beaker, 33 milliliters of distilled water were heated to boiling. The slurry of irradiated and dehulled flour dough, as well as the untreated flour from each sample, was prepared from approximately 10 g of flour. To make porridge, the slurry was added to the boiling water and cooked for 10 min at about 95 °C while being constantly stirred. Then cooled and dried using a freeze dryer (12525, VirTis Company, Gardiner, New York). The dried porridge was ground into a fine flour, sieved through a 0.4 mm mesh, and preserved at 4 °C for subsequent examination.

2.4 Energy sources determination

The proximate composition, including protein, fat, fiber, ash, and moisture content, was assessed using the standard process recommended by Association of Official Analytical Chemists (AOAC) [15], while total carbohydrate was calculated by the difference method employed in the study by Reddy & Viswanath [16].

2.5 Total energy determination

Energy was computed according to the methodology outlined by Osborne and Voogt [17], using the Atwater factors: 1 g of carbohydrate (C) yields 4 kcalories, 1 g of protein (P) yields 4 kcalories, and 1 g of fat (f) yields 9 kcalories.

2.6 Phytic acid determination

The phytic acid concentration of the samples was assessed as previously documented by Wheeler & Ferrel [18]. Approximately 2 g of the flour samples were immersed in 100 mL of 2% hydrochloric acid for 3 hours and subsequently filtered using Whatman (25 mm) channel filter paper. Twenty-five milliliter aliquots of the filtrate were introduced into a conical flask, accompanied by 5.00 milliliters of 0.30% ammonium thiocyanate as an indicator. Approximately 53.5 ml of purified water was used to achieve the optimal acidity. The mixture was titrated with a standard solution of iron (III) chloride, resulting in a persistent brownish-yellow hue for 5 minutes. Phytate content was determined in mg/100 g.

2.7 Determination of in vitro protein digestibility (IVPD)

IVPD was conducted using the procedure outlined by Monjula and John [19] with a slight modification. A 16 mg nitrogen sample was analyzed in triplicate and digested with 1 mg of pepsin in 15 ml of 0.1 N HCl at 37 °C for 2 hours. The process was halted by the introduction of 15 ml of 10% trichloroacetic acid (TCA). The mixture was subsequently quantitatively filtered through Whatman No. 1 filter paper. The TCA-soluble fraction was analyzed for nitrogen content using the micro-Kjeldahl method [15]. Digestibility was assessed utilizing the following equation:

$$\text{IVPD\%} = \frac{\text{N in supernatant - N in pepsin}}{\text{N in sample}} \quad \text{X 100}$$

2.8 Statistical analysis

Each determination was conducted on three distinct samples and examined in triplicate on a dry-weight basis; the results were subsequently averaged. Data were examined via analysis of variance. Comparisons of treatment means were conducted using Duncan's multiple-range test. Significance was established at $P \leq 0.05$.

3. Results and discussion

3.1 Effect of treatments on protein, fat, carbohydrate, and total energy of millet flour during storage

3.1.1 Protein content

Figure 1 shows the effect of dehulling, irradiation, and cooking on protein (%) of millet cultivars (Ashana and Dembi) stored at 4 °C for different periods of time. As shown in Figure 1A, the protein content of the cultivar Ashana was 14.46% of the whole flour and reduced to 14.13% and 13.90% after storage for 30 and 60 days at 4 °C. Cooking whole flour significantly reduced protein content, with the lowest value (13.11%) observed at the end of the storage period (60 days). Irradiation alone did not significantly affect protein content during storage, but cooking irradiated flour significantly decreased it, with a minimum of 13.08% at the end of the storage period. Compared with whole-seed flour, dehulling significantly reduced protein content to 13.38%, and further reductions were observed after cooking and storage. Irradiation of the dehulled flour did not affect protein content; at the end of the storage period, it slightly decreased, and further decreases were observed after cooking, with a minimum value (12.75%) at the end of storage. As shown in Figure 1B, the protein content of the cultivar Dembi was 13.62% of the whole flour. The effects of all treatments were similar to those obtained for Ashana (Figure 1A). Protein is an essential component in evaluating the nutritional value of food, establishing dietary sufficiency, and understanding its effects on overall health [20]. The data indicate that storage, heating, and dehulling of the flour greatly lower its protein concentration. Nonetheless, irradiation alone did not markedly influence protein content during storage, whereas heating irradiated flour resulted in a considerable reduction. The protein loss could be attributed to changes in denaturation and aggregation caused by higher temperatures [21]. These findings corroborate earlier research by Kibar et al. [22], which documented analogous protein degradation over prolonged storage in the Titicaca variety and in composite flours derived from wheat, maize, and cassava. Regardless of storage conditions, Alain-Martial et al. [23] found a significant drop in crude protein across storage periods, with the loss rising with storage time. Lancelot et al. [24] investigated the impact of prolonged storage conditions on wheat flour and observed that protein content remained consistent at low temperatures during the storage duration. Dehulling is a process that removes the seed coat, which has been shown to improve palatability and flavor while decreasing antinutrient content, predominantly found in the seed coat of pulses [25]. Pal et al. [26] found that dehulling did not significantly affect protein content; nevertheless, protein levels declined in most cultivars after cooking. Conversely, Valdez-González et al. [27] observed that dehulling enhanced the protein content of chickpeas. Reddy et al. [16] reported that irradiation significantly increased the crude protein content of finger millet flour, attributing this rise to enhanced extractability due to the dissociation of complex protein molecules into simpler forms, as well as to the moisture content of individual samples, which may have contributed to the observed increase in crude protein levels.

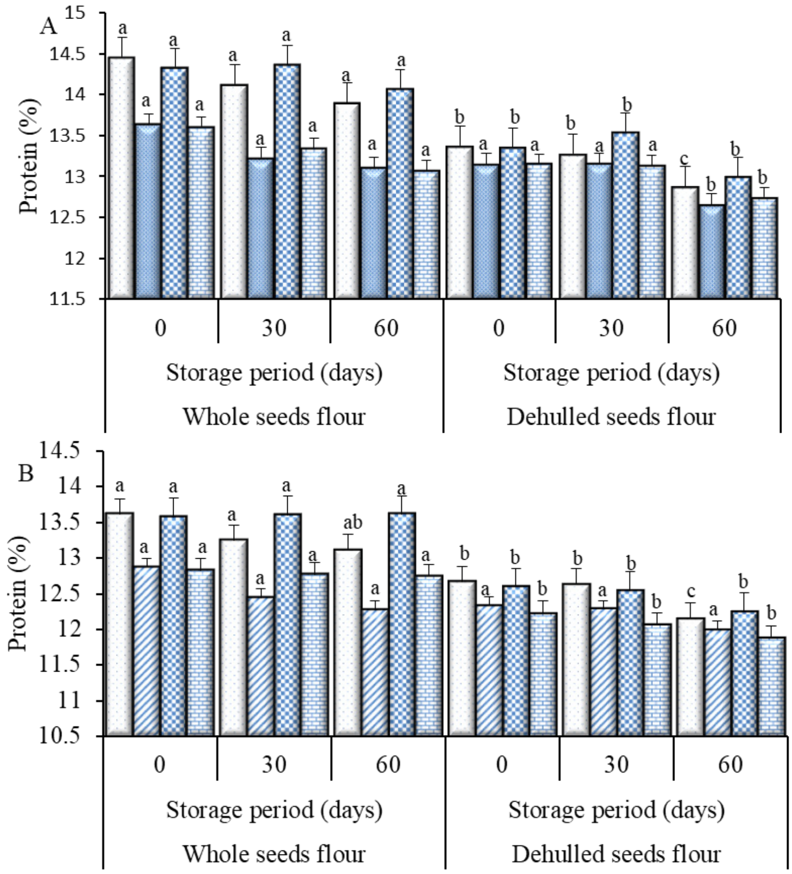

Figure 1. Effect of dehulling, irradiation, and cooking on protein (%) of millet cultivars stored at 4 °C for different periods of time. A. Ashana, and B. Dembi. From left to right, columns 1, 2, 3, and 4 for each storage period represent control, cooked, irradiated, and irradiated and cooked samples, respectively. Values are means of three samples. Error bar indicates standard deviation. Small letters denote significant difference ($P \leq 0.05$) between raw whole or dehulled and each treatment during storage

3.1.2 Fat content

Figure 2 shows the effect of dehulling, irradiation, and cooking on fat (%) of millet cultivars (Ashana and Dembi) stored at 4 °C for different periods of time. As shown in Figure 2A, the fat content of the cultivar Ashana was 8.09% of the whole flour and reduced to 7.92% and 7.82% after storage for 30 and 60 days at 4 °C. Cooking whole flour significantly reduced the fat content, with the lowest value (7.79%) observed at the end of the storage period (60 days). Irradiation alone slightly decreased fat content; a greater reduction was observed during storage. However, cooking of irradiated flour decreased the fat content, even during storage, with a minimum value of 7.72% at the end of the storage period. Compared with whole-seed flour, dehulling significantly reduced the fat content to 7.49%, and further reductions were observed after cooking and storage. Irradiation of the dehulled flour slightly reduced the fat content during the storage period, and a further decrease was observed after cooking, with a minimum value (7.22%) obtained at the end of storage. As shown in Figure 2B, the fat content of the cultivar Dembi was 7.52% of the whole flour. The effects of all treatments were similar to those obtained for Ashana (Figure 2A). Dietary fats are essential macronutrients that are involved in many biological processes, such as signal transduction regulation, ion channel activity modulation, transport and absorption of fat-soluble vitamins, cell membrane maintenance, and metabolic fuel [28]. The fat content of the cultivar's whole flour diminishes following storage, dehulling, cooking, and irradiation. The elimination of the oil-laden bran and germ during dehulling diminished the fat level. The noted reduction in fat content is due to lipid oxidation (rancidity) and enzymatic hydrolysis, processes significantly affected by the fatty acid composition and environmental factors like temperature, moisture, and light exposure [29]. The results align with Forsido et al. [30], who observed a decrease in fat content in composite flours during three months of storage. According to Sruthi et al. [31], storage does not markedly reduce the overall fat content of millet flour; however, it leads to considerable lipid deterioration (rancidity), thereby impairing the quality and nutritional value of the fat. Also, Sharma et al. [32] indicated that during storage, carbohydrates and proteins declined, while lipid rancidity and anti-nutrient levels increased. Lipid and protein degradation accelerated significantly in high-fat genotypes relative to low-fat genotypes. Pal et al. [26] reported that lipid content increased markedly after dehulling but decreased dramatically after cooking. Cooking markedly reduced the fat content of lentil types compared with raw seeds. The lipid content of irradiated finger millet flours increased slightly, regardless of the irradiation dose [33].

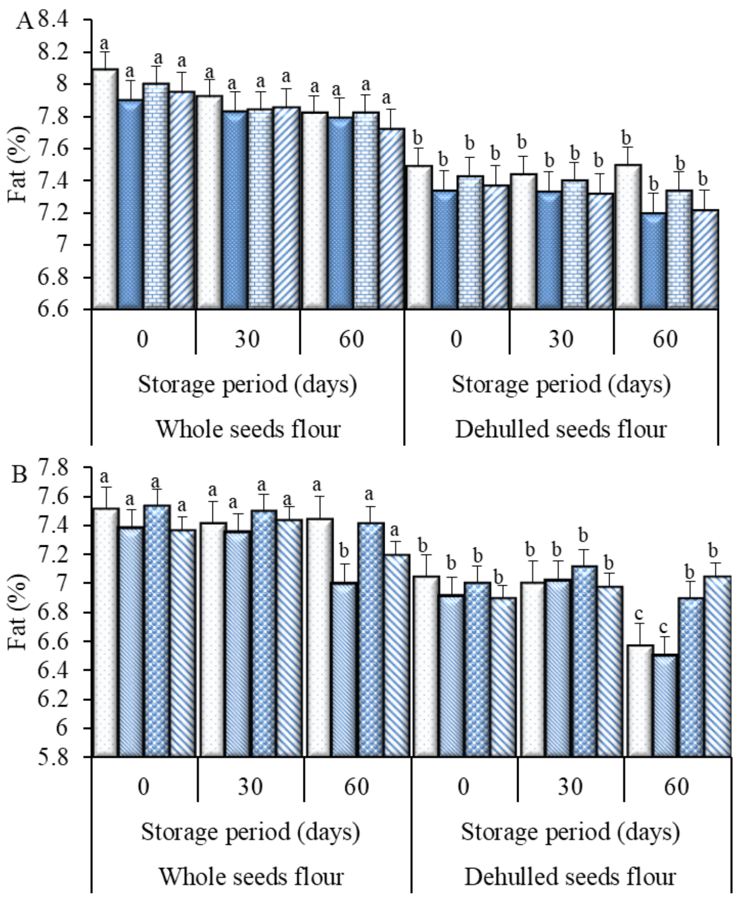

Figure 2. Effect of dehulling, irradiation, and cooking on fat (%) of millet cultivars stored at 4 °C for different periods of time. A. Ashana, and B. Dembi. From left to right, columns 1, 2, 3, and 4 for each storage period represent control, cooked, irradiated, and irradiated and cooked samples, respectively. Values are means of three samples. Error bar indicates standard deviation. Small letters denote significant difference (P ≤ 0.05) between raw whole or dehulled and each treatment during storage

3.1.3 Carbohydrate content

Figure 3 shows the effect of dehulling, irradiation, and cooking on carbohydrates (%) of millet cultivars (Ashana and Dembi) stored at 4 °C for different periods of time. As shown in Figure 3A, the carbohydrate content of the cultivar Ashana was 63.66% of the whole flour and slightly increased to 64% and 64.38% after storage for 30 and 60 days at 4 °C. Cooking of whole flour significantly increased the carbohydrate content, even during storage, with a maximum value (65.32%) obtained at the end of the storage period. Irradiation increased the carbohydrate content, and the increase was greater during storage. However, cooking irradiated flour further significantly increased the carbohydrate content, even during storage, with a maximum value of 64.97% at the end of the storage period. Compared with whole-seed flour, dehulling significantly increased the carbohydrate content to 66.67%, and further increases were observed after cooking and storage. Irradiation of the dehulled flour slightly reduced the carbohydrate content during the storage period, and a further increase was observed after cooking, with a maximum value (67.27%) obtained at the beginning of storage. As shown in Figure 3B, the carbohydrate content of the cultivar Dembi was 65.94% of the whole flour. The effects of all treatments were similar to those obtained for Ashana (Figure 3A). The carbohydrate levels of the cultivars increased following storage, heating, irradiation, and dehulling. The data indicate that chilled storage significantly restricts carbohydrate breakdown, exhibiting negligible variability across storage settings. The modest rise in carbohydrate content may result from the corresponding decrease in protein and fat, considering their inverse correlation with carbohydrate levels in dietary matrices [34]. Azhari et al. [35] indicated that boiling raw millet dough enhanced its protein, carbohydrate, and total calorie content. Theodoro et al. [36] indicate that heating both germinated and ungerminated whole pearl millet substantially enhances carbohydrate content. The depletion of non-carbohydrate constituents, including oil, fiber, protein, and minerals, increased the grain's carb content after dehulling. Singh et al. [37] found that dehulling kodo millet increased carbohydrate availability, attributed to starch in the kernel core. Mala et al. [38] indicated that the carbohydrate content of foxtail millets rose following irradiation. The elevation in carbohydrate content post-irradiation may result from the depolymerization of polysaccharides via the radiolysis of starch.

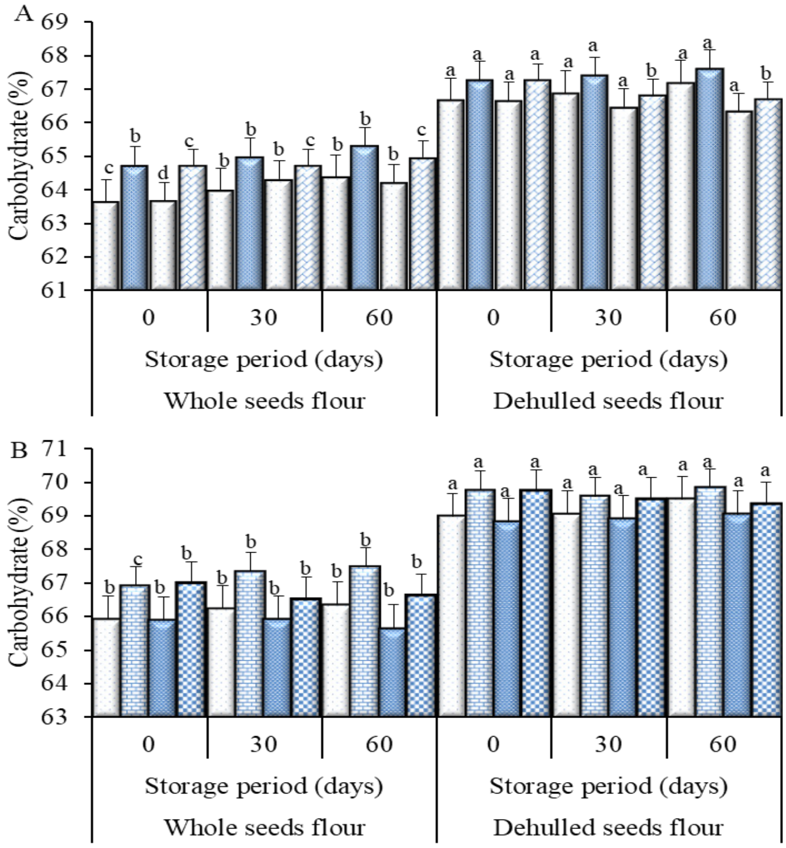

Figure 3. Effect of dehulling, irradiation, and cooking on carbohydrates (%) of millet cultivars stored at 4 °C for different periods of time. A. Ashana, and B. Dembi. From left to right, columns 1, 2, 3, and 4 for each storage period represent control, cooked, irradiated, and irradiated and cooked samples, respectively. Values are means of three samples. Error bar indicates standard deviation. Small letters denote significant difference ($P \leq 0.05$) between raw whole or dehulled and each treatment during storage

3.1.4 Total energy content

Figure 4 shows the effect of dehulling, irradiation, and cooking on total energy (Kcal/100g) of millet cultivars (Ashana and Dembi) stored at 4 °C for different periods of time. As shown in Figure 4A, the total energy content of the cultivar Ashana was 385.26 Kcal/100g of whole flour and significantly decreased to 384.44 and 383.90 Kcal/100g after storage for 30 and 60 days at 4 °C, respectively. Cooking of whole flour significantly decreased the total energy content, even during storage, with a minimum value (383.85 Kcal/100g) obtained at the end of the storage period. Irradiation increased the total energy content during 30 days and thereafter decreased. However, cooking irradiated flour leads to a further significant decrease in total energy content, even after storage, with a minimum of 384.10 Kcal/100g at the end of the storage period. Compared with whole-seed flour, dehulling significantly increased the total energy content to 387.65 Kcal/100g, and further increases were observed after cooking and storage. Irradiation of the dehulled flour increased the total energy content before storage to 387.81 Kcal/100g, but during storage, it decreased to a minimum value (385.98 Kcal/100g) at the end of storage. Cooking irradiated dehulled flour slightly increased energy, but during storage, it decreased significantly. As shown in Figure 4B, the total energy content of the cultivar Dembi was 385.96 Kcal/100g of the whole flour. The effects of all treatments were similar to those obtained for Ashana (Figure 4A). The overall energy content of the cultivars markedly decreased after storage, heating, and irradiation, although dehulling increased it. The increase in total energy during seed dehulling is attributed to increased carbohydrate content in both cultivars. The energy values under various storage conditions showed only slight reductions. Significantly, storage at room temperature did not cause significant energy degradation. The minor reductions can be attributed to the loss of protein and fat content over time [39]. Dely et al. [40] indicated that irradiation increased the gross energy of millet flour subjected to electron-beam treatment, except at the maximum dosage (4 kGy); however, this increase was not statistically significant compared with the control flour. Conversely, there is a notable disparity in gross energy across the flours irradiated with varying doses compared with the control. The dehulling (or decortication) of millet grain eliminates the outer fibrous seed coat (bran), resulting in an elevated concentration of total carbohydrate and, subsequently, a higher total energy value in the flour produced.

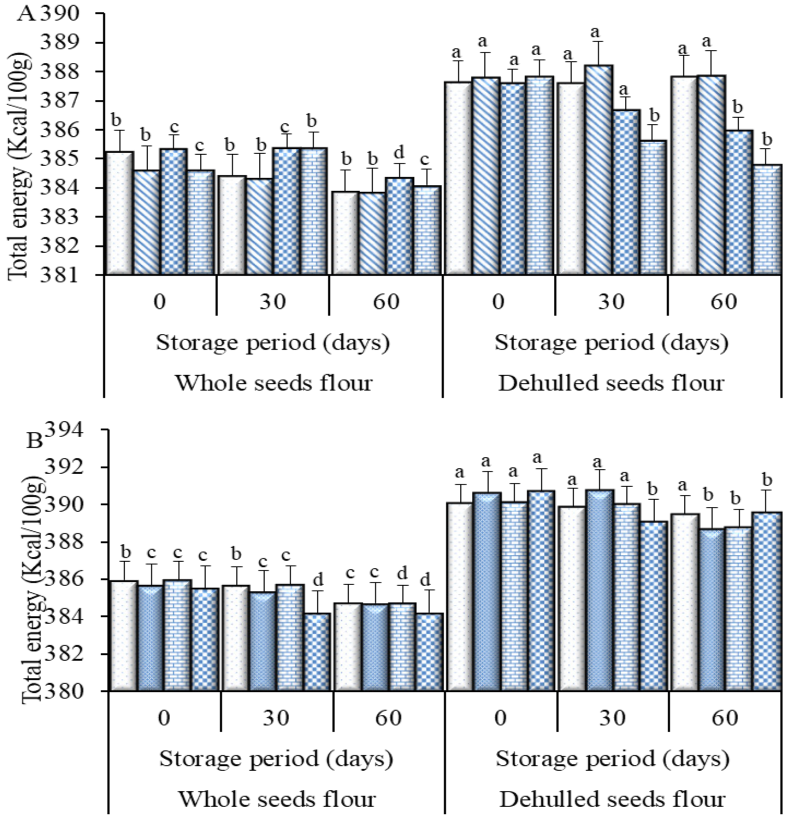

Figure 4. Effect of dehulling, irradiation, and cooking on total energy (Kcal/100 g) of millet cultivars stored at 4 °C for different periods of time. A. Ashana, and B. Dembi. From left to right, columns 1, 2, 3, and 4 for each storage period represent control, cooked, irradiated, and irradiated and cooked samples, respectively. Values are means of three samples. Error bar indicates standard deviation. Small letters denote significant difference ($P \leq 0.05$) between raw whole or dehulled and each treatment during storage

3.2 Effect of treatments on phytate and IVPD of millet flour during storage

Figure 5 summarizes the data for phytate content (mg/100 g) of whole and dehulled raw and processed flour during storage periods (0, 30, and 60 days) of two millet cultivars (Ashana and Dembi). The results obtained for phytic acid content after dehulling, irradiation, and cooking showed that the phytate content of the cultivar Ashana (Figure 5A) was 768.21 mg/100g of whole flour and increased slightly to 768.92 and 769.56 mg/100g after storage for 30 and 60 days at 4 °C, respectively. Cooking of whole flour significantly decreased the phytate content, even during storage, with a minimum value (761.68 mg/100g) obtained before storage. Irradiation decreased phytate content before storage but had no effect during storage. However, cooking irradiated flour led to a further significant decrease in phytate content before storage, but during storage, the decrease was lower than before. Compared with whole-seed flour, dehulling significantly reduced phytate content to 302.79 mg/100g, and further decreases were observed after cooking. Irradiation of the dehulled flour also decreased the phytate content, even after cooking of irradiated dehulled flour. However, storage of all treated samples did not affect the cultivar's phytate content. As shown in Figure 5B, the phytate content of the cultivar Dembi was 722.31 mg/100g of the whole flour. The effects of all treatments were similar to those obtained for Ashana (Figure 5A). Figure 6 shows the effect of the radiation process of whole and dehulled raw and processed flour during storage periods (0, 30, and 60 days) on *in vitro* protein digestibility (IVPD) of Ashana and Dembi cultivars. The IVPD of the whole raw flour of Ashana (Figure 6A) was found to be 46.43% and slightly decreased to 45.65 and 45.23%, after storage for 30 and 60 days at 4 °C. Cooking the whole flour significantly increased the IVPD before storage to 48.35%, but it decreased during storage. Irradiation marginally increased the IVPD before storage, but during storage, it increased significantly. However, cooking irradiated flour results in a significant increase in IVPD before and after storage. Compared to whole seed flour, dehulling significantly increased the IVPD to 55.54%, and further increases were observed after cooking and irradiation, with a maximum value (66.36%) obtained before storage. As shown in Figure 6B,

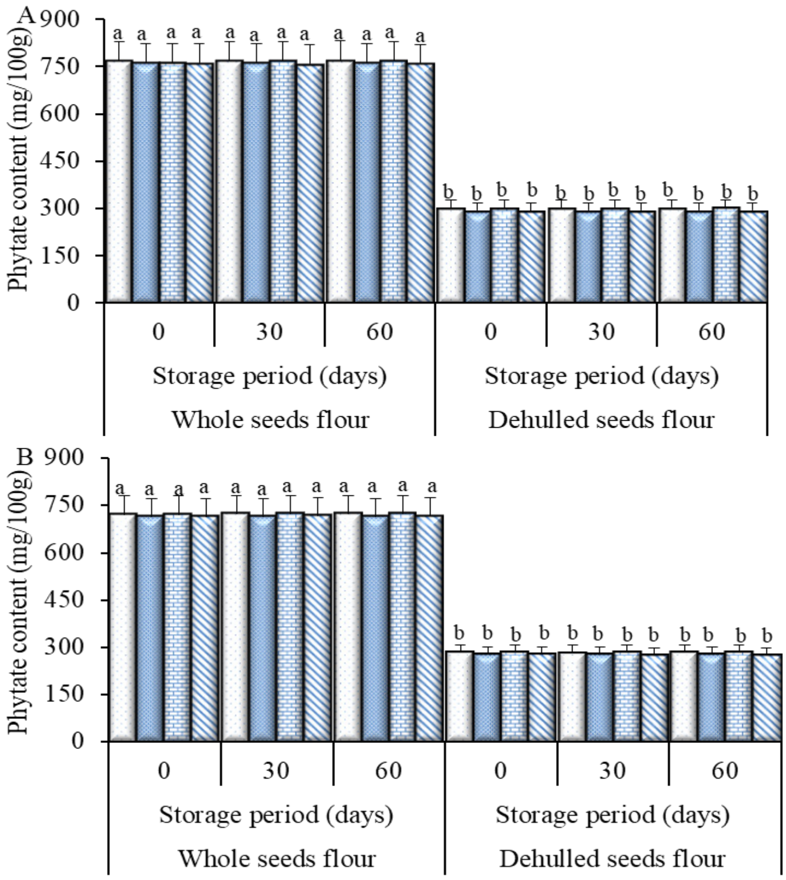

Figure 5. Effect of dehulling, irradiation, and cooking on phytate content (mg/100 g) of millet cultivars stored at 4 °C for different periods of time. A. Ashana, and B. Dembi. From left to right, columns 1, 2, 3, and 4 for each storage period represent control, cooked, irradiated, and irradiated and cooked samples, respectively. Values are means of three samples. Error bar indicates standard deviation. Small letters denote significant difference ($P \leq 0.05$) between raw whole or dehulled and each treatment during storage

the IVPD of the cultivar Dembi was 47.43% of the whole flour. The effects of all treatments were similar to those observed for Ashana (Figure 6A). Post-treatment phytic acid content indicated that phytate levels in both cultivars were unchanged during storage but declined considerably after boiling and irradiation, with a more pronounced reduction in dehulled flour. After a decrease in phytate, protein digestibility markedly improved in both cultivars. Millet flour possesses a significant concentration of phytic acid [41]. Anti-nutrients are primarily located in the outer pericarp and are reduced by dehulling and polishing of the grain, thereby enhancing protein digestibility [42]. Phytic acid is present in elevated concentrations in the hulls and germ of plant seeds [43]; hence, the elimination of the hull (seed coat) may have resulted in the reduced phytic acid levels in dehulled flours. Dehulling diminishes antinutrients that obstruct protein digestibility, as polyphenols, particularly those of elevated molecular weight, can precipitate proteins and impair protein digestibility [44]. The existence of anti-nutrients in the bran layer diminishes the digestibility, absorption, and utilization of nutrients in grains [45]. The anti-nutrient is diminished through the processes of dehulling and polishing the grain. The decrease in phytic acid during cooking and radiation may result from the chemical decomposition of phytate into reduced inositol phosphates and inositol, facilitated by free radicals generated by radiation, or from the cleavage of the phytate ring itself [46]. The enhanced protein digestibility of dehulled flours may be attributed to the elimination of antinutrients found in seed coatings during the dehulling process [47]. Mashau et al. [48] demonstrated that the cotyledons of seeds contain low polyphenol levels, whereas the seed coats are rich in these compounds. Moreover, reduced phytic acid levels may be attributed to the improved protein digestibility of the dehulled flours. Nonetheless, antinutrients are not the sole cause contributing to reduced protein digestion. Dietary fiber may reduce protein digestibility; nevertheless, increases in soluble dietary fiber and decreases in insoluble dietary fiber after processing may correlate with improved protein digestibility [48]. Consequently, the improvement in protein digestibility may also correlate with a reduced crude fiber concentration in dehulled flours.

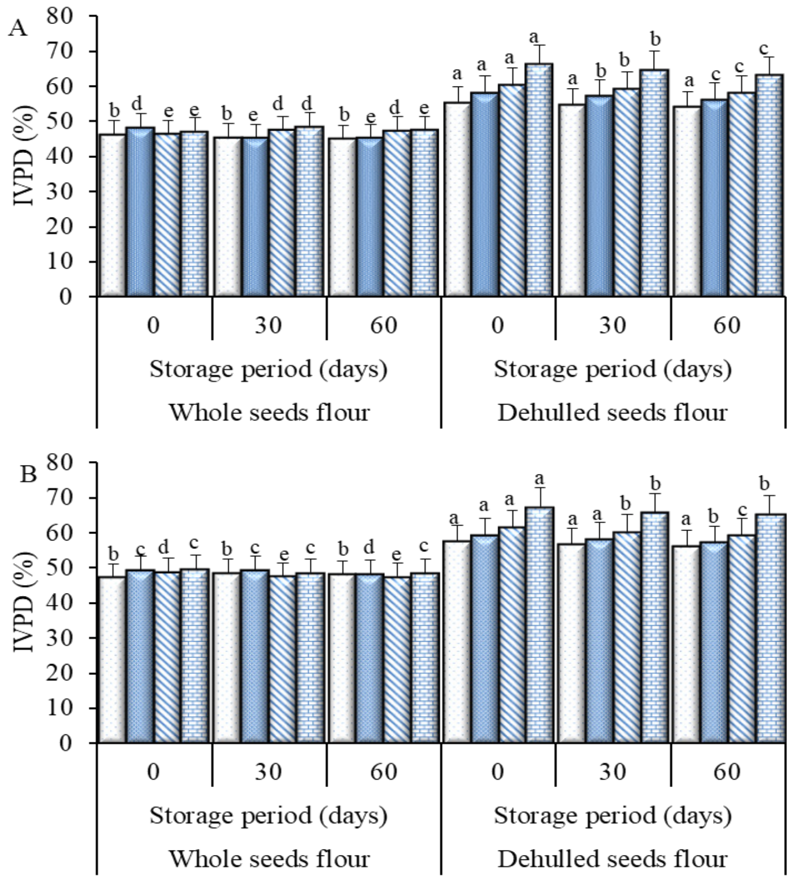

Figure 6. Effect of dehulling, irradiation, and cooking on *in vitro* protein digestibility (IVPD, %) of millet cultivars stored at 4 °C for different periods of time. A. Ashana, and B. Dembi. From left to right, columns 1, 2, 3, and 4 for each storage period represent control, cooked, irradiated, and irradiated and cooked samples, respectively. Values are means of three samples. Error bar indicates standard deviation. Small letters denote significant difference ($P \leq 0.05$) between raw whole or dehulled and each treatment during storage

4. Conclusion

The data indicate that storage, heating, and dehulling of the flour greatly lower its protein concentration. Nonetheless, irradiation alone did not markedly influence protein content during storage, whereas heating irradiated flour resulted in a considerable reduction. The fat content of the cultivar's whole flour diminishes following storage, dehulling, cooking, and irradiation. The carbohydrate levels of the cultivars increased following storage, heating, irradiation, and dehulling. The overall energy content of the cultivars markedly decreased after storage, heating, and irradiation, although dehulling increased it. The results for phytic acid content after treatments showed that the phytate content of both cultivars was not affected by the storage period but decreased significantly after cooking and irradiation, with a greater decrease observed in dehulled flour. Following a reduction in phytate, protein digestibility increased significantly in both cultivars. The optimal processing combination for maximizing nutritional quality was found to be dehulling followed by cooking. The main limitations of this study were a relatively short storage period (60 days) and the single irradiation dose tested.

Authors' contributions

All persons designated as authors contributed equally to this paper. Their substantial contributions include:

1) Conception, design, analysis, and interpretation of data.

2) Drafting the article and revising it critically for important intellectual content.

3) Final approval of the version to be published.

Conflict of interest

The authors report there are no competing interests to declare.

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