Carbohydrate Polymers 110 (2014) 183–194

Contents lists available at ScienceDirect

Carbohydrate Polymers

journal homepage: www.elsevier.com/locate/carbpol

Gamma irradiation induced modification of bean polysaccharides: Impact on physicochemical, morphological and antioxidant properties

Peerzada R. Hussain[a,*], Idrees A. Wani[b], Prashant P. Suradkar[a], Mohd A. Dar[a]

[a] Astrophysical Sciences Division, Nuclear Research Laboratory, Bhabha Atomic Research Centre, Zakura, Srinagar 190006, India
[b] Department of Food Science and Technology, University of Kashmir, Srinagar 190006, India

ARTICLE INFO

Article history:
Received 1 October 2013
Received in revised form 1 March 2014
Accepted 9 March 2014
Available online 27 March 2014

Keywords:
Bean starch
Gamma irradiation
Physicochemical properties
Antioxidant activity
In vitro digestibility

ABSTRACT

In the present study starches from four bean varieties viz. red, yellow, black and white, were gamma irradiated in the dose range of 5–25 kGy to investigate the effect of radiation processing on physicochemical, morphological and antioxidant properties. Studies revealed positive correlation between gamma irradiation and solubility ($r = 0.91$), irradiation and water absorption capacity ($r = 0.82$) and negative correlations between irradiation and swelling power ($r = -0.92$), irradiation and pasting properties ($r = -0.91$) and irradiation and thermal properties ($r = -0.89$). Microscopic observation under scanning electron microscope indicated the development of surface cracking and fractures on the surface of starch granules with increase in dose. X-ray diffractometry revealed no significant change in diffraction patterns between control and irradiated starches, except a decrease in relative crystallinity. Irradiation increased the proportions of both rapidly digestible starch and enzyme resistant starch of bean starches and significantly prevented the retrogradation of bean starches during storage. Results of the DPPH radical scavenging activity and ferric reducing power indicated significant ($p \leq 0.05$) increase in antioxidant activity of all irradiated bean starches with increase in dose.

1. Introduction

Gamma irradiation is a non-thermal method of preservation and has been extensively studied to extend the shelf-life of perishable foods and food products. It has also been used to protect the grain seeds from insect infestation and microbial contamination during storage and has proved to be an efficient alternative to the use to chemical preservatives like methyl bromide, ethylene dibromide and ethylene oxide, in addition to its use as quarantine treatment for export purposes and development of radiation induced mutants for improvement of crop yield and disease resistance (Kume, Furuta, Todoriki, Uenoyama, & Kobayashi, 2009; Liu & Chung, 2010; Liu, Ma, Xue, & Shi, 2012; Sabato et al., 2009). In addition to the above applications, gamma irradiation has also been used to bring about the modifications of polysaccharides like starch through crosslinking (Choi et al., 2009; Nagasawa, Yagi, Kume, & Yoshi, 2004), grafting (Kiatkamjornwong, Mongkolsawat, & Sonsuk, 2002) and degradation (Bertolini, Mestres, Colonna, & Raffi, 2001; Kim et al., 2008). The versatility and edge of gamma irradiation over other modification techniques, such as pre-gelatinization, chemical crosslinking and oxidation; which are complex and time consuming, lies in the fact that gamma irradiation is a low cost and environmentally-friendly alternative to produce modified polymer materials (Xu, Sun, Yang, Ding, & Pang, 2007; Zainol, Akil, & Mastor, 2009). It has been reported that polysaccharide modification through degradation by gamma irradiation leads to the cleavage of the glycosidic bonds (Byun et al., 2008; Cho, Kim, & Rhim, 2003). The basic advantage of the degradation of polysaccharides by radiation is the ability to produce changes which are both reproducible and quantitative in nature (Choi et al., 2009).

Among the major legumes, beans occupy an important place and constitute a rich and inexpensive source of protein and carbohydrate. Carbohydrate represents the main fraction of beans, accounting up to 50–80% of the dry matter; of these starch and non-starch polysaccharides (dietary fiber) are the major constituents (Hoover & Sosulski, 1991). As a major ingredient, starch can be used to control structure, texture, consistency and appeal to many food and non-food products (Jobling, 2004). However the properties of starch like low solubility, high viscosity, shear resistance, thermal resistance, thermal decomposition, high resistance toward swelling and rupture and tendency toward retrogradation limit its use in food applications (Liu et al., 2012). The literature review reveals that extensive work has been done on modification of starch from maize (Liu et al., 2012), rice (Yu & Wang, 2007),

* Corresponding author. Tel.: +91 1942422420; fax: +91 1942422420.
E-mail address: hussainpr@rediffmail.com (P.R. Hussain).

http://dx.doi.org/10.1016/j.carbpol.2014.03.028
0144-8617/

cassava (Bertolini et al., 2001), corn (Yoon et al., 2010) and potato (Ezekiel, Rana, Singh, & Singh, 2007; Luo, Huang, Fu, Zhang, & Yu, 2009) in relation to their morphological and physicochemical properties. However, such studies on radiation induced modification of starch are limited in case of beans and other legumes (Hoover, Hughes, Chung, & Liu, 2010). Further studies on radiation induced enhancement of antioxidant activity of bean polysaccharides, i.e., starch are also limited in the literature. Therefore, the present study was undertaken to investigate the effect of gamma irradiation on physicochemical and morphological modification of bean starch and enhancement of antioxidant properties so as to increase its food applications.

2. Materials and methods

2.1. Materials

Seeds of red, white, black and yellow kidney beans (*Phaseolus vulgaris*) harvested during 2012 were procured from Seed Research Centre of Sheri Kashmir University of Agricultural Sciences and Technology, Shalimar, Jammu and Kashmir, India. Seeds were cleaned from dust and foreign materials manually and stored at room temperature till further use.

2.2. Starch extraction

Two kilogram sample in duplicates of each bean seed was soaked in 4 L of double distilled water for 24 h at room temperature. After soaking, the coats of the seeds were removed and slurry was prepared along with water using a mixer blender. The slurry obtained was again diluted ten times with distilled water and pH of the slurry was raised to 10 with 0.5 N sodium hydroxide. After pH adjustment, the slurry was continuously mixed for 1 h using magnetic shaker followed by filtration through a 75 μ mesh sieve to separate fiber. The filtered slurry was then centrifuged at 5000 × g for 45 min at 10 °C using Eppendorf Centrifuge (5810R, Germany). The aqueous phase obtained on centrifugation was discarded and the white sediment portion was recovered as starch. The starch obtained was dried to a constant weight at 45 °C in a hot air oven. The percentage of starch recovery was about 75–80%.

2.3. Gamma irradiation

The starch samples were packed in polyethylene bags and irradiated in the dose range of 5–25 kGy using PANBIT irradiator having Co-60 as the gamma-ray source. The samples were irradiated at a dose rate of 185 Gy/h. To ensure that starch samples received the exact dose, the dosimeters were placed along with the samples. A ceric-cerous dosimeter was used to measure the absorbed dose of gamma irradiation by the samples. The samples that received no radiation treatment were considered as control. For all the irradiation treatments including control, the sample size used was approximately 150 g of starch in duplicate. After irradiation treatment, the samples were kept at 10 ± 2 °C till further use.

2.4. Solubility and swelling power

Solubility and swelling power were determined by the method of Subramanian, Hoseney, and Bramel-Cox (1994). Starch (0.5 g) was mixed with 30 ml of distilled water and heated with constant stirring at 80 °C for 30 min. After heating to desired temperature, the sample was centrifuged for 30 min at 1500 × *g*. The supernatant was decanted and dried at 120 °C in an oven to a constant weight (M_1). The settled and swollen starch was carefully taken out and weighed as (M_2). The solubility and swelling power were determined by mass balance equations as under

$$\text{Solubility}\,(\text{g}/100\,\text{g}) = \left(\frac{M_1}{M_0}\right) \times 100$$

$$\text{Swelling power}\,(\text{g}/\text{g}) = \frac{M_2}{M_0}$$

where M_0 is the initial weight of starch taken.

2.5. Carboxyl content and pH

The carboxyl content of the irradiated and control starch samples were determined using the method of Chattopadhyay, Singhal, and Kulkarni (1997). To 0.5–1.0 g of starch, 25 ml of 0.1 N HCl was added and the mixture was allowed to stand for 30 min with occasional stirring. The slurry was filtered through a fritted glass crucible and washed with distilled water until it was free from chlorine. The starch was then transferred to a 500 ml beaker to which 300 ml distilled water was added. It was then boiled for 5–10 min for complete gelatinization, followed by titration with 0.1 N NaOH using phenolphthalein as indicator. A blank test was also performed with unmodified starch. Carboxyl content was calculated as follows:

$$\text{Milli-Eq. of acid}/100\,\text{g starch} = (A - B) \times 0.1\,\text{N NaOH} \times 100/W$$

where A is titer value for sample; B is titer value for blank; and W is weight of sample in grams.

$$\text{Apparent percent carboxyl} = \text{Milli-equivalents of acid}/100\,\text{g starch} \times 0.045.$$

pH of the starch slurry (30 g/100 ml) was determined using a digital pH meter (Eutech Instruments, USA) calibrated using buffer pH 4.

2.6. Starch retro-gradation

Starch retro-gradation was determined indirectly as a function of light transmitted by an aqueous solution of starch. An aqueous solution of starch (0.5%, w/v) was prepared by heating at 90 °C in a water bath for 45 min with constant stirring. The solution was cooled to room temperature and stored for 5 days at refrigeration temperature. Absorbance of the solution was taken every day at 640 nm using UV–vis spectrophotometer (Hitachi 330, Japan) and the percent transmittance values were calculated using absorbance–transmittance relationship.

2.7. Apparent amylose content and amylose leaching

Apparent amylase content was determined as per the method of Williams, Kuzina, and Hlynka (1970). A starch suspension was made by dissolving 20 mg of starch in 10 ml of 0.5 N KOH and the contents were mixed thoroughly. The samples were then transferred to a 100 ml volumetric flask and the volume was made up to the mark with distilled water. An aliquot (10 ml) of the sample was taken into 50 ml volumetric flask and 5 ml of 0.1 N HCl were added followed by 0.5 ml of iodine reagent. The contents were again diluted to 50 ml and the absorbance was measured at 625 nm. The content of amylase was determined from the standard curve of amylose and amylopectin blends from potato starch.

For determining amylose leaching, a starch suspension of (0.5%, w/v) was heated at temperature range of 60–80 °C for 30 min followed by centrifugation at 1500 × *g* for 30 min. The amount of leached amylose was estimated by determining the amount of amylose in the resultant solution as above.

2.8. Water absorption capacity (WAC)

Water absorption capacity (WAC) was determined according to the method described by Mishra and Rai (2006) with a few modifications. Known weight of starch (1 g) was taken in a pre-weighed centrifuge tube and the combined weight of starch and centrifuge tube was designated as W_1. An aqueous suspension was made by dissolving of starch in 20 ml of water. The suspension was agitated for 1 h on shaker after which it was centrifuged for 20 min at $2000 \times g$. The free water was decanted from the wet starch and the tube was allowed to drain for 10 min at 45° angle. The tube containing the wet starch was again weighed and the weight designated as W_2 to calculate the water absorption capacity as:

$$\text{WAC} = \frac{W_2 - W_1}{\text{Weight of starch taken}}.$$

2.9. Viscosity/pasting parameters

The viscosity parameters such as peak viscosity (PV), trough viscosity (TV), final viscosity (FV), breakdown viscosity (BV), setback viscosity (SV) and pasting temperature (PT) of irradiated as well as control starch samples were determined using a Rapid Visco-Analyzer (RVA-Ezi, Newport Scientific Pvt. Ltd., Warriewood, Australia). Starch (3.0 g) was mixed with 25 ml of distilled water in RVA sample container. The heating and cooling cycles were programmed. Starch slurry was held at 50 °C for 1 min, heated to 95 °C within 3 min 42 s, held at 95 °C for 2 min 30 s before cooling to 50 °C within 3 min 48 s, and held at 50 °C for 2 min. The paddle speed was set at 960 rpm for the first 10 s to evenly disperse the starch slurry and reduced to 160 rpm throughout the rest of the experiment. The viscosities were recorded in cP.

2.10. Thermal properties

Thermal properties of the starch samples were determined by using a differential scanning calorimeter (DSC-6, Perkin-Elmer, USA) provided with a intra-cooling system. Starch samples (10 mg) and distilled water (24 ml) was loaded in to a high-volume pan, sealed and allowed to stand overnight at room temperature before DSC analysis. Sample pan was heated from 5 to 180 °C at the rate of 10°/min. The instrument was calibrated with indium and deionized water as a reference. Characteristic temperatures of the transitions were onset temperature (T_0), peak temperature (T_p), conclusion temperature (T_c) and enthalpy of gelatinization (ΔH). Enthalpy of gelatinization was calculated by the following equation:

$$\Delta H = S/K \times m$$

where S represents the area of the endothermic peak, k is a constant and m is the mass of starch sample (g).

2.11. In vitro digestibility of starch

The *in vitro* starch digestibility of control and gamma irradiated starch samples was determined by following the method of Englyst, Kingman, and Cummings (1992) as modified by Chung, Lim, and Lim (2006). The various starch fractions (RDS: rapidly digestible starch, SDS: slowly digestible starch, RS: resistant starch) were measured after incubation with invertase, pancreatin and amyloglucosidase at 37 °C in capped tubes immersed in a shaking water bath. The amount of starch fractions based on digestibility was calculated by using the method of Englyst et al. (1992). The rapidly digestible starch was defined as the starch fraction that was hydrolyzed within 20 min incubation and resistant starch was defined as the fraction that remained unhydrolyzed after 180 min incubation. The slowly digestible starch as the starch digested during the period between 20 and 180 min and was calculated as the difference between RDS and RS.

2.12. Scanning electron microscopy

The granular morphology of irradiated and control starches was examined with a field emission scanning electron microscope (S-4500 Hitachi, Tokyo, Japan). The starch samples were sprayed on a metal plate previously covered with double-sided adhesive tape and coated with gold and palladium (60:40) using a sputter coater (Polaron SC500, Quorum Technologies, East Sussex, UK). The samples were examined at 7.0 kV accelerating voltage and the resulting morphological characteristics were studied from SEM micrographs taken at 700× magnification.

2.13. X-ray diffractometry and relative crystallinity

X-ray diffraction patterns of the control and irradiated starch samples (approx. 20% moisture) were taken with a Rigaku RPT 300 PC X-ray diffractometer (Rigaku-Denki Co., Tokyo, Japan) equipped with Cu$K\alpha$ radiation. An accelerating voltage and current of 40 kV and 100 mA, were used, respectively. The diffractograms were recorded in a 2θ between 2° and 49° with a scanning rate of 2.0°/min. The relative crystallinity was quantitatively estimated according to the method of Nara and Komiya (1983) using Origin 6.0 software (Microcal Inc., Northampton, MA, USA).

2.14. Antioxidant activity

2.14.1. DPPH radical scavenging activity

DPPH radical scavenging activity of gamma irradiated starch samples was measured according to the method of Brand-Williams, Cuvelier, and Berset (1995) with some modifications. Starch solution of concentration 1 mg/ml (w/v) was prepared in double distilled water. 5 ml of starch solution was mixed with 5 ml of a 60 mM solution of DPPH in ethanol. The mixture was shaken vigorously and kept in the dark at room temperature for 30 min. Absorbance of the mixture was measured at 517 nm in a UV–vis spectrophotometer (HITACHI, 330). Ethanol was used to zero the spectrophotometer. The DPPH solution was prepared daily, stored in flasks, covered with aluminum foils and kept in dark at 4 ± 1 °C until the measurements were taken. The scavenging activity of the solution was expressed as the percentage of inhibition of the DPPH radical.

$$\text{Inhibition percentage (IP)} = \frac{[A_{\text{control}} - A_{\text{sample}} \times 100]}{A_{\text{control}}}$$

where A_{control} is the absorbance of the control (containing all reagents except the sample), A_{sample} is the absorbance of the sample, both measured at 517 nm.

2.14.2. Ferric reducing/antioxidant power (FRAP)

The ferric reducing power of starch was determined according to the method of Oyaizu (1986). A starch working solution of concentration 5 mg/ml (w/v) was prepared in double distilled water and 1 ml of the working solution was mixed with 2.5 ml of 0.2 M sodium phosphate buffer (pH 6.6) and 2.5 ml of 1% potassium ferricyanide. The reaction mixtures were incubated in a temperature controlled water bath at 50 °C for 20 min followed by the addition of 2.5 ml of 10% trichloroacetic acid. The mixtures were then centrifuged at $750 \times g$ using low temperature centrifuge (5180R, Eppendroff, Germany) for 10 min. The supernatant obtained (5 ml) was treated with 5 ml of distilled water and 1 ml of 1% ferric chloride. The absorbance of the reaction mixture was measured at

700 nm. An increase in absorbance was used as a measure of the reducing power.

2.15. Statistical analysis

The data was analyzed statistically using completely randomized design experiment (Cochran & Cox, 1975). For each measurement, three replicates of samples were tested per treatment and mean ± standard deviation values were reported. Analysis of variance (ANOVA) of the data was performed using MINITAB statistical analysis software package (Minitab, version 11.12, 32 bit, Minitab). Difference between means of data was compared by least significant difference (LSD) and Student's t test was applied to determine if the difference was statistically significant. Differences at $p \leq 0.05$ were considered to be statistically significant. Duncan's multiple range test was used to compare the mean values and coefficient of correlation was determined by Karl Pearson method.

3. Results and discussion

3.1. Solubility

The data pertaining to solubility indicated that irradiation at all dose levels resulted in significant ($p \leq 0.05$) increase in solubility in all the bean starches (Table 1). Data analysis also revealed a strong positive correlation ($r = 0.91$) between irradiation treatment and solubility. Among the un-irradiated bean starches, solubility was significantly ($p \leq 0.05$) higher in black bean starch (21.4 ± 1.2 g/100 g) followed by red bean (18.6 ± 1.1 g/100 g), white bean (17.3 ± 0.9 g/100 g) and yellow bean (15.2 ± 0.8 g/100 g) starches, respectively. In case of irradiated samples, the solubility of red, white and yellow bean starches was significantly ($p \leq 0.05$) different at each dose level, where as in black bean starch the solubility of samples irradiated at 10 and 15 kGy differed marginally ($p \geq 0.05$). Similar trend was also observed in samples irradiated at 20 and 25 kGy. The percentage increase in solubility of red, white, black and yellow bean starches irradiated at 25 kGy was of the order of 70.2%, 71.3%, 67.2% and 74.3%, respectively. The enhancement in solubility of radiation processed bean starches is attributed to radiation induced depolymerization of starch molecules and increase in proportion of short chain amylopectin which have greater hydration tendency than the native starch (Chung, Hoover, & Liu, 2009; Wu, Shu, Wang & Xia, 2002). Further, the increased polarity due to breakage of glucosidic bonds and chain scission during irradiation treatment and the subsequent decrease in inter-chain hydrogen bonds also contribute to the increased solubility. Liu et al. (2012) also reported improved solubility of maize starch processed by gamma irradiation. Similar results have been reported in corn and potato starches with X-ray and electron beam irradiation treatment (De Kerf, Mondelaers, Lahorte, Vervaet, & Remon, 2001).

3.2. Swelling power

The data on swelling power indicated that degree of swelling of un-irradiated red, white, black and yellow bean starches was in the range of 10.2 ± 1.2 to 11.9 ± 1.4 g/g (Table 1). Highest degree of swelling (11.9 ± 1.4 g/g) was recorded in red bean starch follows by white bean starch (11.2 ± 0.4 g/g). Data analysis further indicated that swelling power of irradiated bean starches was dose dependent and decreased significantly ($p \leq 0.05$) with increase in irradiation dose in all the four bean starches. Data analysis revealed a strong negative correlation ($r = -0.92$) between irradiation treatment and swelling power, thereby confirming the decrease in swelling with increase in irradiation dose. Among irradiated samples, swelling power was non-significantly ($p \geq 0.05$) different for white, yellow and black bean starches irradiated at 10 and 15 kGy and at 20 and 25 kGy, respectively. For red bean starch, similar trend in swelling power was observed at doses of 5 and 10 kGy. The extent of decrease in swelling power of bean starches irradiated at 25 kGy as compared to control starch was 9.1%, 9.0% and 9.2% for red, white, black and yellow bean starches, respectively. Singh, Singh, Ezekiel, and Kaur (2011) also reported a swelling decrease of 12.2% and 10.5% in gamma irradiated potato starches of Kufri Jyoti and Kufri Chipsona-2 varieties. The authors correlated that decrease in swelling with irradiation is attributed to the loss in crystallinity; since swelling power is affected by the extent of interactions between starch chains within the amorphous and crystalline domains of starch granules. De-Kerf et al. (2001) also reported radiation induced decrease in amylopectin fraction of various starches and a subsequent reduction in swelling power. This decrease in swelling power upon irradiation could prove beneficial in improving the textural quality of starch during cooking by avoiding or preventing its bursting. Further, the modified starches with reduced swelling and decreased crystallinity can be used as additives for frozen foods to prevent them from dripping when defrosted, to improve their freeze–thaw stability without syneresis and keep their ingredients together in addition to their use as edible coatings for fruits and vegetables and strong binders for seasonings on snacks and cereals.

3.3. Water absorption capacity

Water absorption capacity also recorded a significant increase with irradiation dose up to 20 kGy in all the bean starches (Table 1). Beyond 20 kGy water absorption capacity either decreased or remained same irrespective of bean starch. Among the control starches, water absorption capacity was significantly ($p \leq 0.05$) higher (2.2 ± 0.2 g/g) in red bean and lower (1.9 ± 0.2 g/g) in white bean starch. Statistical analysis revealed no significant difference in water absorption capacity between control black and yellow bean starches. Among the irradiated bean varieties, significant ($p \leq 0.05$) difference in water absorption capacity was recorded in starch samples irradiated at 15 and 20 kGy. The increase in water absorption capacity was statistically non-significant in white and black bean starches irradiated at doses of 10 and 15 kGy, respectively. Maximum increase in water absorption capacity of bean starches irradiated at 20 kGy was 27.3% for red bean, 26.3% for white bean, 19.0% for black bean and 23.8% for yellow bean starches, respectively. The increase in water absorption capacity with increase in irradiation up to 20 kGy is attributed to radiation induced degradation of starch in to the lower monomers which have greater affinity for water than the native starch. However, a slight decreasing shift in water absorption capacity of bean starches irradiated at 25 kGy was not exactly known, although there was a concomitant and significant increase in solubility of bean starches irradiated at 25 kGy which clearly indicates radiation induced degradation of starch in to lower monomers which have greater affinity for water.

3.4. Apparent amylose content and amylose leaching

Apparent amylose content and amylose leaching exhibited a decreasing and increasing trend with increase in irradiation treatment from 5 to 25 kGy in all the bean starches (Table 2). For red, white and black bean starches, decrease in apparent amylose content was significant ($p \leq 0.05$) at all the doses; whereas in yellow bean starch, the decrease was statistically non significant in samples irradiated at 15 and 20 kGy, respectively. However, increase in amylose leaching was statistically significant in all the bean starches. In un-irradiated bean starches, a significant difference was also noted in apparent amylose content and amylose leaching among the varieties and the contents were higher in

Table 1
Effect of gamma irradiation treatment on solubility, swelling power and water absorption capacity of bean starches.

Bean variety	Dose (kGy)						
	0	5	10	15	20	25	LSD
Solubility (g/100 g)							
Red bean	$18.6^{a,2}$ (1.1)	$32.4^{b,2}$ (0.8)	$40.6^{c,2}$ (1.1)	$46.5^{d,2}$ (0.9)	$55.3^{e,2}$ (1.4)	$62.4^{f,2}$ (1.3)	4.1
White bean	$17.3^{a,1}$ (0.9)	$30.8^{b,2}$ (0.8)	$38.4^{c,2}$ (1.1)	$44.3^{d,2}$ (0.9)	$53.4^{e,2}$ (1.3)	$60.2^{f,1}$ (1.2)	4.5
Black bean	$21.4^{a,3}$ (1.2)	$34.6^{b,3}$ (0.9)	$44.5^{c,3}$ (1.2)	$48.2^{c,3}$ (1.4)	$58.3^{d,3}$ (1.5)	$65.2^{d,3}$ (1.6)	5.1
Yellow bean	$15.2^{a,1}$ (0.8)	$27.2^{b,1}$ (0.9)	$34.1^{c,1}$ (1.1)	$41.3^{d,1}$ (1.1)	$50.2^{e,1}$ (0.9)	$59.2^{f,1}$ (1.1)	4.2
LSD ($p \leq 0.05$)	2.1	2.5	3.1	2.6	2.4	2.1	
Swelling power (g/g)							
Red bean	$11.9^{e,4}$ (1.4)	$8.4^{d,4}$ (0.6)	$7.6^{d,3}$ (1.1)	$5.7^{c,2}$ (0.6)	$4.1^{b,4}$ (0.4)	$2.8^{a,4}$ (0.3)	1.1
White bean	$11.2^{e,3}$ (0.4)	$7.8^{d,3}$ (0.8)	$6.1^{c,2}$ (0.5)	$5.3^{c,2}$ (0.5)	$3.4^{b,3}$ (0.3)	$2.2^{a,3}$ (0.2)	0.8
Black bean	$10.2^{d,1}$ (1.2)	$6.6^{c,1}$ (0.6)	$5.1^{b,1}$ (0.5)	$4.2^{b,1}$ (0.4)	$2.2^{a,1}$ (0.5)	$1.2^{a,1}$ (0.6)	1.0
Yellow bean	$10.9^{e,2}$ (0.8)	$7.2^{d,2}$ (0.5)	$5.7^{c,1}$ (0.6)	$4.8^{c,1}$ (0.5)	$2.9^{b,2}$ (0.4)	$1.7^{a,2}$ (0.5)	0.9
LSD ($p \leq 0.05$)	0.4	0.4	0.6	0.6	0.5	0.3	
Water absorption capacity (g/g)							
Red bean	$2.2^{a,3}$ (0.2)	$2.4^{b,3}$ (0.2)	$2.6^{c,3}$ (0.1)	$2.7^{d,4}$ (0.1)	$2.8^{e,4}$ (0.2)	$2.6^{f,3}$ (0.1)	0.02
White bean	$1.9^{a,1}$ (0.4)	$2.1^{b,1}$ (0.8)	$2.3^{c,1}$ (0.5)	$2.3^{c,1}$ (0.5)	$2.4^{d,1}$ (0.3)	$2.4^{d,1}$ (0.2)	0.03
Black bean	$2.1^{a,2}$ (0.2)	$2.2^{b,2}$ (0.3)	$2.4^{c,2}$ (0.2)	$2.4^{c,2}$ (0.2)	$2.5^{d,2}$ (0.3)	$2.6^{e,3}$ (0.3)	0.02
Yellow bean	$2.1^{a,2}$ (0.2)	$2.2^{b,2}$ (0.1)	$2.4^{c,2}$ (0.2)	$2.5^{d,3}$ (0.2)	$2.6^{e,3}$ (0.1)	$2.5^{d,2}$ (0.1)	0.02
LSD ($p \leq 0.05$)	0.03	0.02	0.03	0.04	0.03	0.03	

Values are mean ± SD ($n = 3$); values in parenthesis represent SD.
Values within treatments in a row not sharing a common superscript lowercase letters (a–f) are significantly ($p \leq 0.05$) different.
Values within varieties in a column not sharing a common superscript numerical (1–4) are significantly ($p \leq 0.05$) different.
LSD, least significant difference.

yellow bean starch followed by white, red and black bean starches, respectively. Similar findings regarding apparent amylose content have also been reported by Yu and Wang (2007) in rice starch and Chung and Liu (2009) in normal maize starch. The decrease in apparent amylose content with increase in dose is largely due to the severe degradation of amylose fraction by irradiation which results in decrease in its iodine binding ability (Sokhey & Chinnaswamy, 1993). The maximum decrease in apparent amylose content recorded at 25 kGy was of the order of 21.9% for black bean starch followed by 21.5%, 19.5% and 17.3% for red, yellow and white bean starches, respectively. Yu and Wang (2007) reported that the decrease of apparent amylose content resulted from the breakage or cleavage of partly branched long chains in amylopectin during irradiation. The increase in amylose leaching recorded at 25 kGy was of the order of 39.9% for red bean starch followed by 36.9%, 36.5% and 34.3% for black, white and yellow bean starches, respectively. The degradation of long chains of amylopectin during irradiation allows it to be easily leached out during heating, thereby resulting in increased amylose leaching (Chung & Liu, 2010).

3.5. Carboxyl content and pH

The bean starches in their native form had pH values of 4.8 ± 0.01, 4.7 ± 0.01 and 4.9 ± 0.01 for red, white, yellow and black bean starches and zero percent carboxyl content (Table 3). Data analysis revealed that carboxyl content increased and pH decreased in all the bean starches with increase in irradiation dose from 5 to 25 kGy. Carboxyl content increased to maximum of 0.09 ± 0.01% and 0.1 ± 0.01% in 25 kGy irradiated starches of white, red, black and yellow beans; while as pH values decreased to 4.1 ± 0.01 and 4.2 ± 0.01 for the above indicated bean starches. The increase in carboxyl content could be attributed to the formation of degradation products of native starch mainly the carboxylic acids in the bean starches during irradiation The formation of carboxylic acids caused an increase in carboxyl content and a subsequent decrease in pH values of bean starches. Similar increase and decrease in carboxyl content and pH has also been reported by Chung and Liu (2009) with increase in irradiation dose in corn starch. Chung and Liu (2010) and Riyas-Duarte and Rupnow (1994) also reported that

Table 2
Effect of gamma irradiation treatment on apparent amylose conten and amylose leaching of bean starches.

Bean variety	Dose (kGy)						
	0	5	10	15	20	25	LSD
Apparent amylose content (g/100 g)							
Red bean	$38.5^{f,2}$ (0.4)	$37.1^{e,2}$ (0.3)	$36.1^{d,2}$ (0.5)	$34.3^{c,2}$ (0.5)	$32.1^{b,2}$ (0.4)	$30.2^{a,2}$ (0.4)	0.8
White bean	$39.4^{f,3}$ (0.4)	$38.4^{e,3}$ (0.2)	$37.3^{d,3}$ (0.5)	$35.9^{c,3}$ (0.5)	$34.4^{b,3}$ (0.3)	$32.6^{a,3}$ (0.2)	0.7
Black bean	$36.1^{e,1}$ (0.2)	$35.4^{e,1}$ (0.3)	$33.8^{d,1}$ (0.4)	$32.4^{c,1}$ (0.4)	$30.5^{b,1}$ (0.5)	$28.2^{a,1}$ (0.3)	1.1
Yellow bean	$42.6^{e,4}$ (0.2)	$40.3^{d,4}$ (0.3)	$38.1^{c,4}$ (0.2)	$36.5^{b,4}$ (0.4)	$35.7^{b,4}$ (0.4)	$34.3^{a,4}$ (0.3)	0.9
LSD ($p \leq 0.05$)	0.5	0.4	0.6	0.4	0.5	0.6	
Amylose leaching (%)							
Red bean	$26.2^{a,2}$ (0.4)	$28.4^{b,2}$ (0.5)	$30.6^{c,3}$ (0.4)	$32.1^{d,3}$ (0.5)	$34.2^{e,3}$ (0.4)	$36.4^{f,3}$ (0.4)	1.2
White bean	$25.5^{a,1}$ (0.4)	$27.1^{b,1}$ (0.6)	$29.4^{c,2}$ (0.5)	$31.3^{d,2}$ (0.5)	$33.1^{e,2}$ (0.5)	$34.8^{f,2}$ (0.2)	1.1
Black bean	$27.1^{a,3}$ (0.5)	$29.1^{b,2}$ (0.3)	$31.4^{c,4}$ (0.6)	$32.8^{d,3}$ (0.4)	$34.8^{e,3}$ (0.3)	$37.1^{f,3}$ (0.3)	1.3
Yellow bean	$25.1^{a,1}$ (0.5)	$26.4^{b,1}$ (0.4)	$27.8^{c,1}$ (0.5)	$29.5^{d,1}$ (0.4)	$31.6^{e,2}$ (0.4)	$33.7^{f,1}$ (0.3)	1.1
LSD ($p \leq 0.05$)	0.6	0.7	0.5	0.7	0.6	0.7	

Values are mean ± SD ($n = 3$); values in parenthesis represent SD.
Values within treatments in a row not sharing a common superscript lowercase letter (a–f) are significantly ($p \leq 0.05$) different.
Values within varieties in a column not sharing a common superscript numerical (1–4) are significantly ($p \leq 0.05$) different.
LSD, least significant difference.

Table 3
Effect of gamma irradiation treatment on apparent amylose content and amylose leaching of bean starches.

Bean variety	Dose (kGy)						
	0	5	10	15	20	25	LSD
Carboxyl content (%)							
Red bean	0.00	$0.03^{a,1}$ (0.01)	$0.05^{b,1}$ (0.01)	$0.07^{c,1}$ (0.02)	$0.08^{c,1}$ (0.02)	$0.1^{d,1}$ (0.01)	0.01
White bean	0.00	$0.02^{a,1}$ (0.01)	$0.04^{b,1}$ (0.01)	$0.06^{c,1}$ (0.02)	$0.07^{c,1}$ (0.01)	$0.09^{d,1}$ (0.01)	0.01
Black bean	0.00	$0.03^{a,1}$ (0.01)	$0.05^{a,1}$ (0.01)	$0.06^{b,1}$ (0.02)	$0.08^{b,1}$ (0.02)	$0.1^{c,1}$ (0.01)	0.02
Yellow bean	0.00	$00.4^{a,2}$ (0.01)	$0.06^{b,1}$ (0.02)	$0.08^{c,2}$ (0.01)	$0.09^{c,2}$ (0.01)	$0.1^{d,1}$ (0.01)	0.01
LSD ($p \leq 0.05$)	–	0.01	0.02	0.01	0.01	0.01	
pH							
Red bean	$4.8^{f,2}$ (0.01)	$4.7^{e,2}$ (0.01)	$4.6^{d,2}$ (0.01)	$4.4^{c,2}$ (0.01)	$4.3^{b,2}$ (0.01)	$4.2^{a,2}$ (0.01)	0.01
White bean	$4.7^{f,1}$ (0.01)	$4.6^{e,1}$ (0.01)	$4.5^{d,1}$ (0.01)	$4.3^{c,1}$ (0.01)	$4.2^{b,1}$ (0.01)	$4.1^{a,1}$ (0.01)	0.01
Black bean	$4.9^{f,3}$ (0.01)	$4.8^{e,3}$ (0.01)	$4.6^{d,2}$ (0.01)	$4.4^{c,2}$ (0.01)	$4.3^{b,2}$ (0.01)	$4.2^{a,2}$ (0.01)	0.02
Yellow bean	$4.7^{f,1}$ (0.01)	$4.6^{e,1}$ (0.01)	$4.5^{d,1}$ (0.01)	$4.4^{c,2}$ (0.01)	$4.3^{b,2}$ (0.01)	$4.2^{a,2}$ (0.01)	0.02
LSD ($p \leq 0.05$)	0.01	0.01	0.02	0.01	0.01	0.01	

Values are mean ± SD ($n = 3$); values in parenthesis represent SD.
Values within treatments in a row not sharing a common superscript lowercase letter (a–f) are significantly ($p \leq 0.05$) different.
Values within varieties in a column not sharing a common superscript numerical (1–3) are significantly ($p \leq 0.05$) different.
LSD, least significant difference.

acidity and pH values of bean and potato starch increased with increasing irradiation dose. The radiation degradation of starch is initiated by the generation and transformation of free radicals and follows the low-molecular products with the number of carboxylic acids and aldehydes in addition to formic, acetic, pyruvic and gluconic acids (Sharpatyi, 2003).

3.6. In vitro digestibility

The *in vitro* digestibility of gamma irradiated bean starches is shown in Table 4. The data revealed consistent and significant ($p \leq 0.05$) increase in rapidly digestible starch (RDS) with increase in irradiation dose. The percentage increase in the proportion of RDS was of the order of 3.9–14.4% for red bean starch, 3.9–12.4% for white, 3.9–14.3% for black and 4.4–13.7% for yellow bean starches, respectively, at doses of 5–25 kGy. It is also clear from Table 4 that among un-irradiated bean starches, RDS was higher in black bean starch (14.9 ± 1.5%) followed by red (12.8 ± 1.2%), white (11.7 ± 1.1%) and yellow (10.2 ± 1.1%) bean starches, respectively. The digestibility increase in irradiated bean starches resulted from the structural degradation of both granular as well as molecular starch which facilitated easy access of digestive enzyme to starch. In comparison to RDS, irradiation caused a decrease in slowly digestible starch (SDS) in all the bean starches at all the doses applied. The maximum decrease in the proportion of SDS of bean starches irradiated at 25 kGy was of the magnitude of 24.1%, 20.4%, 22.3% and 21.3% in red, white, black and yellow bean starches, respectively. Among the un-irradiated samples, black bean starch recorded highest SDS followed by red, yellow and white bean starch, respectively. Similar findings regarding RDS and SDS were also reported by Yoon et al. (2010) in gamma irradiated corn starch. The radiation induced decrease in SDS could be attributed to its partial transformation to resistant starch (RS) by irradiation. The free radicals produced during irradiation may result in chain associations and formation of stable matrices with increased resistance against digestive enzymes (Yoon et al., 2010). On the other hand, the proportion of resistant starch (RS) increased significantly ($p \leq 0.05$) with increase in dose. The increase in RS is indicative of the fact that both structural changes as well as chain cleavage has taken place during irradiation of bean starches. The cleavage of glycosidic linkages increases the accessibility of the digestive enzymes and result in decrease in RS content. During irradiation, starch chains gain mobility by the cleavage of glycosidic linkages and thus readily align to packed starch matrices. The starch chains in the packed matrices are less accessible to digestive enzymes (Rombo, Taylor, & Minnaar, 2001; Zuleta, Dyner, Sambucetti, & Francisco, 2006), thus contributing to increase in RS. Further, it has been reported that irradiation might induce the formation of new chemical bonds between anhydrous glucose units as a result of transglucosidation which was resistant to enzymatic hydrolysis (Rombo et al., 2001).

3.7. Starch retrogradation

Starch retrogradation was determined indirectly through decrease in transmittance of starch solution over a period of 5 days of storage. The results indicated that transmittance decreased in all the bean starches in both control as well as irradiated samples; the decrease was significantly ($p \leq 0.05$) higher in control bean starches compared to irradiated starches (Table 5). In case of control red, yellow, black and white bean starches, decrease in transmittance was significant up to 2 and 3 days of storage, respectively. Among irradiated samples, decrease in transmittance was significant throughout the 5 days of storage for red bean starch and up to 3 days only in all other bean starches. The factors responsible for variation in transmittance among bean starches include aggregates made of leached amylose, amylose and amylopectin chain lengths, intra or intermolecular bonding, granule swelling and granule remnants (Craig, Maningat, Seib, & Hoseney, 1989). The decrease in transmittance of bean starches is attributed to the starch retrogradation resulting from amylose reorganization to form aggregates during storage (Tetchi, Amani, & Kamenan, 2007). Since irradiation causes disintegration of starch molecule, thereby prevents the aggregate formation and hence delays the occurrence of starch retrogradation. This could be the reason behind the higher transmittance of irradiated samples compared to control samples.

3.8. Viscosity parameters (pasting properties)

Viscosity parameters (peak, through, breakdown, final and setback viscosities) of gamma irradiated bean starches with different doses are presented in Table 6. Data revealed a significant reduction in pasting properties with increase in irradiation dose in all the bean starches. Peak viscosity of the bean starches irradiated at 25 kGy decreased by 88.5% in red bean, 83.9% in yellow bean, 89.4% in black bean and 89.7% in white bean starches, respectively. It has been reported that the peak viscosity is mainly related to the swelling power of starch granules. Degradation of amylopectin and amylose in starch following irradiation caused a substantial reduction in water binding capacity and thus decreased the swelling power of starch granules, which led to a significant decrease in

Table 4
Effect of gamma irradiation treatment on *in vitro* digestibility of bean starches.

Bean variety	Dose (kGy)						
	0	5	10	15	20	25	LSD
Rapidly digestible starch (RDS) (%)							
Red bean	$12.8^{a,2}$ (1.2)	$16.7^{b,2}$ (1.4)	$20.6^{c,2}$ (1.5)	$22.4^{c,1}$ (2.1)	$24.3^{d,2}$ (1.6)	$27.2^{e,2}$ (1.9)	2.1
White bean	$11.7^{a,1}$ (1.1)	$15.6^{b,1}$ (1.3)	$19.5^{c,1}$ (1.4)	$21.3^{c,1}$ (1.7)	$22.7^{d,1}$ (1.5)	$24.1^{d,1}$ (1.8)	1.8
Black bean	$14.9^{a,3}$ (1.5)	$18.8^{b,3}$ (1.6)	$21.6^{c,2}$ (1.7)	$24.4^{d,2}$ (2.1)	$26.3^{e,3}$ (1.7)	$29.2^{f,3}$ (2.1)	1.5
Yellow bean	$10.2^{a,1}$ (1.1)	$14.6^{b,1}$ (1.1)	$18.4^{c,1}$ (1.5)	$21.1^{d,1}$ (1.4)	$22.3^{d,1}$ (1.5)	$23.9^{e,1}$ (1.5)	1.2
LSD ($p \leq 0.05$)	1.5	1.3	1.2	1.3	1.1	1.1	
Slowly digestible starch (SDS) (%)							
Red bean	$31.3^{f,2}$ (0.6)	$24.4^{e,1}$ (0.5)	$19.2^{d,1}$ (0.4)	$15.9^{c,1}$ (0.5)	$12.4^{b,1}$ (0.3)	$7.2^{a,1}$ (0.2)	2.4
White bean	$29.2^{f,1}$ (0.4)	$23.8^{e,1}$ (0.4)	$18.8^{d,1}$ (0.3)	$15.1^{c,1}$ (0.3)	$12.1^{b,1}$ (0.3)	$8.8^{a,2}$ (0.3)	2.1
Black bean	$31.9^{f,2}$ (0.4)	$25.4^{e,2}$ (0.6)	$21.8^{d,2}$ (0.6)	$18.2^{c,2}$ (0.4)	$14.4^{b,2}$ (0.4)	$9.6^{a,2}$ (0.3)	2.6
Yellow bean	$29.7^{f,1}$ (0.5)	$23.8^{e,1}$ (0.3)	$19.1^{d,1}$ (0.3)	$15.5^{c,1}$ (0.4)	$12.4^{b,1}$ (0.4)	$8.4^{a,1}$ (0.3)	2.7
LSD ($p \leq 0.05$)	1.1	1.4	1.2	1.1	1.3	1.2	
Resistant starch (RS) (%)							
Red bean	$56.1^{a,2}$ (1.3)	$58.9^{b,2}$ (1.5)	$60.2^{b,2}$ (1.6)	$61.7^{c,2}$ (1.6)	$63.3^{c,2}$ (1.9)	$65.2^{d,2}$ (2.1)	1.5
White bean	$59.1^{a,3}$ (1.1)	$60.6^{b,3}$ (1.6)	$61.7^{b,3}$ (1.5)	$63.6^{c,3}$ (1.4)	$65.2^{d,3}$ (1.8)	$67.1^{d,3}$ (2.1)	1.1
Black bean	$53.2^{a,1}$ (1.4)	$55.8^{b,1}$ (1.3)	$56.6^{b,1}$ (1.5)	$57.4^{c,1}$ (1.5)	$59.3^{d,1}$ (1.6)	$61.2^{e,1}$ (2.3)	1.1
Yellow bean	$60.1^{a,3}$ (1.6)	$61.6^{b,3}$ (1.4)	$62.5^{b,3}$ (1.3)	$63.4^{c,3}$ (1.4)	$65.3^{d,3}$ (1.5)	$67.7^{e,3}$ (2.4)	1.2
LSD ($p \leq 0.05$)	1.4	1.5	1.2	1.3	1.2	1.3	

Values are mean ± SD ($n = 3$); values in parenthesis represent SD.
Values within treatments in a row not sharing a common superscript lowercase letter (a–f) are significantly ($p \leq 0.05$) different.
Values within varieties in a column not sharing a common superscript numerical (1–3) are significantly ($p \leq 0.05$) different.
LSD, least significant difference.

peak viscosity (Chung & Liu, 2010; Vandeputte, Derycke, Geeroms, & Delcour, 2003; Yu & Wang, 2007). Karim et al. (2008) concluded that the reduction in peak viscosity following irradiation resulted from the reduction in granule integrity and rigidity due to glycosidic bond cleavage. Further variation in swelling power may account for difference in peak viscosity among the bean starches. The setback and final viscosities are mainly due to the re-ordering or polymerization of leached amylose and long linear amylopectin. The decrease in setback and final viscosities is therefore likely related to the degradation or shortening of amylose and longer amylopectin branch chains by irradiation (Abu, Duodu, & Minnaar, 2006; Wu et al., 2002). Therefore, it can be inferred from the data that bean

Table 5
Effect of gamma irradiation treatment on starch retrogradation of bean starches during storage.

Starch type	Irradiation dose (kGy)	Percent transmittance					
		Day-1	Day-2	Day-3	Day-4	Day-5	LSD
Red bean	0	$1.3^{c,3}$ (0.11)	$0.95^{b,2}$ (0.05)	$0.55^{a,1}$ (0.04)	$0.49^{a,1}$ (0.04)	$0.47^{a,1}$ (0.05)	0.1
	5	$1.6^{e,5}$ (0.13)	$1.2^{d,4}$ (0.09)	$0.91^{c,3}$ (0.07)	$0.72^{b,2}$ (0.06)	$0.58^{a,1}$ (0.04)	0.1
	10	$2.1^{e,5}$ (0.12)	$1.9^{d,4}$ (0.11)	$1.4^{c,3}$ (0.11)	$0.9^{b,2}$ (0.05)	$0.75^{a,1}$ (0.05)	0.1
	15	$2.4^{e,5}$ (0.14)	$2.1^{d,4}$ (0.14)	$1.8^{c,3}$ (0.12)	$1.3^{b,2}$ (0.11)	$0.91^{a,1}$ (0.04)	0.2
	20	$2.6^{d,4}$ (0.13)	$2.4^{d,4}$ (0.13)	$2.1^{c,3}$ (0.14)	$1.6^{b,2}$ (0.21)	$1.1^{a,1}$ (0.11)	0.2
	25	$2.9^{e,5}$ (0.13)	$2.6^{d,4}$ (0.22)	$2.3^{c,3}$ (0.22)	$1.8^{b,2}$ (0.14)	$1.2^{a,1}$ (0.13)	0.2
	LSD ($p \leq 0.05$)	0.3	0.2	0.3	0.3	0.2	
Yellow bean	0	$1.2^{d,4}$ (0.21)	$0.88^{c,3}$ (0.04)	$0.50^{b,2}$ (0.03)	$0.42^{a,1}$ (0.03)	$0.35^{a,1}$ (0.02)	0.1
	5	$1.4^{d,4}$ (0.31)	$0.96^{c,3}$ (0.02)	$0.71^{b,2}$ (0.02)	$0.51^{a,1}$ (0.04)	$0.41^{a,1}$ (0.03)	0.1
	10	$1.6^{d,4}$ (0.33)	$1.3^{c,3}$ (0.11)	$0.94^{b,2}$ (0.04)	$0.72^{a,1}$ (0.02)	$0.55^{a,1}$ (0.03)	0.2
	15	$1.8^{e,5}$ (0.24)	$1.5^{d,4}$ (0.20)	$1.1^{c,3}$ (0.12)	$0.91^{b,2}$ (0.05)	$0.72^{a,1}$ (0.02)	0.1
	20	$2.1^{d,4}$ (0.31)	$1.8^{c,3}$ (0.22)	$1.3^{b,2}$ (0.12)	$0.98^{a,1}$ (0.03)	$0.81^{a,1}$ (0.04)	0.2
	25	$2.3^{d,4}$ (0.41)	$1.9^{c,3}$ (0.13)	$1.5^{b,2}$ (0.14)	$1.1^{a,1}$ (0.11)	$0.91^{a,1}$ (0.04)	0.2
	LSD ($p \leq 0.05$)	0.3	0.2	0.3	0.3	0.2	
Black bean	0	$0.98^{d,4}$ (0.12)	$0.79^{c,3}$ (0.03)	$0.45^{b,2}$ (0.02)	$0.31^{a,1}$ (0.02)	$0.27^{a,1}$ (0.01)	0.1
	5	$1.2^{d,4}$ (0.13)	$0.90^{c,3}$ (0.04)	$0.63^{b,2}$ (0.04)	$0.45^{a,1}$ (0.03)	$0.35^{a,1}$ (0.02)	0.1
	10	$1.4^{d,4}$ (0.16)	$0.98^{c,3}$ (0.04)	$0.72^{b,2}$ (0.04)	$0.61^{a,1}$ (0.05)	$0.43^{a,1}$ (0.03)	0.2
	15	$1.7^{d,4}$ (0.14)	$1.2^{c,3}$ (0.11)	$0.92^{b,2}$ (0.05)	$0.76^{a,1}$ (0.04)	$0.56^{a,1}$ (0.02)	0.2
	20	$1.9^{d,4}$ (0.22)	$1.4^{c,3}$ (0.14)	$1.1^{b,2}$ (0.11)	$0.91^{a,1}$ (0.03)	$0.73^{a,1}$ (0.04)	0.2
	25	$2.1^{d,4}$ (0.21)	$1.7^{c,3}$ (0.13)	$1.4^{b,2}$ (0.12)	$0.98^{a,1}$ (0.03)	$0.81^{a,1}$ (0.03)	0.2
	LSD ($p \leq 0.05$)	0.2	0.2	0.3	0.2	0.2	
White bean	0	$0.91^{c,3}$ (0.04)	$0.88^{c,3}$ (0.04)	$0.50^{b,2}$ (0.03)	$0.42^{a,1}$ (0.03)	$0.35^{a,1}$ (0.02)	0.1
	5	$1.3^{d,4}$ (0.11)	$0.96^{c,3}$ (0.02)	$0.71^{b,2}$ (0.02)	$0.51^{a,1}$ (0.04)	$0.41^{a,1}$ (0.03)	0.1
	10	$1.6^{d,4}$ (0.14)	$1.3^{c,3}$ (0.11)	$0.94^{b,2}$ (0.04)	$0.74^{a,1}$ (0.02)	$0.55^{a,1}$ (0.03)	0.2
	15	$1.9^{e,5}$ (0.21)	$1.5^{d,4}$ (0.20)	$1.1^{c,3}$ (0.12)	$0.91^{b,2}$ (0.05)	$0.72^{a,1}$ (0.02)	0.1
	20	$2.1^{d,4}$ (0.14)	$1.8^{c,3}$ (0.22)	$1.3^{b,2}$ (0.12)	$0.98^{a,1}$ (0.03)	$0.81^{a,1}$ (0.04)	0.2
	25	$2.3^{d,4}$ (0.22)	$1.9^{c,3}$ (0.13)	$1.5^{b,2}$ (0.14)	$1.1^{a,1}$ (0.11)	$0.91^{a,1}$ (0.04)	0.2
	LSD ($p \leq 0.05$)	0.3	0.2	0.3	0.3	0.2	

Values are mean ± SD ($n = 3$); values in parenthesis represent SD.
Values within treatments in a column not sharing a common superscript lowercase letter (a–e) are significantly ($p \leq 0.05$) different.
Values within storage days in a row not sharing a common superscript numerical (1–5) are significantly ($p \leq 0.05$) different.
LSD, least significant difference.

Table 6
Effect of gamma irradiation treatment on viscosity parameters (cP) of bean starches.

Dose (kGy)	Red bean	Yellow bean	Black bean	White bean	LSD (p≤0.05)
Peak viscosity					
0	2185.0^{f,2} (15.5)	2562.0^{f,3} (17.5)	2064.0^{f,1} (15.2)	2054.0^{f,1} (15.2)	20
5	1521.0^{e,2} (13.3)	1945.0^{e,3} (15.4)	1431.0^{e,1} (13.5)	1421.0^{e,1} (13.5)	24
10	1012.0^{d,2} (12.5)	1245.0^{d,3} (14.6)	982.0^{d,1} (10.2)	980.0^{d,1} (10.2)	26
15	895.0^{c,2} (10.3)	1015.0^{c,3} (12.3)	712.0^{c,1} (9.6)	702.0^{c,1} (9.6)	19
20	512.0^{b,2} (10.2)	985.0^{b,3} (11.3)	470.0^{b,1} (8.5)	461.0^{b,1} (8.5)	22
25	250.0^{a,2} (8.2)	412.0^{a,3} (9.8)	218.0^{a,1} (8.5)	210.0^{a,1} (8.5)	21
LSD ($p \leq 0.05$)	23	26	21	24	
Trough viscosity					
0	1725.0^{f,2} (15.5)	1862.0^{f,4} (16.5)	1764.0^{f,3} (14.2)	1654.0^{f,1} (12.2)	22
5	1321.0^{e,2} (16.3)	1445.0^{e,4} (15.4)	1351.0^{e,3} (13.5)	1221.0^{e,1} (11.5)	21
10	902.0^{d,1} (11.5)	1045.0^{d,3} (13.6)	962.0^{d,2} (11.2)	880.0^{d,1} (10.2)	28
15	695.0^{c,2} (11.3)	715.0^{c,2} (10.3)	705.0^{c,2} (10.6)	612.0^{c,1} (8.6)	21
20	311.0^{b,1} (10.2)	385.0^{b,3} (9.3)	340.0^{b,2} (9.5)	291.0^{b,1} (7.5)	20
25	120.0^{a,1} (9.2)	182.0^{a,2} (9.2)	158.0^{a,2} (8.5)	110.0^{a,1} (6.5)	24
LSD ($p \leq 0.05$)	22	22	21	26	
Breakdown viscosity					
0	525.0^{e,1} (10.5)	662.0^{f,3} (12.5)	464.0^{f,2} (11.2)	514.0^{f,1} (11.2)	19
5	321.0^{d,1} (11.3)	445.0^{e,2} (11.4)	301.0^{e,1} (10.5)	311.0^{e,1} (10.8)	22
10	272.0^{c,2} (9.5)	345.0^{d,3} (10.6)	242.0^{d,1} (9.2)	250.0^{d,1} (9.2)	20
15	202.0^{b,1} (7.3)	265.0^{c,2} (9.3)	185.0^{c,1} (8.6)	192.0^{c,1} (8.6)	19
20	182.0^{b,2} (6.2)	215.0^{b,3} (7.3)	140.0^{b,1} (7.5)	161.0^{b,1} (6.5)	21
25	110.0^{a,1} (5.2)	162.0^{a,2} (6.2)	104.0^{a,1} (6.5)	106.0^{a,1} (5.5)	18
LSD ($p \leq 0.05$)	20	24	22	19	
Final viscosity					
0	3085.0^{f,2} (19.5)	3120.0^{f,3} (19.5)	3064.0^{f,1} (18.2)	3054.0^{f,1} (11.2)	18
5	1621.0^{e,1} (17.3)	2250.0^{e,2} (18.4)	1601.0^{e,1} (16.5)	1606.0^{e,1} (10.8)	24
10	1066.0^{d,1} (15.5)	1345.0^{d,2} (17.6)	1042.0^{d,1} (14.2)	1050.0^{d,1} (9.2)	26
15	405.0^{c,1} (11.3)	765.0^{c,2} (13.3)	424.0^{c,1} (10.6)	422.0^{c,1} (8.6)	19
20	282.0^{b,2} (9.2)	515.0^{b,3} (11.3)	264.0^{b,1} (8.5)	251.0^{b,1} (6.5)	22
25	130.0^{a,1} (8.2)	362.0^{a,2} (9.2)	124.0^{a,1} (6.5)	116.0^{a,1} (5.5)	21
LSD ($p \leq 0.05$)	23	22	20	24	
Setback viscosity					
0	1425.0^{f,1} (12.5)	1912.0^{f,3} (12.5)	1434.0^{f,1} (11.2)	1514.0^{f,2} (10.2)	15
5	521.0^{e,1} (10.3)	945.0^{e,3} (11.4)	511.0^{e,1} (10.5)	551.0^{e,2} (9.8)	14
10	462.0^{d,1} (9.5)	745.0^{d,2} (10.6)	442.0^{d,1} (9.2)	450.0^{d,1} (9.2)	20
15	383.0^{c,1} (8.3)	565.0^{c,3} (9.3)	365.0^{c,1} (8.6)	392.0^{c,2} (8.6)	19
20	242.0^{b,1} (6.2)	315.0^{b,3} (7.3)	230.0^{b,1} (7.5)	261.0^{b,2} (6.5)	22
25	150.0^{a,1} (5.2)	222.0^{a,3} (6.2)	134.0^{a,1} (6.5)	186.0^{a,2} (5.5)	21
LSD ($p \leq 0.05$)	19	23	22	20	

Values are mean ± SD (n = 3); values in parenthesis represent SD.
Values within treatments in a column not sharing a common superscript lowercase letter (a–f) are significantly ($p \leq 0.05$) different.
Values within varieties in a row not sharing a common superscript numerical (1–3) are significantly ($p \leq 0.05$) different.
LSD, least significant difference.

starch gels were softer with little tendencies to retrograde after exposure to irradiation. This is attributed to the decrease in degree of polymerization of gamma irradiated starches (Liu et al., 2012). Differences in setback and final viscosities among bean starches can be attributed to the difference in extent of polymerization of leached amylose and amylopectin molecules. Breakdown viscosity is the difference between peak viscosity and trough viscosity and is a measure of fragility of granules. Breakdown viscosity indicates the stability of the starch pastes and the tendency of starch granules to resist shear force during heating process (Liu et al., 2012; Luo et al., 2009). Breakdown viscosity also recorded a decreasing trend with increase in irradiation dose. Breakdown viscosity of bean starches irradiated at 25 kGy were of the order of 110 cP for red bean, 162 cP for yellow bean, 104 cP for black bean and 106 cP for white bean starch, respectively. The results on pasting properties presented here were consistent with the statements that values of PV, TV, FV and SV for rice starch were reduced considerably with increasing dose (Yu & Wang, 2007).

3.9. Thermal properties and relative crystallinity

Thermal properties and relative crystallinity of control and gamma irradiated bean starches are shown in Table 7. The data analysis indicated that the gelatinization temperatures (T_0, T_p, T_c) and gelatinization enthalpy of all the control bean starches were significantly higher compared to irradiated starches. Among the bean starches, a significant decrease in onset of gelatinization temperature was observed only in red bean starch between control and irradiated samples. Negative correlation ($r = -0.88$) existed between gelatinization temperatures and irradiation dose, thereby indicating a decrease in gelatinization temperatures with increase in irradiation dose in all the bean starches. The data analysis also revealed a significant decreasing trend in relative crystallinity in irradiated bean starches compared to control in all the bean varieties. Decrease in gelatinization temperatures by irradiation have also been reported in cowpea and potato starches (Abu et al., 2006; Ezekiel et al., 2007; Riyas-Duarte & Rupnow, 1994). Gelatinization temperatures indicate the stability of starch crystallinities. Since gamma irradiation causes the production of defective crystalline structures and an increase in the proportion of short chains in amylopectin, which could have resulted in decrease in gelatinization temperatures (Chung & Liu, 2010). Cook and Gidley (1992) reported that the gelatinization enthalpy indicated loss of double helical order rather than the loss of crystalline order (dense packing in crystalline structure). However, the crystalline structure as determined by X-ray diffractometry and relative crystallinity also

Table 7
Effect of gamma irradiation treatment on thermal properties and relative crystallinity of bean starches.

Starches	Dose (kGy)	Thermal properties				Relative crystallinity (%)
		T_0 (°C)	T_p (°C)	T_c (°C)	ΔH (J/g)	
Red bean	0	69.4^f (0.5)	77.7^d (0.5)	92.5^d (0.2)	14.9^d (0.2)	29.5^e (0.3)
	5	68.6^e (0.3)	77.1^c (0.4)	91.8^c (0.2)	14.1^c (0.3)	28.4^d (0.2)
	10	68.1^d (0.3)	76.8^c (0.3)	91.4^c (0.3)	13.7^b (0.2)	27.5^c (0.4)
	15	67.7^c (0.3)	76.5^b (0.3)	91.1^b (0.4)	13.4^b (0.4)	27.1^c (0.3)
	20	67.1^b (0.2)	76.2^b (0.3)	90.7^b (0.5)	13.3^b (0.5)	26.7^b (0.4)
	25	66.6^a (0.2)	75.5^a (0.4)	90.1^a (0.3)	12 .7^a (0.2)	26.1^a (0.3)
	LSD	0.3	0.3	0.4	0.4	0.4
Yellow bean	0	69.9^e (0.5)	78.3^e (0.5)	93.6^e (0.2)	15.6^e (0.3)	29.6^e (0.4)
	5	69.1^d (0.4)	77.6^d (0.3)	92.8^d (0.2)	14.9^d (0.3)	28.8^d (0.3)
	10	68.6^c (0.3)	77.2^c (0.3)	92.1^c (0.2)	14.3^c (0.1)	28.2^c (0.2)
	15	68.1^b (0.4)	76.8^b (0.2)	91.8^b (0.4)	13.8^b (0.3)	27.6^b (0.3)
	20	67.8^b (0.3)	76.6^b (0.2)	91.3^b (0.4)	13.6^b (0.2)	27.1^b (0.4)
	25	67.2^a (0.2)	76.1^a (0.3)	90.4^a (0.2)	13.1^a (0.3)	26.5^a (0.3)
	LSD	0.3	0.2	0.5	0.3	0.4
Black bean	0	69.7^e (0.5)	78.1^e (0.5)	93.3^f (0.2)	14.9^d (0.3)	29.3^d (0.4)
	5	69.2^d (0.4)	77.5^d (0.3)	92.6^e (0.2)	14.4^c (0.3)	28.6^c (0.3)
	10	68.6^c (0.3)	77.1^c (0.3)	92.1^d (0.2)	14.1^c (0.1)	28.1^c (0.2)
	15	68.1^b (0.4)	76.5^b (0.2)	91.6^c (0.4)	13.5^b (0.3)	27.7^b(0.3)
	20	67.8^b (0.3)	76.3^b (0.2)	91.1^b (0.4)	13.1^b (0.2)	27.2^b (0.4)
	25	67.3^a (0.2)	75.8^a (0.3)	90.5^a (0.2)	12.5^a (0.3)	26.4^a (0.3)
	LSD	0.3	0.2	0.3	0.4	0.5
White bean	0	69.3^e (0.5)	77.3^e (0.5)	91.9^d (0.2)	14.6^e (0.3)	29.1^e (0.4)
	5	68.5^d (0.4)	76.7^d (0.3)	91.2^c (0.2)	13.9^d (0.3)	28.3^d (0.3)
	10	68.1^c (0.3)	76.2^c (0.3)	90.8^c (0.2)	13.4^c (0.1)	27.6^c (0.2)
	15	67.8^c (0.4)	75.7^b (0.2)	90.6^b (0.4)	13.1^b (0.3)	27.2^b (0.3)
	20	67.2^b (0.3)	75.5^b (0.2)	90.2^b (0.4)	12.8^b (0.2)	26.8^b (0.4)
	25	66.5^a (0.2)	75.1^a (0.3)	89.4^a (0.2)	12.1^a (0.3)	26.1^a (0.3)
	LSD	0.3	0.2	0.4	0.3	0.4

Values are mean ± SD (n = 3); values in parenthesis represent SD.
Values within treatments in a column not sharing a common superscript lowercase letter (a–f) are significantly ($p \leq 0.05$) different.
T_0, onset temperature; T_p, peak temperature; T_c, conclusion temperature; ΔH, enthalpy of gelatinization (DWB based on starch weight); LSD, least significant difference.

recorded a decrease with increase in dose, it is therefore suggested that decrease in gelatinization enthalpy during irradiation could be due to the disruption of the crystalline domain of starch granules in addition to disruption of double helical order.

3.10. Scanning electron microscopy and X-ray diffractometry

Microscopic observation of the bean starches indicated surface cracking of the starch samples with irradiation treatment. The extent of surface cracking was dose dependent and increased with increase in irradiation dose (Fig. 1). Data also revealed that with increase in dose, the number of fractured starch granules also increased. The cracks and fractures on the surface of irradiated starch granules are attributed to radiation induced disintegration of starch. Similar findings have also been reported by Chung and Liu (2010) and Wu et al. (2002) in irradiated potato and bean starches. X-ray diffraction pattern of control and irradiated bean starches are presented in Fig. 2. The control and irradiated bean starched showed the characteristic C-type pattern of legume starch which represents a combination of A- and B-type polymorphs (Chung & Liu, 2010). Irradiated bean starches indicated no significant change in diffraction pattern when compared with un-irradiated bean starches, except a slight decrease in intensity of X-ray diffraction. The relative crystallinity as determined by X-ray diffraction pattern was decreased with increase in irradiation dose. The decrease in relative crystallinity of bean starches irradiated at 25 kGy was of the order of 3.4%, 3.1%, 2.9% and 3.0% for red, yellow, black and white bean starches, respectively. Ciesla, Gwardys, and Zoltowski (1991) also reported a decrease in relative crystallinity of irradiated potato starch at 20 or 30 kGy. Chung and Liu (2009) found a decrease of 1.6% in relative crystallinity of irradiated corn starch at 50 kGy. Decrease in relative crystallinity by irradiation depends upon the type of crystalline polymorph. In C-type crystalline structure, the center regions are rich in B-type and the peripheral regions are rich in A-type polymorphs (Bogracheva, Morris, & Hedley, 1998). Consequently, the B-type polymorphic forms might be sensitive to irradiation, thereby resulting in greater decrease in crystallinity.

3.11. DPPH radical scavenging activity and reducing power

The scavenging activity of control and irradiated bean starches, expressed as inhibition percentage (IP) of DPPH radical is presented in Fig. 3. The data indicate a significant ($p \leq 0.05$) increase in IP in irradiated bean starches compared to un-irradiated controls. Positive correlation (r = 0.89) existed between IP and dose applied, thus indicating increase in DPPH radical scavenging activity of bean starches with increase in irradiation dose. Increase in DPPH radical scavenging activity of the bean starches irradiated at 25 kGy was of the order of 25%, 23.9%, 25.1% and 24% for red, white, black and yellow bean starches, respectively. Similar increase in DPPH radical scavenging has also been reported in gamma irradiated seaweed polysaccharides (Choi et al., 2009). The increase in DPPH radical scavenging activity of gamma irradiated bean starches could be attributed to the formation of new double bonds as a result of radiation degradation, which reduced the reactivity of free radicals (Choi et al., 2009). An irradiation-induced dose-dependent increase in ferric reducing/antioxidant power (FRAP) was observed in all the bean starches (Fig. 4). Among irradiated samples significant ($p \leq 0.05$) increase in FRAP was observed in starch samples irradiated at 25 kGy. After irradiation, FRAP values of irradiated starches were in the range of 0.37–0.91 (OD at 700 nm) compared to the FRAP values in the range 0.2–0.24 (OD at 700 nm) for control starches. Choi et al. (2009) also reported increase in ferric reducing ability of fucoidan and laminarin following irradiation in the

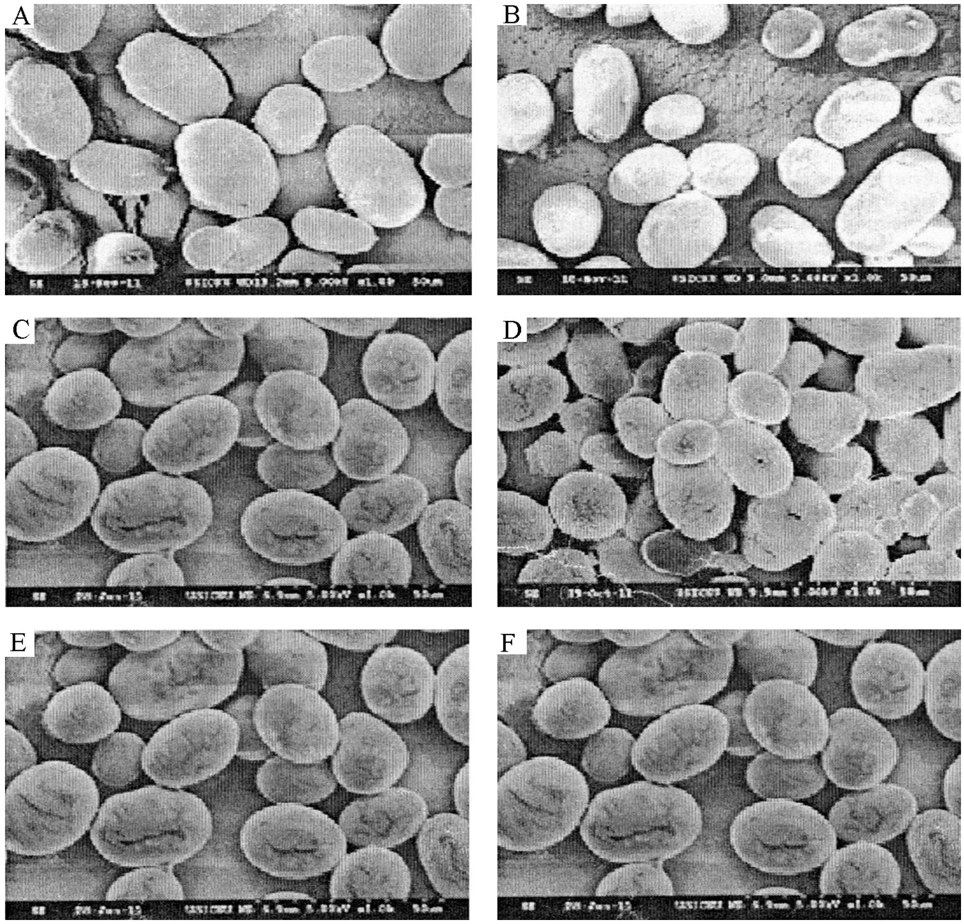

Fig. 1. Scanning electron microscopic examination of gamma irradiated bean starches. A = control; B = 5 kGy; C = 10 kGy; D = 15 kGy; E = 20 kGy; F = 25 kGy.

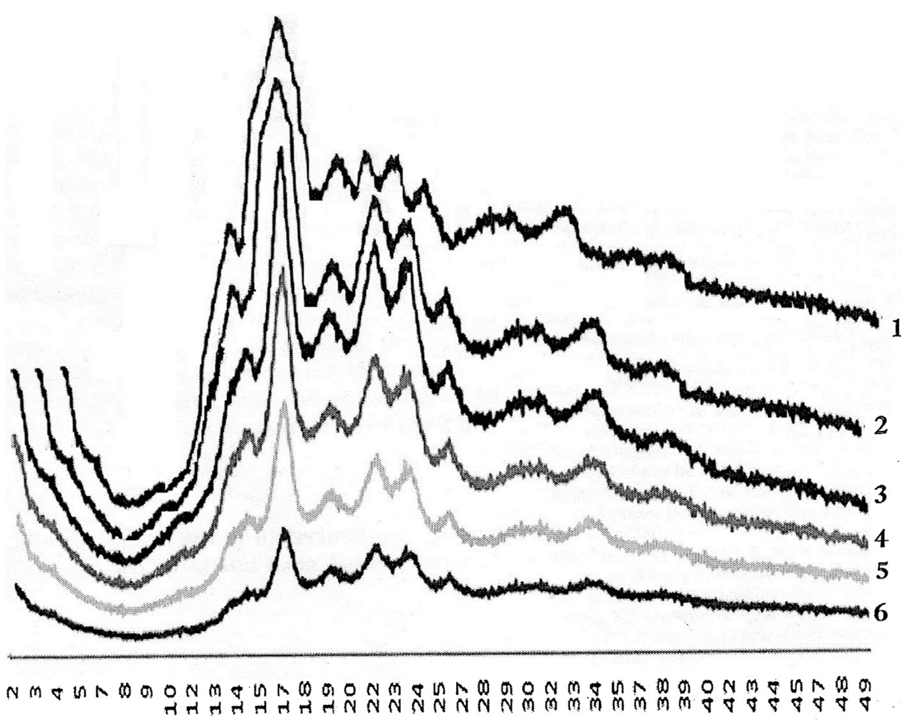

Fig. 2. X-ray diffraction patterns of gamma irradiated bean starches. 1 = control; 2 = 5 kGy; 3 = 10 kGy; 4 = 15 kGy; 5 = 20 kGy; 6 = 25 kGy.

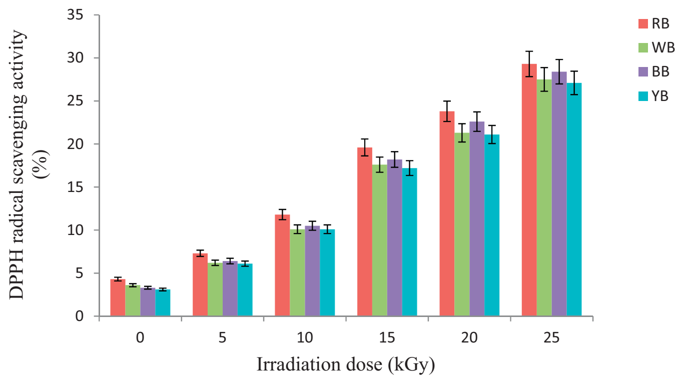

Fig. 3. DPPH radical scavenging activity of gamma irradiated bean starches. RB, red bean; WB, white bean; BB, black bean; YB, yellow bean.

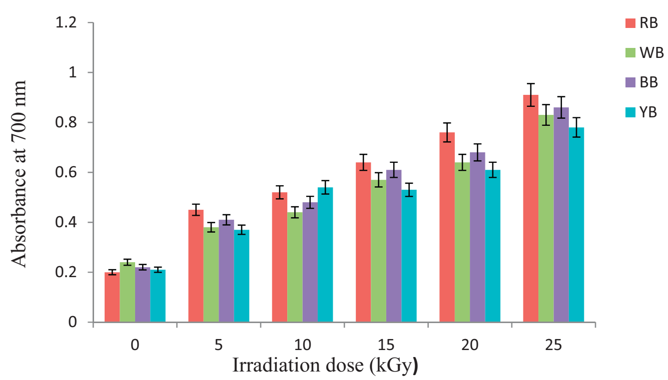

Fig. 4. Ferric reducing power of gamma irradiated bean starches. RB, red bean; WB, white bean; BB, black bean; YB, yellow bean.

dose range of 10–50 kGy. To account for the formation of new double bonds thought to be responsible for increased DPPH activity in bean starches after exposure to irradiation, UV spectra of starch samples was taken as shown in Fig. 5. The increase in absorbance observed at 265 nm could be assigned to the double bonds formed in starch samples due to chain scission or hydrogen abstraction reaction by irradiation (Nagasawa, Mitomo, Yoshii, & Kume, 2000). Irradiation of chitosan showed an increase of UV absorbance at 247 and 290 nm which was attributed to the formation of carbonyl groups and carboxyl groups, respectively (Ulanski & Rosiak, 1992). Kim et al. (2008) also showed an increase in absorbance at 265 nm of hyaluronic acid by gamma irradiation.

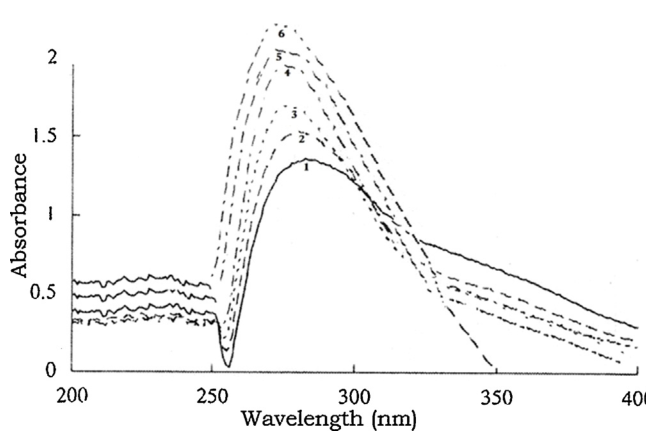

Fig. 5. Effect of gamma irradiation on UV absorbance of bean starches. 1 = control; 2 = 5 kGy; 3 = 10 kGy; 4 = 15 kGy; 5 = 20 kGy; 6 = 25 kGy.

4. Conclusion

Gamma irradiation treatment to bean starches resulted in significant increase in solubility and water absorption capacity and decrease in viscosity properties and swelling index. Decrease in swelling index could prove beneficial in improving texture upon cooking and reduce syneresis of frozen foods. Decrease in setback and breakdown viscosity reduced the tendency of irradiated bean starches to retrograde. Irradiation of bean starches did not change surface structure of starch granules as the treated starches still retained their C-type diffraction pattern; however the crystallinity of bean starches decreased with increase in dose. Irradiation was negatively correlated to thermal properties, while as thermal and pasting properties were positively correlated with each other. Irradiation increased the proportions of both rapidly digestible starch and enzyme resistant starch of bean starches. Irradiation also resulted in significant enhancement of antioxidant potential of bean starches, thereby increasing their use in different nutritionally important food products. Therefore, the modified starches through gamma irradiation can be used as additives for frozen foods to prevent them from dripping when defrosted, to improve their freeze–thaw stability without syneresis and keep their ingredients together in addition to their use as edible coatings for fruits and vegetables and strong binders for seasonings on snacks and cereals.

References

Abu, J. O., Duodu, K. G., & Minnaar, A. (2006). Effect of γ-irradiation on some physicochemical and thermal properties of cowpea (*Vigna unguiculata* L., Walpa) starch. *Food Chemistry*, *95*, 386–393.

Bertolini, A. C., Mestres, C., Colonna, P., & Raffi, J. (2001). Free radical formation in UV- and gamma-irradiated cassava starch. *Carbohydrate Polymers*, *44*(3), 269–271.

Bogracheva, T. Y., Morris, V. J., & Hedley, R. C. L. (1998). *Biopolymers*, *45*, 323–332.

Brand-Williams, W., Cuvelier, M. E., & Berset, C. (1995). Use of free radical method to evaluate antioxidant activity. *Lebensmittel Wissenschaft und Technologie*, *28*, 25–30.

Byun, E. H., Kim, J. H., Sung, N. Y., Choi, J., Lim, S. T., Kim, K. H., et al. (2008). Effect of gamma irradiation on the physical and structural properties of β-glucan. *Radiation Physics and Chemistry*, *77*(6), 781–786.

Chattopadhyay, S., Singhal, R. S., & Kulkarni, P. R. (1997). Optimizations of conditions of synthesis of oxidized starch from corn and amaranth for use in film forming applications. *Carbohydrate Polymers*, *34*(4), 203–212.

Cho, M., Kim, B. Y., & Rhim, J. H. (2003). Degradation of alginate solution and powder by gamma irradiation. *Food Engineering Programme*, *7*, 141–145.

Choi, J. I., Kim, J. K., Srinivasan, P., Kim, J. H., Park, H. J., Byun, M. W., et al. (2009). Comparison of gamma ray and electron beam irradiation on extraction yield, morphological and antioxidant properties of polysaccharides from tamarind seed. *Radiation Physics and Chemistry*, *78*, 605–609.

Chung, H. J., Hoover, R., & Liu, Q. (2009). The impact of single and dual hydrothermal modifications o the molecular structure and physicochemical properties of normal corn starch. *International Journal of Biological Macromolecules*, *44*, 203–210.

Chung, H. J., Lim, H. S., & Lim, S. T. (2006). Effect of partial geletinization and retrogradation on the enzymatic digestion of waxy rice starch. *Journal of Cereal Science*, *43*, 353–359.

Chung, H. J., & Liu, Q. (2009). Effect of gamma irradiation on molecular structure and physicochemical properties of corn starch. *Journal of Food Science*, *74*, 353–361.

Chung, H. J., & Liu, Q. (2010). Molecular structure and physicochemical properties of potato and bean starches as affected by gamma irradiation. *International Journal of Biological Macromolecules*, *47*, 214–222.

Ciesla, K., Zoltowski, T., & Mogilevsky, L. Y. (1991). Detection of starch transformation under gamma irradiation by small angle X-ray scatting. *Starch/Starke*, *43*, 11–16.

Cochran, W. G., & Cox, G. M. (1975). *Experimental designs*. New York: John Willey & Sons Inc.

Cook, D., & Gidley, M. J. (1992). Loss of crystalline and molecular order during starch gelatinisation: Origin of the enthalpic transition. *Carbohydrate Research*, *227*, 103–112.

Craig, S. A. S., Maningat, C. C., Seib, P. A., & Hoseney, R. C. (1989). Starch paste clarity. *Cereal Chemistry*, *66*, 173–182.

De-Kerf, M., Mondelaers, W., Lahorte, P., Vervaet, C., & Remon, J. P. (2001). Characterization and disintegration properties of irradiated starch. *International Journal of Pharmaceutics*, *22*, 69–76.

Englyst, H. N., Kingman, S. M., & Cummings, J. H. (1992). Classification and measurement of nutritionally important starch fraction. *European Journal of Clinical Nutrition*, *36*, 10–14.

Ezekiel, R., Rana, G., Singh, N., & Singh, S. (2007). Physicochemical, thermal and pasting properties of starch separated from gamma irradiated and stored potatoes. *Food Chemistry*, *105*, 1420–1429.

Hoover, R., Hughes, T., Chung, H. J., & Liu, Q. (2010). Composition, molecular structure, properties and modification of pulse starches: A review. *Food Research International*, *43*, 399–413.

Hoover, R., & Sosulski, F. (1991). Composition, structure, functionality and chemical modification of legume starches: A review. *Canadian Journal of Physiology and Pharmacology*, *69*, 79–92.

Jobling, S. (2004). Improving starch for food and industrial applications. *Current Opinion in Plant Biology*, *7*, 210–218.

Karim, A. A., Nadiha, M. Z., Chen, F. K., Phuah, Y. P., Chui, Y. M., & Fazilah, A. (2008). Pasting and retrogradation properties of alkali-treated sago (*Metroxylon sagu*) starch. *Food Hydrocolloids*, *22*(6), 1044–1053.

Kiatkamjornwong, S., Mongkolsawat, K., & Sonsuk, M. (2002). Synthesis and property characterization of cassava starch grafted poly[acrylamide-co-(maleic acid)] superabsorbent via gamma irradiation. *Polymer*, *43*(14), 3915–3924.

Kim, J. K., Srinivasan, P., Kim, J. H., Choi, J., Park, H. J., Byun, M. W., et al. (2008). Structural and antioxidant properties of gamma irradiated hyaluronic acid. *Food Chemistry*, *109*(4), 763–770.

Kume, T., Furuta, M., Todoriki, S., Uenoyama, N., & Kobayashi, Y. (2009). Status of food irradiation in the world. *Radiation Physics and Chemistry*, *78*(3), 222–226.

Liu, T., Ma, Y., Xue, S., & Shi, J. (2012). Modification of structure and physicochemical properties of maize starch by gamma irradiation treatments. *LWT – Food Science and Technology*, *46*, 156–163.

Liu, Q., & Chung, H.-J. (2010). Molecular structure and physicochemical properties of potato and bean starches as affected by gamma irradiation. *International Journal of Biological Macromolecules*, *47*, 214–222.

Luo, F. X., Huang, Q., Fu, X., Zhang, L., & Yu, X. S. J. (2009). Preparation and characterization of crosslinked waxy potato starch. *Food Chemistry*, *115*(2), 563–568.

Mishra, S., & Rai, T. (2006). Morphological and functional properties of corn, potato and tapioca starches. *Food Hydrocolloids*, *20*, 557–566.

Nagasawa, N., Yagi, T., Kume, T., & Yoshii, F. (2004). Radiation processing of carboxylmethyl starch. *Carbohydrate Polymers*, *58*, 109–113.

Nagasawa, N., Mitomo, H., Yoshii, F., & Kume, T. (2000). Radiation induced degradation of sodium alginate. *Polymer Degradation and Stability*, *69*, 279–285.

Nara, S., & Komiya, T. (1983). Studies on the relationship between water saturated sate and crystallinity by the diffraction method for miistened potato starch. *Starch-Starke*, *35*(12), 407–410.

Oyaizu, M. (1986). Studies on products of browning reactions: Antioxidant activity of products of browning reaction prepared from glucosamine. *Japanese Journal of Nutrition*, *44*, 307–315.

Riyas-Duarte, P., & Rupnow, J. H. (1994). Gamma irradiation affects some physical properties of dry bean (*Phaseolus vulgaris*) starch. *Journal of Food Science*, *58*, 389–394.

Rombo, G. Q., Taylor, J. R. N., & Minnaar, A. (2001). Effect of irradiation with and without cooking of maize and kidney bean flours, on porridge viscosity and *in vitro* starch digestibility. *Journal of the Science of Food and Agriculture*, *81*, 497–502.

Sabato, S. F., Silva, J. M., Curz, J. N., Broisler, P. O., Rela, P. R., Salmieri, S., et al. (2009). Advances in commercial applications of gamma irradiation in tropical fruits at Brazil. *Radiation Physics and Chemistry*, *78*(7/8), 655–658.

Sharpatyi, V. A. (2003). Radiation chemistry of polysaccharides: 1. Mechanism of carbon monoxide and formic acid formation. *High Energy Chemistry*, *37*, 369–372.

Singh, S., Singh, N., Ezekiel, R., & Kaur, A. (2011). Effects of gamma irradiation on morphological, structural, thermal and rheological properties of potato starches. *Carbohydrate Polymers*, *83*, 1521–1528.

Sokhey, A. S., & Chinnaswamy, R. (1993). Chemical and molecular properties of irradiated starch extrudates. *Cereal Chemistry*, *70*, 260–268.

Subramanian, V., Hoseney, R. C., & Bramel-Cox, P. (1994). Shear thinning properties of sorghum and corn starches. *Cereal Chemistry*, *71*, 272–275.

Tetchi, F. A., Amani, N. G., & Kamenan, A. (2007). Contribution to light transmittance modeling in starch. *African Journal of Biotechnology*, *6*, 569–575.

Ulanski, P., & Rosiak, J. M. (1992). Preliminary study on radiation-induced changes in chitosan. *Radiation Physics and Chemistry*, *39*(1), 53–57.

Vandeputte, G. E., Derycke, J., Geeroms, J., & Delcour, J. A. (2003). Rice starches: II. Structural aspects provide insight in swelling and pasting properties. *Journal of Cereal Science*, *38*, 53–59.

Williams, P. C., Kuzina, F. D., & Hlynka, I. (1970). A rapid colorimetric procedure for estimating amylose content of starches and flours. *Cereal Chemistry*, *47*, 411–420.

Wu, D., Shu, Q., Wang, Z., & Xia, Y. (2002). Effect of gamma irradiation on starch viscosity and physicochemical properties of different rice. *Radiation Physics and Chemistry*, *65*, 79–86.

Xu, Z., Sun, Y., Yang, Y., Ding, J., & Pang, J. (2007). Effect of gamma irradiation on some physicochemical properties of konjac glucomannan. *Carbohydrate Polymers*, *70*(4), 444–450.

Yoon, H. S., Yoo, J. Y., Kim, J. H., Lee, J. W., Byun, M. W., Baik, B. K., et al. (2010). *In vitro* digestibility of gamma irradiated corn starches. *Carbohydrate Polymers*, *81*(4), 961–963.

Yu, W., & Wang, J. (2007). Effect of gamma irradiation on starch granule structure and physicochemical properties of rice. *Food Research International*, *40*, 297–303.

Zainol, I., Akil, H. M., & Mastor, A. (2009). Effect of gamma irradiation on physical and mechanical properties of chitosan powder. *Materials Science and Engineering C*, *29*(1), 292–297.

Zuleta, A., Dyner, L., Sambucetti, M. E., & Francisco, A. (2006). Effect of gamma irradiation on the functional and nutritive properties of rice flours from different cultivars. *Cereal Chemistry*, *83*, 76–79.