Effect of electron beam irradiated barley grains on growth performance, blood parameters, nutrient digestibility, microbial population, and intestinal histomorphometry in broiler chickens

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ABSTRACT
The aim of this study was to examine the effect of electron beam-irradiated barley on performance and some physiological parameters of broiler chicks. Treatments were barley (25% and 50% of diet, raw and irradiated at 40 kGy) and control diet that used with five dietary treatments in a completely randomized design. Irradiation decreased the negative effects of barley on weight gain during the entire production phases at the level of 50%. Relative weight of breast increased in birds fed 25% irradiated barley compared to those fed 50% barley (P<.05). The relative weight of the gizzard as well as the lengths of the duodenum, jejunum and ileum was higher (P<.05) in birds fed 50% raw barley compared to that of the other treatments. Broilers fed a 50% barley diet had lower (P<.05) cholesterol and triglycerides concentrations compared to the birds fed 25% barley. The ileal apparent digestibility of nutrients decreased in birds fed 50% barley compared to those fed 25% barley. The caecal population of Lactobacillus was decreased (P<.05) in broilers fed on 50% raw barley. It is concluded that electron irradiation seems to be an effective procedure to improve the performance parameters of broiler chickens when the birds are fed high levels of barley.

Introduction
Cereals are the major part of a poultry diet and primary sources of feed energy. Due to the high cost of corn production, barley and wheat grain are commonly used as alternatives (Donohue and Cunningham 2009). However, high content of soluble non-starch polysaccharides (NSP), such as β-glucans, has limited the application of barley in poultry diets (Nahas and Lefrancois 2001; Knudsen 2014). It has been shown that soluble NSP can increase intestinal viscosity, reduce litter quality (White et al. 1983; Salih et al. 1991; Fuente et al. 1998), compromising the access of digestive enzymes to dietary components by protecting lipids, starch, and protein, and cause poor productive performance (Lázaro et al. 2003, 2004; García et al. 2008). There is considerable evidence that the negative effects of soluble NSP in poultry diets are related to the gut microbiota of broilers (Annison and Choct 1991). There have been reports on the alteration in mucosal morphology of chickens on diets based on barley (Viveros et al. 1994; Sieo et al. 2005). Therefore, the processing of barley grains to remove antinutritional factors and to improve their nutrient bioavailability before adding them to the diet is highly beneficial. Several methods such as germination, soaking, cooking, fermentation, enzymatic digestion and gamma irradiation are known to reduce antinutritional factors effectively and upgrade the nutritional quality of barley grain (Jacob and Pescatore 2012). The common practice is the use of exogenous enzymes (NSP-degrading enzymes) in poultry diets (Alagawany et al. 2018; Saeed et al. 2019). The irradiation with electron beam and gamma ray has been recognized as a safe and reliable method for improving/inactivating antinutritional factors of feeds (Al-Kaisey et al. 2002; Bahraini et al. 2017). Radiation is known as a physical processing method uses electron and gamma rays to improve the value of foodstuffs. Using ionizing radiation causes less damage to nutrients, especially protein, fewer indigestible reactions such as the Maillard reaction, a reduction of microbial and fungal contamination, as well as a decrease in the antinutritional factors and an increase in the digestibility of nutrients (Siddhuraju et al. 2002). Electron beam irradiation can decrease water extract viscosity, increase protein hydroporphicity of barley grain (Shawrang et al. 2013) and increase protein digestibility of canola meal and sorghum grains (Shawrang et al. 2011). It has been shown that electron beam and gamma-ray irradiation can reduce gossypol and crude fibre and increase protein digestibility of cotton seed meal but have no effect on protein quality of cotton seed meal (Bahraini et al. 2017). Gharaghani et al. (2008) showed that gamma-ray irradiation reduced the glucosinolate content of canola meal as the radiation dose increased (10, 20 and 30 kGy). Nayef et al. (2015) observed that FI and body weight gain (BWG) in broiler chicks fed diets containing 12% electron beam-irradiated...
(30 kGy) cotton seed meal can increase when compared to those fed a control diet.

As the literature lacks a thorough study of the effect of electron beam irradiation of barley grain on the production percentage, the effect of electron beam-irradiated barley grain at different levels on the production performance, carcass traits, nutrient digestibility, some blood parameters, microbial population, and intestinal histomorphometry of broiler chicks was evaluated.

Materials and methods

Electron beam irradiation

Barley grain samples were packed in 30 × 40 × 5 cm nylon bags and exposed to electron beam irradiation at the Yazd radiation processing centre (AEOI, Yazd centre, Iran) at a dose of 40 kGy. All the samples were irradiated according to the method described by Bahraini et al. (2017).

Chemical analyses

Barley grain samples (raw and irradiated at 40 kGy) were analysed for dry matter (DM), crude protein (CP), ash and ether extract (EE) according to the methods of AOAC (1990). The starch was determined as described by Clegg (1956). β-Glucan assay was conducted according to the method of the McCleary for mixed-linkage β-glucans (McCleary and Codd 1991), using the β-glucan enzymatic assay kit (Megazyme International, Co., Wicklow, Ireland). The content of neutral detergent fibre (NDF) and acid detergent fibre (ADF) was determined according to Van Soest et al. (1991).

Birds, diets, and general procedures

A total of 240 one-d-old male broiler chicks (Ross-308) were obtained from a local hatchery and were individually weighed. Chicks were randomly distributed into 5 treatments with 4 replicates (12 chicks, 100 cm × 120 cm per pen) for each treatment. During the first 3 d after the hatching lights were continuously on. For the rest of the treatment duration, the lighting schedule was changed to 23L:1D. The temperature at d 0 was 33°C and decreased to 2°C every week until the temperature of 23°C was reached. Five diets containing 25 and 50 percentage of barley (raw and irradiated at 40 kGy) and a corn-soya bean meal diet (as control) were used during the two feeding regimens consisting of a starter (1–21 d) and grower (22–42 d) diet that they are isoenergetic and isonitrogenous in each phase. The AME of treated barley used for formulation of the experimental diets was 2795 kcal/kg. All diets were formulated to meet the nutrient requirements of broilers according to NRC.

Table 1. Chemical composition of raw and electron beam irradiated barley grain (%) of DM.

| Treatments           | DM   | CP   | EE   | Ash  | Starch | β-Glucan | NDF* | ADFb |
|----------------------|------|------|------|------|--------|----------|------|------|
| Raw barley           | 94.45| 12.51| 3.50 | 3.75 | 55.27  | 3.93     | 19.25| 6.71 |
| Irradiated barley (40 kGy) | 94.83| 12.41| 3.52 | 3.49 | 56.00  | 3.68     | 15.04| 5.71 |

*Neutral Detergent Fibre.  
bAcid Detergent Fibre.

Table 2. Ingredient composition and chemical analysis of diets used in the experiment.

| Ingredient, % of diet (as fed) | Level of barley in diet, % (starter) | Level of barley in diet, % (grower) |
|-------------------------------|-------------------------------------|-------------------------------------|
|                              | 0  | 25 | 50 | 0  | 25 | 50 |
| Corn                          | 58.49 | 33.77 | 9.70 | 67.21 | 41.45 | 16.84 |
| Soybean meal (44% CP)         | 34.70 | 30.61 | 26.57 | 27.52 | 25.22 | 21.10 |
| Barley                        | 0.00 | 25.00 | 50.00 | 0.00 | 25.00 | 50.00 |
| Sunflower oil                 | 1.58 | 4.18 | 6.54 | 0.72 | 3.63 | 6.19 |
| Fish meal                     | 1.00 | 2.50 | 3.87 | 1.13 | 1.45 | 2.96 |
| Calcium carbonate             | 1.49 | 1.53 | 1.35 | 1.45 | 1.42 | 1.41 |
| Dicalcium phosphate           | 1.57 | 1.27 | 0.83 | 1.03 | 0.88 | 0.59 |
| Common salt                   | 0.49 | 0.46 | 0.38 | 0.33 | 0.31 | 0.27 |
| Vitamin–mineral premix        | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 |
| DL-Methionine                 | 0.18 | 0.18 | 0.16 | 0.07 | 0.08 | 0.07 |
| L-Lysine HCL                  | 0.00 | 0.00 | 0.00 | 0.04 | 0.06 | 0.07 |
| Calculated composition        | 2900 | 2900 | 2900 | 2960 | 2960 | 2960 |
| AME (kcal/kg)                 | 20.84 | 20.84 | 20.84 | 18.50 | 18.49 | 18.49 |
| CP (%)                        | 0.50 | 0.50 | 0.50 | 0.38 | 0.38 | 0.38 |
| Methionine (%)                | 0.84 | 0.84 | 0.83 | 0.69 | 0.69 | 0.69 |
| Methionine + cystine (%)      | 0.79 | 0.78 | 0.76 | 0.71 | 0.68 | 0.67 |
| Threonine (%)                 | 1.13 | 1.12 | 1.11 | 1.00 | 1.00 | 1.00 |
| Lysine (%)                    | 0.45 | 0.45 | 0.45 | 0.35 | 0.35 | 0.35 |
| Available phosphorus (%)      | 0.45 | 1.00 | 1.00 | 0.90 | 0.90 | 0.90 |
| Calcium (%)                   | 0.20 | 0.20 | 0.20 | 0.15 | 0.15 | 0.15 |
| Sodium (%)                    | 0.34 | 0.35 | 0.34 | 0.24 | 0.26 | 0.27 |
| Chloride (%)                  | 3.72 | 4.28 | 4.85 | 3.41 | 4.06 | 4.62 |

*Vitamin and mineral premix provided the following per kilogram of diet: retinyl acetate, 1.55 mg; cholecalciferol, 0.025 mg; α-tocopherol acetate, 20 mg; menadione, 1.3 mg; thiamine, 2.2 mg; riboflavin, 10 mg; calcium pantothenate, 10 mg; choline chloride, 400 mg; nicotinamide, 50 mg; pyridoxine HCl, 4 mg; biotin, 0.04 mg; folic acid, 1 mg; vitamin B12 (cobalamin), 1.013 mg; Fe, 60 mg; Mn, 100 mg; Zn, 60 mg; Cu, 10 mg; I, 1 mg; Co, 0.2 mg; and Se, 0.15 mg.
(1994). All birds were allowed \textit{ad libitum} access to feed and water. The ingredients and chemical composition of diets are shown in Table 2.

\textbf{Performance}

Weekly BWG and feed intake (FI) of each replicate were recorded. Feed conversion ratio (FCR) was calculated by dividing FI by BWG.

\textbf{Blood lipid metabolites, bacterial enumeration and size of different organs}

At the end of the study (42 d), two birds per replicate were killed by cervical dislocation, and the relative weight (based on BW) of birds’ organs including breast, thigh, pancreas, liver, gizzard, proventriculus and abdominal fat were measured. The length of different birds’ intestinal segments, i.e. duodenum, jejunum and ileum were measured. Blood was drawn from the jugular vein of killed birds. Serum was separated after centrifugation at 4500g and 4°C for 10 min, and frozen at −20°C until further analysis was conducted for blood biochemical parameters. Sera samples were analysed for concentrations of low-density lipoprotein (LDL) and high-density lipoprotein (HDL), cholesterol, glucose and triglycerides (TG) using standard kits (Zist Shimi, Tehran, Iran) with an autoanalyser (Autolab PM 4000; Medical System, Rome, Italy). Caecal digesta (1 g) from each bird were aseptically transferred into 9 ml of sterile saline solution and serially diluted. Lactobacilli, Coliforms, \textit{E. coli}, and total aerobic bacteria were grown on Rogosa–Sharpe agar, MacConkey Agar, Eosin Methylene Blue Agar, and Plate Count Agar, respectively. Plates for \textit{Lactobacillus} have incubated anaerobically for 48 h at 37°C. Microbial populations for total aerobic, \textit{E. coli} and Coliforms were counted after aerobic incubation at 37°C for 24 h. All samples were plated in duplicate (Engberg et al. 2004).

\textbf{Ileal viscosity}

On d 42, two birds per replicate (i.e. eight birds per treatment) were randomly selected and killed by cervical dislocation. The small intestine was then removed, and the digesta content of the ileum from Meckel’s diverticulum to the ileoceleal junction was immediately collected. To measure the ileal digesta viscosity, approximately 2 g of fresh digesta was centrifuged (12,000g for 10 min at 4°C). The supernatant from each sample was stored separately at −20°C until use. The supernatants were thawed on ice before the viscosity was measured. The viscosity of the supernatant (0.5 ml) was determined using a Brookfield DV III viscometer (Brookfield Engineering Laboratories, Stoughton, MA, USA) at 25°C with a CP40 cone and shear rate of 5–500/s. The samples did not exhibit shear-thinning at these shear rates (Sieo et al. 2005).

\textbf{pH of ileum}

At 42 d of age, two birds/replicate were randomly selected and killed by cervical dislocation, the digestive organs were excised, and ileal digesta samples were taken for pH measurement. One gram of the ileal contents of each bird was immediately collected and placed into clean falcon tubes. The samples were mixed with deionized water (1:10 wt/vol), and the pH of the solution was measured with a digital pH metre (pH-3110 SET2, Germany) at room temperature (Pang and Applegate 2007).

\textbf{Apparent ileal nutrient digestibility}

The chromic oxide (Cr$_2$O$_3$) marker method reported by Sales and Janssens (2003) was used to measure ileal nutrient digestibility. Marker-containing diets (supplemented with 3 g/kg of Cr$_2$O$_3$) were fed for 7 consecutive days, from d 36 to d 42 of the experimental period. At the end of the study, three birds per replicate were killed by cervical dislocation and ileal contents, from Meckel’s diverticulum to the ileocecal junction, and collected in sealed bags. The pooled digesta samples (on pen basis) were kept frozen at −20°C until further analysis was performed. Prior to analysis, excreta samples were later thawed, homogenized, oven-dried (60°C for 72 h), ground (0.5-mm screen), and stored for analysis. Diet and digesta samples were analysed according to the methods of the AOAC (1990). Analyses were conducted for DM, OM, CP, and EE. Chromic oxide concentration in the feed and excreta samples was determined according to Williams et al. (1962). The apparent ileal nutrient digestibility was then calculated relative to the Cr$_2$O$_3$ concentration.

\textbf{Gut histomorphology}

At the end of 42 days, two birds from each replicate were randomly selected and killed by cervical dislocation, and the following segments were removed: jejunum (from the pancreatic loop to Meckel’s diverticulum) and ileum (from Meckel’s diverticulum to 1 cm above ileocecal junction). Segments about 5 cm in length of ileum and jejunum were taken for histological study. The gut samples were then fixed in 10% formaline in 0.1 M phosphate buffer (pH = 7.0), where they were gently shaken to remove any adherent intestinal content. The processing consisted of serial dehydration in graded ethanol solutions (50%, 70%, 80%, 96% and 100%), clearing with xylene and embedding in paraffin. Tissue samples were then sectioned using a microscope at a thickness of 5 μm (three cross sections from each sample). The sections were stained with haematoxylin and eosin (Rebole et al. 2010). The micrometrical analysis was done using Dino-Lite Digital Microscope, Digital Dino-Lite Eye-Piece and Dino-Capture II software on microphotographs.

\textbf{Statistical analysis}

All data were evaluated by analysis of variance following the GLM procedure in a completely randomized design using the SAS software program (SAS Institute Inc 2001) with the statistical model of $Y_{ijk} = \mu + T_i + e_{ijk}$, where $Y_{ijk}$ is the dependent variable, $\mu$ is the overall mean, $T_i$ is the effect of treatment, and $e_{ijk}$ is the residual effect. The main effects (barley levels and levels of electron beam irradiation) and interactions were studied in a 2 × 2 factorial arrangement. Performance data were analysed
considering all birds in a pen as an experimental unit. Differences among treatments were compared using the Fisher’s LSD test, and a probability value of \( P < 0.05 \) was considered to be significant.

**Results**

**Performance parameters**

Mortality was lower than 3% with no differences between the groups. Data representing the effect of dietary treatments on the performance of broilers are shown in Table 3. There were significant levels of barley * irradiation interactions related to FI during the starter (1–21 days) period \( P < 0.05 \). Birds fed 50% raw barley had the lowest FI \( P < 0.05 \) compared to other treatments. Also, broilers fed a 50% irradiated barley diet had significantly increased \( P < 0.05 \) FI compared to the 50% raw barley diet. FI of broilers was not affected by the treatments during grower (22–42 days) and the whole period of experiment (1–42 days) \( P > 0.05 \). There were significant levels of barley * irradiation interactions related to BWG during the starter (1–21 days) period \( P < 0.05 \). The birds that consumed 50% raw barley diet had significantly lower \( P < 0.05 \) BWG compared with other treatments at the starter, grower and the whole period of the experiment. Chicks fed a 25% irradiated barley diet gained significantly better \( P < 0.05 \) than those fed 50% raw barley and control diet at the grower period. There was no interaction between the level of barley and irradiation on BWG of broiler at the grower and whole period of the experiment \( P > 0.05 \), and therefore, the main effects are discussed independently. Broilers fed 25% of barley had higher \( P < 0.05 \) BWG than broilers fed 50% barley, and also, broilers fed irradiated barley had higher BWG than those fed raw barley during the grower and whole period of the experiment \( P < 0.05 \). The birds that consumed 25% barley showed better FCR than those fed 50% barley at the starter period \( P < 0.05 \). There were significant levels of barley * irradiation interactions related to FCR during the grower and the whole period of the experiment \( P < 0.05 \). Radiation of barley was more effective in improving FCR at the level of 50% compared to 25% in the grower and the whole period of the experiment.

**Blood parameters**

As shown in Table 4, the plasma concentration of glucose, LDL and HDL were not affected significantly by the treatments. Broilers fed a 50% barley (raw or irradiated) diet had significantly lower \( P < 0.05 \) cholesterol and triglycerides concentrations compared to the other treatments. No interactions between the level of barley and irradiation were observed for blood concentrations \( P > 0.05 \). However, the radiation of barley had no significant effect on blood parameters but cholesterol and triglyceride concentrations were significantly reduced in birds consumed 50% barley compared to those in the birds fed 25% barley \( P < 0.05 \).

**Microbial population**

As noted in Table 5, caecal populations of *Lactobacillus* decreased significantly in broilers fed 50% barley (raw or irradiated) compared to the control group \( P < 0.05 \). No interactions between the level of barley and irradiation were observed for a microbial population of caecum \( P > 0.05 \). Also, the main effects of the level of barley were significant for *Lactobacillus*, and the effects of irradiation were significant for *E. coli*. The caecal population of *Lactobacillus* was decreased \( P < 0.05 \) in broilers fed on 50% barley compared to 25% barley \( P < 0.05 \). Also, irradiated barley has significantly decreased \( P < 0.05 \) populations of *E. coli* compared to raw barley.

**Size of different organs and length of intestine**

According to data presented in Table 6, the relative weight of the thigh, proventriculus, pancreas, liver and abdominal fat were not influenced significantly by the treatments. The relative weight of breast significantly increased in birds fed 25% irradiated barley compared to those fed 50% barley (raw or irradiated) \( P < 0.05 \). No interactions between the level of barley and irradiation on organ weights were observed.

**Table 3. Effect of treatments on performance parameters of chickens.**

| Treatment | FI (g/bird) | BWG (g/bird) | Feed conversion ratio |
|-----------|-------------|--------------|-----------------------|
|           | 1–21 d | 22–42 d | 1–42 d | 1–21 d | 22–42 d | 1–42 d | 1–21 d | 22–42 d | 1–42 d |
| Control   |     |     |     |     |     |     |     |     |     |
| 25% RB    | 916^a | 2344 | 3250 | 585^a | 1123^bc | 1708^b | 1.5^b | 2.0^4 | 1.8^6 |
| 25% IB    | 907^b | 2571 | 3477 | 614^a | 1264^a | 1877^a | 1.47^b | 2.03 | 1.85 |
| 50% RB    | 753^a | 2342 | 3094 | 476^a | 1029^a | 1505^a | 1.58^b | 2.27 | 2.05 |
| 50% IB    | 857^b | 2468 | 3325 | 543^b | 1163^b | 1709^b | 1.57^b | 2.12 | 1.94 |
| SEM       | 15.42 | 46.95 | 53.71 | 13.03 | 24.15 | 34.56 | 0.01 | 0.02 | 0.02 |
| P-value   | .001  | .312  | .203  | .001  | .023  | .002  | .004  | .001 | .001 |
| Irradiation |       |       |       |       |       |       |       |       |
| RB        | 834^a | 2338 | 3173 | 545^b | 1087^b | 1632^b | 1.5^b | 2.16 | 1.95 |
| IB        | 882^a | 2519 | 3401 | 580^a | 1213^a | 1793^a | 1.5^c | 2.08 | 1.90 |
| SEM       | 23.74 | 152.86 | 176.16 | 18.12 | 78.04 | 95.52 | 0.01 | 0.01 | 0.01 |
| Levels of barley |       |       |       |       |       |       |       |       |
| 25%       | 912^a | 2452 | 3364 | 614^a | 1204^a | 1819^a | 1.4^b | 2.0^4 | 1.8^6 |
| 50%       | 805^b | 2405 | 3210 | 511^b | 1096^b | 160^b | 1.5^b | 2.20 | 2.0^b |
| SEM       | 13.63 | 91.15 | 99.68 | 10.47 | 44.10 | 51.73 | 0.01 | 0.01 | 0.01 |
| Probability |       |       |       |       |       |       |       |       |
| Irradiation | 0.027 | 0.124 | 0.084 | 0.025 | 0.020 | 0.016 | 0.383 | 0.004 | 0.006 |
| levels of barley | 0.0001 | 0.675 | 0.232 | 0.0001 | 0.039 | 0.003 | 0.0001 | 0.0001 | 0.0001 |
| Irradiation × levels of barley | 0.011 | 0.623 | 0.988 | 0.022 | 0.880 | 0.466 | 1.00 | 0.008 | 0.004 |

Note: RB: raw barley; IB: irradiated barley; SEM: standard error of the mean. Means within a column with no common superscript letter differ significantly \( P < 0.05 \).
barley diet had significantly higher ($P < .05$) ileal viscosity compared to the other treatments. There was no interaction between the level of barley and irradiation on ileal digesta viscosity ($P > .05$), and therefore, the main effects are discussed independently. Broilers fed 50% barley had significantly higher ($P < .05$) viscosity compared to the broilers fed 25% barley. However, broilers fed irradiated barley had significantly lower ileal digesta viscosity compared to the birds fed raw barley ($P < .05$). The inclusion of barley in the diet resulted in significantly decreased ($P < .05$) ileal pH when compared with the control diet except for 25% raw barley. However, there was no interaction between the level of barley and irradiation on ileal pH ($P > .05$).

### Apparent ileal digestibility

The ileal apparent digestibility of DM, organic matter (OM), EE and CP significantly decreased ($P < .05$) in birds fed 50% barley (raw or irradiated) compared to those fed other treatments (Table 7). There was no interaction between the level of barley and irradiation for ileal nutrient digestibility ($P > .05$). But the main effect of the level of barley was significant ($P < .05$) for apparent ileal digestibility of nutrients; apparent ileal digestibility of DM, OM, EE, and CP were lower in birds fed 50% barley compared to the birds fed 25% barley.

### Gut histomorphology

The histomorphometry of the jejunum and ileum was not affected by the experimental treatments ($P > .05$) (Table 8). The villus height and ratio of villus height to crypt depth numerically decreased, and villus width, crypt depth, crypt width, number of goblet cells (epithelial, crypt), epithelial thickness, muscle thickness and total wall thickness of the jejunum and ileum increased by 50% raw barley compared to the other treatments. However, radiation numerically improved histological observations at level 25 and 50% barley compared to raw barley in the jejunum and ileum. There was no interaction between the level of barley and irradiation on histomorphometry of the jejunum and ileum ($P > .05$).

### pH and ileal digesta viscosity

As shown in Table 5, pH and ileal digesta viscosity were affected significantly ($P < .05$) by the treatments. Broilers fed a 50% raw barley diet was significantly higher ($P < .05$) ileal viscosity compared to the other treatments. There was no interaction between the level of barley and irradiation on ileal digesta viscosity ($P > .05$), and therefore, the main effects are discussed independently. Broilers fed 50% barley had significantly higher ($P < .05$) viscosity compared to the broilers fed 25% barley. However, broilers fed irradiated barley had significantly lower ileal digesta viscosity compared to the birds fed raw barley ($P < .05$). The inclusion of barley in the diet resulted in significantly decreased ($P < .05$) ileal pH when compared with the control diet except for 25% raw barley. However, there was no interaction between the level of barley and irradiation on ileal pH ($P > .05$).

### Table 4. Effects of treatments on blood parameters of broiler chickens at 42 days of age (mg/dl).

| Item       | LDL  | HDL  | Cholesterol | Triglycerides | Glucose |
|------------|------|------|-------------|---------------|---------|
| Control    | 26.75| 56.50| 115.00a     | 58.00a        | 238     |
| 25% RB     | 27.25| 57.25| 115.00a     | 56.00         | 234     |
| 25% IB     | 27.00| 60.75| 115.00a     | 55.50a        | 237     |
| 50% RB     | 27.50| 62.25| 95.25b      | 47.00b        | 231     |
| 50% IB     | 27.25| 61.50| 94.75b      | 44.25b        | 234     |
| SEM        | 0.31 | 0.89 | 3.29        | 1.52          | 1.01    |

$P$-value

| Irradiation | RB   | IB   | SEM  |
|-------------|------|------|------|
| Control     | .966 | .136 | .042 |
| 25% IB      | .011 | .001 | .250 |
| 50% IB      | .010 | .010 | .010 |

**Irradiation × levels of barley**

| Levels of barley | 25%   | 50%   | SEM  |
|------------------|-------|-------|------|
| Control          | 0.766 | 0.975 | 0.878 |
| 25% IB           | 0.810 | 0.810 | 0.842 |
| 50% IB           | 0.810 | 0.810 | 0.842 |

**Levels of barley**

| Levels of barley | 25%   | 50%   | SEM  |
|------------------|-------|-------|------|
| Control          | 0.020 | 0.020 | 0.020 |
| 25% IB           | 0.020 | 0.020 | 0.020 |
| 50% IB           | 0.020 | 0.020 | 0.020 |

Note: RB: raw barley; IB: irradiated barley; and SEM: standard error of mean. Means within a column with no common superscript letter differ significantly ($P < .05$).

### Table 5. Effect of treatments on caecal microbial population (log CFU/g of digesta), viscosity and pH in ileum digesta of broilers at d 42.

| Item                        | Lactobacilli | Coliform | E. coli | Total bacteria | Viscosity (cPs) | pH   |
|-----------------------------|--------------|----------|---------|----------------|-----------------|------|
| Control                     | 9.12a        | 6.86     | 6.82    | 9.15           | 2.60a           | 6.44a|
| 25% RB                      | 8.95ab       | 7.11     | 7.05    | 9.28           | 2.77a           | 6.20ab|
| 25% IB                      | 9.11b        | 6.94     | 6.84    | 9.19           | 2.68b           | 5.95b |
| 50% RB                      | 8.72c        | 7.12     | 7.09    | 9.30           | 3.32c           | 6.10b |
| 50% IB                      | 8.82bc       | 6.95     | 6.84    | 9.19           | 3.05b           | 6.02b |
| SEM                         | 0.050        | 0.040    | 0.050   | 0.020          | 0.070           | 0.050 |
| $P$-value                   | .035         | .201     | .149    | .211           | .0001           | .005 |
| Irradiation                 |              |          |         |                |                 |      |
| Control                     | 8.84         | 7.11     | 7.07a   | 9.29           | 3.05a           | 6.15 |
| 25% IB                      | 8.97         | 6.95     | 6.84b   | 9.19           | 2.87b           | 5.99 |
| 50% IB                      | 8.77b        | 7.04     | 6.97    | 9.25           | 3.18b           | 6.06 |
| SEM                         | 0.060        | 0.050    | 0.070   | 0.030          | 0.050           | 0.070 |
| Levels of barley            |              |          |         |                |                 |      |
| 25%                          | 9.03a        | 7.03     | 6.95    | 9.24           | 2.73b           | 6.07 |
| 50%                          | 8.77b        | 7.04     | 6.97    | 9.25           | 3.18b           | 6.06 |
| SEM                         | 0.060        | 0.050    | 0.070   | 0.030          | 0.050           | 0.070 |
| Probability                 |              |          |         |                |                 |      |
| Irradiation                 | 0.209        | 0.062    | 0.026   | 0.065          | 0.015           | 0.076 |
| levels of barley            | 0.020        | 0.878    | 0.810   | 0.842          | 0.0001          | 0.884 |
| Irradiation × levels of barley | 0.799       | 0.975    | 0.873   | 0.920          | 0.187           | 0.317 |

Note: RB: raw barley; IB: irradiated barley; and SEM: standard error of mean. Means within a column with no common superscript letter differ significantly ($P < .05$).
Table 6. Effects of treatments on relative weight of selected digestive organs and intestinal length of chicks at 42 days of age (% of body weight).

| Item                     | Breast DM | Thigh OM | Proventriculus EE | Gizzard CP | Pancreas CP | Liver CP | Abdominal fat CP | Duodenum CP | Jejunum CP | Ileum CP |
|--------------------------|-----------|----------|-------------------|-----------|-------------|----------|------------------|-------------|------------|---------|
| Control                  | 65.50 ab  | 66.50 ab | 62.50 ab          | 69.25 ab  |             |          |                  |             |            |         |
| 25% RB                   | 64.00 ab  | 64.75 ab | 61.00 ab          | 67.50 ab  |             |          |                  |             |            |         |
| 25% IB                   | 65.00 ab  | 65.75 ab | 61.75 ab          | 68.50 ab  |             |          |                  |             |            |         |
| 50% RB                   | 56.00 ab  | 55.25 ab | 53.50 ab          | 59.75 ab  |             |          |                  |             |            |         |
| 50% IB                   | 59.50 ab  | 59.75 ab | 56.50 ab          | 63.50 ab  |             |          |                  |             |            |         |
| SEM                      | 0.96      | 1.17     | 0.91              | 0.97      |             |          |                  |             |            |         |
| P-value                  | .0001     | .0006    | .0006             | .0005     |             |          |                  |             |            |         |

Table 7. The effect of treatments on apparent ileal nutrient digestibility of chicks at 42 days of age (%).

| Item                     | DM | OM | EE | CP  |
|--------------------------|----|----|----|-----|
| Control                  | 65.50 | 66.50 | 62.50 | 69.25 |
| 25% RB                  | 64.00 | 64.75 | 61.00 | 67.50 |
| 25% IB                  | 65.00 | 65.75 | 61.75 | 68.50 |
| 50% RB                  | 56.00 | 55.25 | 53.50 | 59.75 |
| 50% IB                  | 59.50 | 59.75 | 56.50 | 63.50 |
| SEM                     | 0.96 | 1.17 | 0.91 | 0.97 |
| P-value                 | .0001 | .0006 | .0006 | .0005 |

The e-value .050 .184 .215 .002 .780 .950 .401 .036 .011 .006

Discussion

Growth performance

In the present study, the feed was formulated with 50% irradiated barley resulting in chick FI and BWG equivalent to the control diet but with increased FCR throughout the whole period of the experiment. Also, the inclusion of barley at the level of 25% (raw or irradiated) in the diet resulted in equal FCR when compared with the control diet. Dietary inclusion of 50% barley decreased BWG and increased FCR compared to 25% barley during the whole period of the experiment. This result is in agreement with the observation of Brake et al. (1997) that the inclusion of barley at the level of 30% in the grower and finisher diets had no effect on the performance of broilers. Although up to 30% barley was suggested as supplements in older broiler foods, untreated barley might not be a good candidate for starter diets (Jeroch and Danicke 1995). Feeding broiler chicks with a higher percentage of barley (up to 35% whole barley) showed no significant effect on live bird performance. On the contrary, Cengiz et al. (2012) reported that growth performance was adversely affected at the level of 25% dietary barley inclusion. Similarly, Yu et al. (1998) and García et al. (2008) have shown that the BWG of broilers decreased linearly with increasing levels of barley in the diet. Radiation of barley at the level of 50% resulted in an increase in FI from d 1–21 compared to raw barley, probably due to the reduction in digesta viscosity (Table 5). On the other hand, this increase in FI did result in an increase in broiler BWG from d 1 to 21 and from d 1 to 42. It seems that the higher intestinal viscosity in birds fed on raw barley diets is related to the lower weight gains in this group, because β-glucans bind to water in the intestines resulting in the formation of gels, which increases the viscosity of the intestinal contents (Jacob and Pescatore 2012) and interferes with nutrient assimilation within the chick intestine (Edney et al. 1989). As shown in Table 1, β-glucan of barley decreased numerically by irradiation at the dose of 40 kGy. Bhatti and MacGregor (1988) reported that starch as well as α-amylase inhibitors were significantly degraded by irradiation of barley. Also, it has been shown that irradiation of oat groats and rye can break down the polymeric structure of viscous carbohydrates (Campbell et al. 1983, 1987). Consequently, the viscosity and antinutritive effects of them decreased. Other studies showed that antinutritional factors, such as phytohaemagglutinins and protease inhibitors (Farag 1998), tannin and α-amylase inhibitors (Abu-Tarboush 1998), are significantly inactivated by gamma irradiation. Therefore, the improved performance of birds that fed irradiated barley in the current study may be due to breakdown of β-glucans, which leads to lower viscosity. However, these findings showed that irradiation of barley significantly compared to those fed raw barley at the level of 50%, while the FCR of birds that consumed 50% irradiated barley was not the same as that of the birds consumed the control diet. Nayeef et al. (2015) reported that broilers fed diets containing 12% electron irradiated cotton seed meal (at 30 kGy) had higher FI and BWG compared to birds fed a diet containing raw cotton seed meal. The greater BWG was attributed to the...
reduction in gossypol by irradiation. Previously, Gharaghani et al. (2008) observed that gamma irradiation processing of canola meal at doses of 10, 20 and 30 kGy had no significant effect on FI, BWG and FCR in chickens. Al-Kaisey et al. (2002) reported irradiation treatment reduced the viscosity of seeds of two barley cultivars (Local Black and Shoaa).

**Blood lipid parameters**

As shown in Table 4, plasma concentrations of HDL, LDL and glucose were not influenced by the treatments. Dietary inclusion of 50% barley (raw or irradiated), however, caused a significant decrease in the plasma cholesterol and triglyceride levels (P < .05). High levels of cholesterol, LDL cholesterol and triglyceride in the body are associated with greater rates of various chronic diseases, including CVDs and arteriosclerosis (Obadi et al. 2021; Leeson et al. 1995). Soluble NSP can reduce serum cholesterol levels (Hughes 1991; Lairon 1996). Studies in humans and animals have revealed that beta-glucan (soluble NSP) of barley specifically reduces total cholesterol and LDL lipoprotein content (Delaney et al. 2003; Åman 2006). The yeast-derived beta-glucan fibre significantly decreased total cholesterol concentrations in men (Nicolosi et al., 1999). In an in vivo test, barley β-glucans promoted the conversion of cholesterol into bile acid in the liver and its excretion in faeces, thereby reducing serum cholesterol levels (Xia et al. 2018). Additionally, barley β-glucan exerts much stronger inhibition effect on 3-hydroxy-3-methylglutaryl CoA (HMGGCoA) reductase compared with oat β-glucan (Tong et al. 2015). Also, the decrease in cholesterol level observed in the present study can be the result of either cholesterol assimilation (or uptake) by the lactobacilli (Buck and Gilliland 1994) or coprecipitation of cholesterol with deconjugated bile salts (Klaver and Van der Meer 1993). In the present study, serum cholesterol and triglyceride concentration of broilers fed 50% barley in the diet were reduced compared to those fed 25% barley. This finding also supports the results of Rama Rao et al. (2004, 2006) in which the serum concentration of triglyceride decreased in birds receiving high-fibre diets. As shown in Table 2, crude fibre of the diet increased by increasing the levels of barley in the diet. Barley is the major dietary source of phytoesters and phenolic compounds (Obadi et al. 2021). Previous findings have shown that consumption of dietary plant
sterols and phenolic compounds can have beneficial impacts, such as reduction of blood-cholesterol levels, protection against CVD, and anticancer property (Saleh et al. 2019; Zhu et al. 2015). Radiation did not have a significant effect on blood parameters of broilers. These results are in agreement with those of Nayef et al. (2015), who reported that feeding electron irradiated cotton seed meal had no significant effect on blood parameters including triglyceride, cholesterol, HDL, LDL and glucose concentrations.

Caecal bacterial numbers

The antinutritive effects of soluble NSP are mainly attributed to an increased viscosity of digesta associated with higher levels of microbial populations in the intestinal tract (Rebole et al. 2010). Diet composition can impact gut microbiota by changing the physicochemical properties of chyme and by supplying the nutrients for the growth of specific groups of microflora (Shakouri et al. 2009). The absorption of nutrients by the host animal reduces by high intestinal viscosity, the rate of feed passage decreases and mucus production enhances (Piel et al. 2005). High viscosity can lead to an increase in the number of anaerobic bacteria and a decrease in the population of *Lactobacillus* in the small intestine (Collier et al. 2003). Most of the pathogens grow at high pH, and the Positive microorganism population is favourable in an acidic medium (Ricke 2003). In this experiment, caecal population of *Lactobacillus* was decreased (*P < .05*) in broilers fed on a 50% raw barley diet. But, caecal populations of Coliform and total aerobic bacteria were not influenced by the experimental treatments. In consistent with the results of the present study, Masouri et al. (2017) observed that the number of caecal population of *Lactobacillus* is lower in broilers fed on wheat-based diets than those fed on maize-based diets, whereas caecal populations of Coliform, *E. coli* and total aerobic bacteria were not influenced. Rebole et al. (2010) also observed that the addition of xylanase and β-glucanase to wheat and barley-based diet had no significant effect on the number of Lactobacilli and bifidobacteria in the ileum and caecum of broiler chickens. The addition of xylanase to a wheat-based diet had no significant effect on the number of *Lactobacilli*, *E. coli* and total aerobic bacteria in the ileum and caecum of broiler chickens (Luo et al. 2009). Gao et al. (2008) observed that a diet based on wheat supplemented with xylanase did not affect *Lactobacilli* and Coliform bacteria in the caecum. In contrast to our findings, Mathlouthi et al. (2002) reported that wheat and barley consumption, when compared with the corn-based diet, produced an increase in *Lactobacilli* and *E. coli* bacteria in the caecum. They also observed that the addition of xylanase and β-glucanase to the wheat and barley-based diet reduced the total number of aerobic counts and the number of *E. coli*. However, the number of *Lactobacilli* was not significantly modified. Xylanase addition stimulates the growth of lactic acid bacteria in the ileum of broiler chickens, which is confirmed by higher lactic acid concentrations and higher ATP concentrations at that location (Engberg et al. 2004). Vahjen et al. (1998) reported an increased number of mucosa-associated *Lactobacilli* in the small intestine of xylanase-supplemented broilers.

Size of different organs and length of intestine

There were no effects (*P > .05*) of barley radiation on relative weight (percentage of live body weight) of the thigh, prevertri- culus, pancreas, liver and abdominal fat (Table 6). Relative weight of breast was decreased in birds fed 50% barley compared to the birds fed 25% barley (*P < .05*). Radiation of barley had no significant effect on the relative weight of the breast in broiler chicks. The relative weight of gizzard and intestinal length of duode- num, jejunum, and ileum increased in broilers fed on raw barley diet at the level of 50% compared to the other treatments (*P < .05*). The relative weight and length of the digestive tract could be increased if viscous and fibrous grains are added to the bird’s diet (Viveros et al. 1994; Zhao et al. 1995). The reason for the increasing length of the duodenum, jejunum, and ileum on d 42 in chickens that received a high level of raw barley is presumably the high level of crude fibre of diet as shown in Table 2. This result is supported by the findings of Sadeghi et al. (2015), who showed the length of the jejunum increased in broilers given sugar beet pulp (3%) and sugar beet pulp/rice hull compared to those received rice hull (3%). Sugar beet pulp and sugar beet pulp/rice hull significantly enlarged the ileum compared with the other dietary treatments. Crude fibre of sugar beet pulp and rice hull in that study was 15.1% and 44.7%, respectively. In agreement with this, Jiménez-Moreno et al. (2013) reported longer intestines in chicks received sugar beet pulp compared with those fed rice hull at 6 and 12 d of age. In contrast, it has been reported that ileum length at 14 d of age can be decreased if the bird is fed a greater ratio of soluble fibre (Saki et al. 2011). Our results confirm that intake of high fibre diets causes a significant increase in the length of the intestine. This has also been observed in previous studies on birds (Savory and Gentle 1976; Savory 1992), and on other animal species, such as rats (Hansen et al. 1992; Zhao et al. 1995) and pigs (Jørgensen et al. 1996). Nayef et al. (2015) observed no significant effect of irradiation of cotton seed meal at doses of 30 kGy on the relative weight organs of broiler. In contrast, Gharaghani et al. (2008) observed that liver weight decreased in broilers fed irradiated (10–30 kGy) canola meal. Also, the inclusion level of 50% irradiated barley in the diet decreased the lengths of different parts of the small intestine and the relative weight of the gizzard compared with those fed 50% raw barley. The shorter length of different parts of the intestine and smaller size of the gizzard were attributed to the reduction in fibre (NDF and ADF) of barley as shown in Table 1. These results can be due to the positive effects of radiation. These data showed that radiation did not have a significant effect on the relative weight of the broilers organs except for the gizzard.

Ileal viscosity and pH

The results of the present study showed that the viscosity of the ileal digesta of chickens fed with a 50% raw barley diet was significantly higher (*P < .05*) compared with those of chickens fed the other treatments. The increased viscosity was due to the presence of high content of soluble NSP such as β-glucans (Nahas and Lefrancois 2001; Knudsen 2014). It has been reported that the major factor in the antinutritive action
mechanism of NSP is the ability of them to increase the viscosity of the digesta of chickens. The increased viscosity was due to the presence of a water-soluble high-molecular-weight carbohydrate component (Annison 1993). Dietary inclusion of 50% irradiated barley caused a significant decrease ($P < .05$) in the viscosity compared with 50% raw barley. However, reduction of viscosity was numerically in 25% irradiated barley diet compared with 25% raw barley. The water extract viscosity of irradiated barley grain (at doses of 10, 15, 20, 25 and 30 kGy) decreased linearly due to the depolymerization of the $\beta$-glucan by radiolysis, which might result in a decrease in its molecular weight and an increase in the solubility (Shawrang et al. 2013). Campbell et al. (1986) observed that gamma irradiation processing of hulled barley and hull-less barley at doses of 3, 6 and 9 Mrad increased $\beta$-glucan solubility and reduced extract viscosity. Gamma irradiation at doses lower than 50 kGy could change $\beta$-glucan (purified from black yeast) with high solubility and low viscosity (Byun et al. 2008). Al-Kaisey et al. (2002) reported gamma irradiation treatment (at doses of 10–200 kGy) reduced the water extract viscosity of seeds of two barley cultivars (Local Black and Shoaa). They suggest that irradiation treatment of barley seeds could break down the polymeric structure of $\beta$-glucans, which will lead to low content of $\beta$-glucan and low viscosity in the seeds. The depolymerization of starch has also been considered to be responsible for the decrease in the viscosity caused by ionizing irradiation (Wu et al. 2002). There was no information about the effects of irradiation on ileal pH of broiler chickens. Inclusion of barley in the diet resulted in significantly decreased ($P < .05$) ileal pH. However, the radiation of barley had no significant effect on ileal pH of broilers. In consistent with the results of the present study, Jozefak et al. (2005) reported that supplementation of a barley-based diet (61.05%) with $\beta$-glucanase in broiler chickens was not affected by pH of digesta in the crop, gizzard, ileum and caeca. Shakouri et al. (2009) observed that a diet based on barley supplemented with a $\beta$-glucanase/xylanase enzyme complex did not affect ileal pH in broiler chickens. Xylanase did not affect pH values in any parts of the GIT of broilers fed with wheat-based diet (Esmailipour et al. 2011). Rebole et al. (2010) also observed the addition of xylanase and $\beta$-glucanase to wheat and barley-based diet had no significant effect on caecal short-chain fatty acids (acetic, propionic, and n-butyric acids), D-lactic acid concentrations and on caecal pH. The lack of an apparent decrease in the caecal pH is attributed to the buffering capacity of the gut content because of the presence of other dietary components, for example, calcium. Mathlouthi et al. (2002) showed that the pH value of the ileum contents significantly decreased after consumption of the wheat- and barley-based diet compared to the corn-based diet in broiler chickens. In contrast, Mirzae et al. (2012) observed the digesta pH of the different organs of the gastrointestinal tract was not affected by dietary inclusion levels of wheat (0%, 23%, 46% and 69%) in laying hens.

### Apparent ileal digestibility

As shown in Table 7, dietary inclusion of 50% barley (raw or irradiated) caused a significant decrease in the ileal apparent digestibility of DM, OM, EE and CP compared to the other treatments ($P < .05$). Digestibility of nutrients can be reduced due to the viscous properties of soluble NSP (Chocht and Annison 1992; Steenfeldt 2001; Knudsen 2014). This low digestibility has also been reported for barley-enriched or wheat-enriched diets (Chocht et al. 1996; Preston et al. 2001). Wang et al. (1992) reported a negative correlation between intestinal viscosity and digestibility of lipids and protein in broiler chicks fed barley. The barley-based diet (562.5 g/kg barley) decreased the apparent digestibility of DM, OM, CP and EE in male chicks compared with birds fed the corn-based diet (565.5 g/kg corn) (Onderci et al. 2008). Also, Viveros et al. (1994) showed that fat and starch digestibility were reduced in broiler chickens fed a barley–soybean meal diet compared with birds fed the corn-soybean meal diet. The digestibility of OM, DM and starch also decreased with increasing fibre levels (187 and 375 g/kg diet) of pea, wheat bran and oat bran in broiler chickens (Jørgensen et al. 1996). Mirzae et al. (2012) reported that wheat inclusion at levels of 23%, 46%, and 69% reduced-fat digestibility but protein digestibility was not affected by dietary inclusion of wheat in laying hens. In contrast, the levels of wheat substitution for corn did not affect the availabilities of DM, protein and fat in broiler chickens (Chiang et al. 2005). Lipids must be emulsified before digestion and absorption, a process that is hindered by viscous digesta (Wang et al. 1992). The results of this study showed that the bacteria overgrowth in the caecum (Table 5) can reduce lipid solubilization, which is the main reason behind the low lipid digestibility in broiler chickens fed high (i.e. 50%) barley-supplemented diets (Salih et al. 1991; Smits et al. 1998). Also, radiation increased the digestibility of DM, OM, EE and CP in broilers fed 50% barley compared to the raw barley, though this effect was not significant. This increase in digestibility can be due to the decreasing NDF and ADF (Table 1) in irradiated barley compared to raw barley grain. Shawrang et al. (2011) showed that digestibility of DM and CP increased significantly in electron beam-irradiated sorghum grains at doses higher than 15 kGy compared to raw cockerels. This reduction can be due to the presence of tannins and phytate in raw sorghum. Siddhuraju et al. (2002) showed that because of the large size of tannins, it may exert steric effects and prevent enzyme access to the proteins. In contrast with the results of the present study, Shawrang et al. (2013) reported that the protein digestibility of barley increased by increasing electron beam irradiation dose of it. Chamani et al. (2009) fed gamma-irradiated (15–45 kGy) canola meal to the broiler breeders and showed an increase in apparent digestibility of amino acids with increasing doses of irradiation. Glucosinolate levels also decreased by 58% in gamma-irradiated canola meal at 45 kGy. Bahraini et al. (2017) reported gamma-ray irradiation at a dose of 30 kGy, and electron beam irradiation at a dose of 10 kGy in cottonseed meal significantly increased the apparent digestibility of protein compared to raw in Leghorn cockerels.

### Histomorphometry

Intestinal mucosa status and their microscopic structure can be good indicators of the response to active substances in feeds in...
the intestinal tract. Changes in the small intestinal morphology of broilers depend on age, diet and gut microflora (VanLeeuwen et al. 2004). The histology of the intestinal mucosa is indicative of health. A shorter villus and a larger crypt can lead to poor nutrient absorption, increased secretion in the gastrointestinal tract, diarrhoea, reduced disease resistance and low overall performance (Masouri et al. 2017). The epithelial cells of the villi originate in the crypt and a large crypt indicates fast tissue turnover and high demand for new tissues. Any additional tissue turnover will increase nutrient requirements for maintenance and will therefore lower the feed efficiency of the animal (Parsaie et al. 2007).

The length of the villus is related to the absorption capacity of the enterocytes. The presence of short villi decreases the surface area for nutrient absorption. A higher ratio of villus height to crypt depth would indicate higher absorptive function (Xu et al. 2003). In the present experiment, villus height, villus width, crypt depth, crypt width, and ratio of villus height to crypt depth of the jejunum and ileum were not affected by the experimental treatments. Iji et al. (2001) found that xylanase supplementation of a wheat-based diet had no effect on villus height and crypt depth in the duodenum, jejunum and ileum of broilers. Also, Parsaie et al. (2007) reported that xylanase supplementation of a wheat-based diet had no effect on villus height and villus width in the jejunum and crypt depth in the duodenum of broilers. The jejunal villus height was not affected by xylanase at 7 and 21 days of age but the jejunal crypt depth was decreased only at 7 days of age in broilers fed with a wheat-based diet (Yang et al. 2008).

In contrast to the results of this study, the small intestine epithelium of barley-fed birds indicated morphological changes in the jejunum compared to birds fed on a corn diet (shortening, thickening and atrophy of the villi) (Viveros et al. 1994). However, the addition of β-glucanase counteracted these effects (Viveros et al. 1994). Rebole et al. (2010) also observed that the addition of xylanase and β-glucanase to wheat and barley-based diet resulted in a decrease in crypt depth and an increase in villus height to crypt depth ratio in the jejunum. Goblet cells are responsible for the secretion of mucin that is used for the mucinous lining of the intestinal epithelium (Schneeman 1982). Thus, reduced goblet cell numbers may be expected to lower mucin production and endogenous protein losses. Goblet cell numbers of epithelial and crypt depth were not affected by the experimental treatments in the jejunum and ileum in the present study. However, the inclusion of barley in the diet (25%, 50%) resulted in numerically increased goblet cell numbers and radiation tended to decrease these cells. In consistent with the results of the present study, Wu et al. (2004) observed that goblet cell numbers in duodenum and ileum were not affected by the addition of xylanase to wheat-based diet in broilers. In contrast, Viveros et al. (1994) reported that goblet cell numbers in the jejunum of broilers on barley-based diet increased compared with those on a maize-soy diet. However, the addition of β-glucanase to barley-based diet reduced goblet cell numbers. Thinner intestinal epitheliums enhance nutrient absorption and reduce the metabolic demands of the gastrointestinal system (Visek 1978). Different levels of xylanase supplementation had no effects on epithelial thickness and intestinal muscle thickness in the duodenum, jejunum and ileum of broilers on wheat-based diet (Luo et al. 2009). Also, xylanase supplementation had no effects on epithelial thickness in the duodenum and ileum of broilers on wheat-based diet (Wu et al. 2004). The thickness of the muscle layer in the jejunum was not affected by the addition of xylanase and β-glucanase on barley-based diet in broilers (Shakouri et al. 2009).

**Conclusion**

The present study revealed that up to 25% of barley can be used in the substitution of corn in broiler diets without any adverse effect under the condition of this study. In addition, results indicate that irradiated barley can improve FI, BWG and FCR compare to the raw barley at the level of 50% of the diet, while performance parameters are decreased, in comparison to the control diet. The data suggest that radiation is an effective processing method for improving performance and decreasing viscosity of broiler chickens when using high levels of barley in the diet.

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**Disclosure statement**

No potential conflict of interest was reported by the author(s).

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