Research Article

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Changes in cell wall compositions and degradation kinetics of electron beam-irradiated sugarcane bagasse

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Abstract: Electron beam irradiation of sugarcane bagasse at doses of 250 and 500 kGy could change its cell wall composition and ruminal fiber degradation characteristics by breaking off the lignocellulosic bonds. Nylon bags of untreated or electron beam-irradiated bagasse were suspended in the rumen of 3 fistulated rams for up to 72 h, and the resulting data were fitted to a nonlinear degradation model to calculate the degradation parameters of dry matter (DM) and neutral detergent fiber (NDF). Irradiation had no effect on crude protein, ether extract, and ash, but resulted in a linear decrease of the cell wall contents. An increasing electron beam irradiation dose linearly increased the water soluble fraction, degradable fraction, degradation rate, and effective degradability of the DM and NDF ($P < 0.001$ for all). At doses of 250 and 500 kGy, the effective degradability of the NDF at a ruminal passage rate of 0.05/h increased by 11% and 20%, respectively, compared to the untreated sample. In conclusion, electron beam irradiation can be used to improve the nutritive value of roughages in ruminant nutrition.

Key words: Electron beam irradiation, fiber, ruminal degradation, sugarcane bagasse

Introduction

Sugarcane bagasse, the residue after rind removal, is a highly lignified by-product of the sugar industry. In some countries, and in Khuzestan Province, Iran, the treated form of this by-product is a major source of biomass that can be fed to ruminants. Physical and chemical treatments (grinding, steaming, mineral acids, sodium hydroxide, and ammonia) have been used to break down lignocellulose structure and improve its industrial properties (1-3) and nutritional value (4,5). Although these processing methods have benefits, poisonous substances for ruminal microbes (such as furfurans) and hazardous chemicals for animals and the environment may be produced during physical processing.

Ionizing irradiation, a process in which material has been exposed to gamma rays or an electron beam, has been recognized as a reliable and safe method for improving the nutritive value of foods (6) and feeds (7). The effects of gamma irradiation on the quality of feeds have been evaluated. It has a positive effect on the nutritive value and ruminal degradability of agriculture residue (8) and oilseed meals (9,10). Recently, it was reported that electron beam irradiation could enhance cellulose hydrolysis in the wood and paper industry (11). However, information

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about the effect of electron beam irradiation on the nutritive value and ruminal fiber degradability of roughages is limited. Therefore, the objective of this study was to characterize the response of sugarcane bagasse to electron beam irradiation, in terms of changes in cell wall composition and degradation kinetics.

Materials and methods

Sample preparation and irradiation treatments

Bagasse was obtained from the Hafttapeh sugar refinery in Khuzestan Province, Iran, and dried at 40 °C for 7 days. After thorough hand-mixing, the roughage was divided into 2 batches to form duplicate sources for electron beam irradiation. The samples were packed in nylon bags (30 cm × 40 cm × 5 cm, 0.5 mm in thickness) and exposed to electron beam irradiation (Rhodotron TT200 accelerator, IBA Co., Belgium) at the Yazd Radiation Processing Center (AEOI, Yazd Center, Iran) at doses of 250 and 500 kGy at room temperature. Each sample was placed in a metal tray and passed through the accelerator at a rate of 77 cm/min. At a setting of 10 MeV and a current flux of 2.0 mA, 1 passage resulted in an exposure of 28.5 kGy. Multiple passages (9 and 18 passages) were used to obtain 250 and 500 kGy. The dose rate was determined using cellulose triacetate films (12). Uncertainty and Dmax/Dmin were about 3% and 1.2, respectively. Similarly packed samples without irradiation served as the control.

Ruminal degradability

For the in situ experiments, 3 castrated rams, with an average live weight of 65 kg and fitted with rumen fistulas, were used. Nylon bags (7 cm × 14 cm) with a pore size of 45 µm were filled with approximately 3 g of the samples ground to pass a 3-mm screen, according to the method of Ørskov and McDonald (13). Duplicate bags filled with untreated or irradiated sugarcane bagasse were incubated in the rumen for periods of 0, 4, 8, 12, 16, 24, 48, and 72 h. Two series of incubations (96 samples consisting of 4 replicates × 8 incubation periods × 3 sheep) were completed for each feed and sheep. In each series, all of the bags were simultaneously placed in the rumen just before the animals were offered their first meal in the morning, at 0730 hours. After retrieval from the rumen, the bags were washed with tap water and stored at –20 °C. After thawing, the bags were washed 3 times for 5 min in a turbine washing machine. The same procedure was applied to 2 series of 2 bags to obtain the 0-h value. The residues were dried and analyzed for dry matter (DM) and neutral detergent fiber (NDF) to establish the degradation kinetics of the sugarcane bagasse.

Chemical analyses

The moisture content was determined from the mass of samples before and after they were stored overnight in an oven at 105 °C (method 925.09; 14). Nitrogen was determined using a Dosimat-776 Metrohm apparatus (Metrohm Co., Switzerland) according to AOAC procedures (method 984.13; 14). The instrument was calibrated each time with ammonium nitrate as a nitrogen standard. The fat content was determined with a solvent extractor (Behr Labor-Technik, Germany) equipped with 6 Soxhlet posts. The ether extract was determined according to method 920.39 (14). The ash was determined by burning duplicate 2-g samples at 540 °C for 3 h in a muffle furnace (method 942.05; 14). The NDF and acid detergent fiber (ADF) were analyzed according to the method of Van Soest et al. (15), using an automatic fiber analyzer (Velp Scientifica, Italy). Sodium sulfite was omitted from the neutral detergent solution.

Statistical analyses

Disappearances (P) of DM or NDF (including 0-h values) were fitted for each sheep to the exponential model of Ørskov and McDonald (13) as:

$$P = a + b\,(1 - e^{-ct}).$$

In this model, the constants a and b represent, respectively, the soluble fraction and the nonsoluble but degradable component, which disappears at a constant fractional rate, c, per unit time. The effective degradability (ED) was calculated using ED = a + bc / (c + k), and estimated outflow rates (k) of 0.02/h, 0.05/h, and 0.08/h.

Data were analyzed by the general linear models procedure of SAS (16) using a linear model, as follows:

$$Y_{ijk} = \mu + T_i + B_j + e_{ijk},$$

where Y_{ijk} is the dependent variable, μ is the overall mean, T_i is the irradiation effect, B_j is the animal effect, and e_{ijk} is the residual error, assumed normally and independently distributed. Differences among the treatments were separated using polynomial contrasts to determine linear and quadratic responses (17).

Results

Effects on chemical composition

The chemical composition of sugarcane bagasse is shown in Table 1. Electron beam irradiation had no effect on crude protein, ether extract, and ash. Irradiation at doses of 250 and 500 kGy decreased ($P < 0.05$) the NDF content by 5% and 12% and the ADF content by 4% and 10%, respectively.

Effects on DM and NDF degradability

The ruminal degradation characteristics of the DM and NDF of the untreated and irradiated sugarcane bagasse are shown in Table 2. An increasing electron beam irradiation dose increased the soluble fraction (a), degradable fraction (b), degradation rate (c), and effective degradability of DM (linear effect, $P < 0.001$).

An increasing electron beam irradiation dose increased linearly ($P < 0.001$) the soluble fraction (a), degradable fraction (b), degradation rate (c), and effective degradability of the NDF (Table 2). At doses of 250 and 500 kGy, the effective degradability of the NDF at a ruminal passage rate of 0.05/h increased by 11% and 20%, respectively.

Discussion

The fiber content of the sugarcane bagasse decreased as the irradiation dose increased. Flachowsky et al. (18) found that the NDF and ADF contents of wood by-products irradiated with increasing doses of ionizing rays decreased over the range of 100-2000 kGy. The trends of our results are in agreement with those of Gralak et al. (19), who reported that γ-irradiation of wheat and triticale straws significantly reduced the levels of NDF and ADF proportionally to the dose. Similarly, Al-Masri and Zarkawi (8) reported that γ-irradiation significantly decreased the values of NDF and ADF in agricultural by-products. Sandev and Karaivanov (20) also reported that decreases in the fiber content of alfalfa hay, grain straw, corn cobs, and wheat bran due to depolymerization and delignification were directly proportional to the increasing dose of radiation. Banchorndhevakul (21) concluded that the decrease of NDF and ADF in agricultural residues by irradiation treatment could be the cause of the degradation of cellulose and hemicellulose into soluble materials. Takács et al. (7) found that under beam irradiation, cell wall constituents undergo degradation, which is due to the breaking off the glucosidal bond and modification in their structures. Modification may be due to several factors that finally lead to the opening of the anhydroglucose ring.

Similar ruminal degradabilities of DM and NDF were obtained by Gralak et al. (19) in wheat and triticale straws. In their study, irradiation raised the potential rumen degradability and effective degradability of the DM of both straws. Moreover, Leonhardt et al. (22) showed that the DM digestibility of wheat, oat, barley, and rye straws can increase by up to 80% by treatment with γ-rays or accelerated electrons.

Table 1. Chemical composition of the untreated and electron beam-irradiated sugarcane bagasse (g/kg DM) (n = 3).

	Dry matter	Crude protein	Ether extract	Ash	NDF	ADF
Control	920	18	23	149	753^{a}	667^{a}
EB-250 kGy	923	19	22	146	713^{b}	642^{b}
EB-500 kGy	922	18	22	145	660^{c}	594^{c}
SEM	5.7	1.3	1.7	5.9	21.6	23.1

SEM, standard error of the mean; EB, electron beam irradiation.
Means in the same column with different superscripts differ ($P < 0.05$).

Table 2. Ruminal degradation characteristics of the dry matter and the neutral detergent degradability of the untreated and electron beam-irradiated sugarcane bagasse.

Characteristics	Control	Electron beam-irradiated		SEM	Contrasts	
		250 kGy	500 kGy		L	Q
Dry matter						
a (g/kg)	149	165	195	10.4	***	NS
b (g/kg)	247	274	299	14.5	***	NS
c (/h)	0.032	0.034	0.037	0.0045	**	*
Effective rumen degradation of the dry matter (g/kg)						
0.02/h	301	337	389	17.1	***	NS
0.05/h	245	275	322	16.2	***	NS
0.08/h	219	247	289	14.6	***	NS
Neutral detergent fiber						
a (g/kg)	390	432	509	11.5	***	NS
b (g/kg)	316	351	382	16.2	***	NS
c (/h)	0.049	0.053	0.057	0.0059	**	*
Effective rumen degradation of the neutral detergent fiber (g/kg)						
0.02/h	614	686	791	18.3	***	NS
0.05/h	546	612	712	17.6	***	NS
0.08/h	510	571	667	15.2	***	NS

SEM, standard error of the mean; L, linear effect; Q, quadratic effect. Significance: NS, not significant; $^*P < 0.05$; $^{**}P < 0.01$; $^{***}P < 0.001$. *a*, the water-soluble fraction; *b*, the potentially degradable fraction; *c*, the rate of degradation.

Flachowsky et al. (18) also showed that the DM disappearance of wood by-product in the rumen increased with an increasing irradiation dose. These were associated with the apparent decrease in particle size and increased dustiness of the irradiated material. Therefore, it is likely that part of the increased DM disappearance during in situ incubation maybe due to the loss of fine particles from the artificial nylon bags rather than solubilization per se. A reduction in the particle size of the bagasse following the steam treatment and the implications for in situ rumen DM disappearance measurement was also commented on by Castro and Machado (4).

The observed improvement in the effective degradability of the fiber with irradiation is likely to be due to a combination of the decreased particle size increasing the surface area exposed for microbial attachment, a possible increase in solubility, the alteration in the chemical composition (especially the reduction in the NDF content and corresponding increase in sugar content), random depolymerization and decomposition of the cellulose and hemicellulose, and serious weakening of the cellulosic fiber (23,24).

A reduction in the crystallinity of the cellulose (25,26) is another reason for the increasing fiber hydrolysis of the irradiated bagasse in the rumen. In a study by Alberti et al. (27), the reduction in the crystallinity of the cellulose was most evident at doses above 100 kGy. They found that the crystallinity index of microcrystalline cellulose, flax, cotton, and viscose was reduced by up to 12% at a dose of 200 kGy.

In addition, the link of lignin with other compounds in the cell wall is broken by irradiation (28). Lignin is linked to both hemicellulose and cellulose, forming a physical seal around the latter 2 compounds that is an impenetrable barrier preventing the penetration of solutions and enzymes (29). Hence, irradiation treatment has the potential to increase the nutritive value of sugarcane bagasse for ruminants.

The present study provides evidence that electron beam irradiation enhances the nutritive value of sugarcane bagasse for ruminants. The data suggest that electron beam irradiation of up to 500 kGy can be used to improve the DM and fiber degradability of sugarcane bagasse in the rumen. Further extensive research on the processing of agricultural residues by irradiation is required.

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