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Review

Effect of Cereals and Legumes Processing on In Situ Rumen Protein Degradability: A Review

Piera Iommelli [1], Fabio Zicarelli [1], Nadia Musco [1,*], Fiorella Sarubbi [2], Micaela Grossi [1], Daria Lotito [1], Pietro Lombardi [1], Federico Infascelli [1] and Raffaella Tudisco [1]

[1] Department of Veterinary Medicine and Animal Production, University of Naples Federico II, 80137 Napoli, Italy; piera.iommelli@unina.it (P.I.); fabiozicarelli@gmail.com (F.Z.); micaelagrossi@tiscali.it (M.G.); d.lotito97@gmail.com (D.L.); pietro.lombardi@unina.it (P.L.); federico.infascelli@unina.it (F.I.); tudisco@unina.it (R.T.)

[2] Institute for the Animal Production System Mediterranean Environment, National Research Council, 80055 Portici, Italy; fiorella.sarubbi@cnr.it

* Correspondence: nadia.musco@unina.it

Abstract: The determination of the ruminal degradability rate of feeds, mainly starch and crude protein, is one of the most common methods to evaluate the nutritional value of ruminant feed. The protein requirements for ruminants are met from microbial protein and undegraded dietary protein digested in the small intestine. In order to reach maximum productivity, high-quality proteins are needed, and the requirement for undegraded dietary protein increases with the performance of the animal. This protein can be supplied by reducing the ruminal degradation to increase the amount of protein digested post-rumen, but the form in which a feed is administered influences degradability, and grain processing, especially, is a common practice to improve feed efficiency. Despite these aspects, studies on the effects of feed processing methods on protein degradability are limited, even though more and more ruminants are fed with processed feeds. For these reasons, this review investigated the protein degradability of different processed cereals and legumes in ruminants based on the analysis of available literature in order to take stock of the state of the art on this topic. Results showed that: First, the majority of the papers are focused on the energy aspects mainly due to carbohydrate-rich feeds; second, the majority of the studies in the literature are quite old, probably because the changes occurred in the animal testing legislation that made in vivo studies more and more difficult in the last 20 years; third, as a consequence, the few data available in recent years concern in vitro experiments; fourth, we found a high variability of the experimental conditions thus affecting protein degradability and making it quite difficult to compare the different results.

Keywords: rumen protein degradability; cereals; legumes; feed processing

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1. Introduction

Feeds ingested by ruminant animals undergo microbial degradation in the rumen. The end-products of this process, such as ammonia, amino acids, peptides, and volatile fatty acids, are utilized for the synthesis of the microbial biomass. The feed escaping rumen degradation, endogenous protein, and the microbial biomass enter the duodenum and are used to supply energy and protein for the ruminant tissues. Therefore, the nutritional value of a feed depends on its nutrient content, the extent of rumen degradation [1], and on the digestibility of undegraded feed components, especially protein, passing to the small intestine [2]. Ruminants require a dietary supply of protein, sugars, starch, and non-structural polysaccharides for the maintenance and synthesis of the microbial biomass, which is the major protein source needed for their growth and development [3]. The measurement of the rumen carbohydrates and protein degradability provides the necessary information to define the nutritional value of feeds. Several pieces of research all over the world have been performed on this topic, with the aim of obtaining information on individual feeds, the methodological aspects, and the rationing factors that can influence the degradation process.

The most used method, recognized as a reference for the evaluation of rumen degradability, is that proposed by Mehrez and Ørskov [4] and subsequently defined by Ørskov and McDonald [5], which provides *in situ* measurements using a nylon bag technique. According to these authors, degradability is described as a process regulated by first-order kinetics that characterizes the feed protein based on three typical parameters, a soluble and immediately degradable portion (a), an insoluble but degradable portion over time (b) subject to a degradation rate (c).

Such parameters, combined with the rumen transit rate (k, reciprocal of the average retention time), allow an estimate of the amount of feed that is degraded in the rumen, thus defining the effective degradability (ED).

Several factors can modify the rumen degradability of feeds [6], such as animal species [7], diet forage/concentrate ratio [8], dietary supplementation [9], and cultivars [10,11]; the most important are the type and quantity of feed, physical fitness of the feeds to be tested and the technological treatments they underwent, the porosity of the bags and the quantity of sample incubated per unit of the surface of the bags [12]. Cereals and legumes processing represents a large and important part of the feed production chain. Novel feed processing techniques have been introduced to improve nutritional quality, improve or modify physicochemical properties, and increase production and feed efficiency [13]. The determination of the ruminal degradability rate of feeds, especially of starch and crude protein (CP), has therefore become one of the most common methods to evaluate the nutritional value of ruminant feed [2,14]. The protein evaluation systems assume that protein requirements for ruminants are met from microbial protein, and undegraded dietary protein (UDP) digested in the small intestine. To achieve maximum productivity of high-producing or rapidly growing ruminants may require better quality protein than provided by rumen microorganisms [15,16]. The requirement of UDP increases with the performance of the animal. This protein can be supplied by reducing the ruminal degradation and thus increasing the amount of protein digested post-rumen [17]. The form in which a feed is administered will influence degradability, and grain processing is a common practice to improve feed efficiency [18]. Despite these aspects, studies on the effects of feed processing methods on protein degradability are limited, even though more and more ruminants are fed with processed feeds [19]. This review investigated the protein degradability of different processed cereals and legumes in ruminants based on the analysis of available literature.

2. Processing Methods

2.1. Grinding

Grinding is an important intermediate step in the post-production of grains. The goal of the grinding process is to remove the skin and sometimes the layers of bran and to produce an edible portion free of impurities in the form of powder with variable grain size. The principle of methods is applying force to the ingredient so that the bonds between various physical structures in feed materials are broken [20]. Grinding is a major function of feed manufacturing and is by far the most common method of feed processing. The field of feed manufacturing results in a substantial reduction in particle size and increases the surface exposed to the enzymatic action, favoring the rumen digestibility and degradability of the feed [21]. In order to operate at maximum efficiency, the isolated grains must be divided into different sizes by using the differences in the density and weight of the grain fractions [22]. Most graders separate grains based on width, as this is the most accurate way to isolate grains with similar weights. Width separation uses a series of perforated cylinders. The grinding of ingredients generally improves feed digestibility, acceptability, and mixing properties, increases the bulk density of some ingredients, and facilitates further processes such as extrusion and pelleting. Starch gelatinization is the rupture of starch granules, thus allowing the linear and cyclic molecules to hydrate and become sticky in the presence of water [23].

2.2. Dehulling

The hull is highly indigestible, so it must be removed to obtain the maximum nutritional benefits. In modern mills, the first step of dehulling is a rotating disc that has numerous fins running from the center of the disc to the exterior [22]. The grains fall into the center of this rotating disc and are thrown into a series of impact rings on the wall of the dehuller, which causes the groat to be separated from the hull. This process continues until approximately 85% of the grains are dehulled, as too much dehulling will cause the groats to break, which decreases yield. The efficiency of dehulling is dependent on grain weight and moisture content and the throughput of the dehulling machine, which is why the grains are graded into similar weights before dehulling. Rotation speed of the disc should be adjusted to increase the efficiency of dehulling without causing groat breakage. Moisture strongly impacts dehulling efficiency, with high moisture decreasing dehulling and low moisture increasing groat-breakage rates: moisture content of 12–13% is ideal. Overall, dehulling produces a mixture of hulls, groats, unhulled grains, and broken groats that must be further separated. Following dehulling, the grain stream is subjected to aspiration to remove the hulls and fines (small particles formed by breakage). The mostly dehulled grains are then passed through a cylinder with a rough interior to scour off any adhering hulls, followed by a second aspiration. The grains stream is then passed through a table or paddy separator, which separates groats from the unhulled oats based on differences in density and smoothness of the particles. The unhulled grains are then returned to the dehuller. For end products requiring high levels of dehulled grain removal (such as cut oats), several table separators are used in series.

2.3. Flaking

The flaking is a mechanic-hydrotermic process that causes the gelatinizing of the starch, increasing the speed of enzymatic hydrolysis of the polysaccharides, thus favoring the rumen microbial activities.

The final product is characterized by a greater surface for the microbial attack, more than the seed, therefore quickly usable from the rumen bacteria. Flake grains are produced simply by flattening either whole or steel-cut groats with two rotating rollers [22]. However, the groats exiting kiln drying are very susceptible to crushing into powder because of their low moisture content. To avoid this, before rolling, the groats are exposed to steam during agitation, with the goal of adding 3–5% moisture. In an optimal process, moisture equilibration should be achieved with the smallest possible temperature increase over the shortest time to minimize nutrient degradation. The thickness of the flakes can vary from 0.7–1.2 to 0.4 mm for quick-cooking oats. After rolling, the flakes are passed through an air stream to decrease both their temperature and moisture content, returning the flakes to 10–12% water. Finally, the flakes pass over a shaking shifter to break apart clumps of flakes and remove fines and small flakes [22]. The combination of steam followed by drying can cause the starch in the oat flakes to become partially pre-gelatinized. Pre-gelatinized starch will absorb water more rapidly than unprocessed starch, thus decreasing the cooking time [24].

2.4. Crushing

During the crushing process, the grains are passed through rotating rollers, characterized by a groove on the surface. The grain that passes between the rollers is sheared and compressed to be broken. The two rollers can run at different speeds, depending on the function. The greater the speed differential, the greater the shear force applied to the grain. High oil content seeds (e.g., soybeans and rapeseed) and high moisture kernels are generally processed more easily with a higher differential speed, as shearing promotes self-cleaning between the rollers. Roller mills produce cubic-shaped particles of varying sizes. Dry rolling produces a less dusty product with a more uniform particle size than grinding, which crushes the grain on impact. Roller mills generally work well with common grains, including corn, sorghum, or wheat, depending on the moisture content. However, they do not process fibrous materials efficiently and are generally not used for the fine processing of oats, barley, and other grains or fibrous ingredients. A roller mill with variable speed rollers can generally handle high moisture grain more easily than a hammer mill, depending on the desired particle size. Anyway, with more moisture, the grain endosperm becomes elastic and absorbs impact—or shattering energy—by deforming rather than shattering.

2.5. Roasting

Among the minimal processes, roasting is a traditional and rapid feed processing method that uses dry heat for a shorter time. In this short-term high-temperature treatment, heat energy is transferred by conduction. During roasting, the far infrared rays produced by the sand penetrate the grains and help break down the starch, proteins, and fats. This helps to improve digestibility by converting micro and macronutrients into a more digestible form through rapid gelatinization of the starch, simultaneous drying of gelatinized starch, and denaturation of proteins. The result is a higher puff index, a greater crunchiness and volume, and a better texture. It also improves color, aroma, flavor, shelf life and reduces bulk density and antinutrients found in grains. Roasting depends on temperature, temperature profile, and time. Feeds are usually roasted at a variable temperature of 150–350 °C. The roasting process affects the nutritional, antioxidant, sensory, and functional properties of the products.

2.6. Pelleting

Steam pelletization can affect starch availability by altering the properties of starch or its interaction with other components in the feed [25,26]. The impact of steam pelletization on feed properties and digestibility can vary depending on the nature of the feed material and the specific operating conditions. Moisture is added to the preconditioning prior to the start of the pelletizing process to increase the quality of the pellet (shelf life) and the production capacity of the feed mill. Moisture can be added in two forms: water (liquid) and vapor (gas). Vapor quality is defined as the fraction of vapor present within the vapor phase and is calculated as the mass of vapor divided by the mass of vapor and water [27]. Moisture from the vapor can form a cohesive bridge between feed particles [28], and this can improve the durability of the pellet [29]. Wood [30] reported that the water from the condensation vapor is superior to the addition of liquid water due to the reduction and durability of the pellets. This is because the additional heat that results from adding steam can change the physicochemical properties of the feed components, such as starch gelatinization, to improve the bonding between particles.

2.7. Extrusion

Feed expansion is one of the most popular new feed processing technologies developed in the last 20 years, mainly for the production of pet feed, aquatic feed, and other animal feed. Extruding (expansion) technology is a widely used technology in modern feed processing. Feed processed by extrusion technology has many advantages, such as starch gelatinization and degradation, protein denaturation, reducing anti-nutritional factors, increasing palatability, etc. The extrusion process consists of 3 stages:

First—material and screw, material and barrel, as well as the material inside, generate friction so that material is strongly extruded, stirred, and sheared, making the material further refined and homogeneous with the increasing pressure and temperature in the feed extruder machine chamber and the internal friction between the material and screw, material and barrel.

Second—with the increase in temperature, high pressure, and high shear force, the composition of materials has undergone complex physical and chemical changes.

Third—the paste material is ejected from the die hole, which produces instantaneous pressure difference, and the material is expanded, thus forming a loose, porous, and crisp extruded product.

Interestingly, heated extrusion has been shown to improve the functional properties of oat bran, leading to the extruded bran having more aggregates, higher gelatinization temperature, higher solubility, swelling capacity, increased apparent viscosity, and a decrease in the flow behavior index [31]. The latter two changes have been proposed to be beneficial, as they could contribute to a slower gut transit and the perceived 'fuller for longer' of satiety effect [32–34].

3. Data Analysis

Analyzing the literature on the "Scopus" search engine utilizing the keywords "protein rumen degradability" there are 1920 papers published from 1978 to 2022. However, only 17 papers have been taken into consideration for the drafting of this review as many of the studies were conducted only in vitro, and a high number of them analyzed diets or unconventional feedstuffs.

It is possible to observe that there are few data available regarding rumen degradability, especially in recent years, probably due to the problems deriving from the increasingly restrictive regulations on animal welfare.

In particular, as shown in the following tables, many of the experiments conducted do not report complete data, the chemical composition, reported in Table 1, is often overlooked, and in addition, many studies report a protein digestibility coefficient without reporting the parameters relating to the fractions and the degradability time. We focused our attention on the data from studies performed on some of the most used grains in ruminant feeding: barley, corn, oat, wheat, faba bean, and soybean.

Table 1. Chemical composition (g/kg DM) of cereal and legume grains (means ± standard deviation of examined literature).

	n. Samples	DM	CP	NDF
		Cereal Grains		
Barley ground	14	878 ± 4.62	118 ± 15.63	234 ± 18.68
Barley crushed	1	871 ± 0	128 ± 0	
Barley pelleted	1	920 ± 0	121 ± 0	
Corn ground	10	891 ± 1.2	102 ± 6.72	
Corn flaked	1	886 ± 0	80.0 ± 0	
Oats ground	2	903 ± 1.33	105 ± 5.68	
Oats roasted	1			
Oast dehulled	1			
Wheat ground	3	925 ± 4.13	136 ± 6.32	
Wheat pelleted	2	920 ± 1.89	130 ± 8.78	
		Legume		
Faba bean ground	3	902 ± 3.67	279 ± 8.90	
Faba bean crushed	1			
Soybean ground	4	912 ± 4.12	477 ± 15.68	249 ± 6.42
Soybean milled	1	888 ± 0	400 ± 0	
Soybean meal	4	900 ± 3.20	492 ± 20.06	289 ± 8.94
Soybean roasted	3	944 ± 2.51	358 ± 10.85	223 ± 7.56
Soybean roasted, milled	1	923 ± 0	374 ± 0	
Soybean flaked	4	917 ± 4.10	390 ± 7.58	
Soybean flaked, milled	1	925 ± 0	406 ± 0	
Soybean extruded	1	980 ± 0	395 ± 0	
Soybean extruded, milled	1	903 ± 0	397 ± 0	
Soybean electronbeamirradiated	1	909 ± 0	390 ± 0	164 ± 0

DM: dry matter; CP; crude protein; NDF: neutral detergent fiber.

4. Results and Discussion

Despite the high number of studies included in this review, they mainly analyzed cereals; thus, the majority of the papers were focused on the energy aspect mainly due to carbohydrates, and only a few researchers investigated protein degradability in such feeds. Furthermore, since the protein content of cereals is considered of low biological value [11], the nutritional importance of proteins in such feeds is low if compared to other sources. Further, the majority of the studies we found in the literature are quite old, probably because the changes occurred in the animal testing legislation, mainly due to animal welfare, that made in vivo studies more and more difficult in the last 20 years. Indeed, the few data available in recent years concern in vitro experiments, and, consequently, we did not consider it in this review.

Another interesting aspect of our analysis concerned the high variability of the experimental conditions in which the experiments were conducted, thus affecting protein degradability and making it quite difficult to compare the final results.

4.1. Barley

Barley grain (*Hordeum vulgare* L.) is characterized by a thick fibrous mantle, a high level of ß-glucans, and simply arranged starch granules. Compared to corn, barley has more protein, methionine, lysine, cysteine, and tryptophan. For ruminants, barley is the third most easily degradable cereal after oats and wheat. Barley can be used with excellent results in the diet of all ruminants, both for milk and for meat production. Table 2 shows the differences in protein degradability in bovine, buffalo, and goat species. When comparing different varieties of grain barley, the degradability is, on the whole, higher in bovine than in buffalo. As seen, differences were also reported in the same species, probably because of the processing methods. Concerning the influence of the processing method, the results reported in the bibliography appear to be controversial. Different authors [35,36] reported a positive effect of the pelletizing treatment in barley; in particular, they recorded a higher dietary intake and a higher degradability in vivo. This result could be due to the effect of pelletization on the soluble and slowly digestible fractions of the grain. On the contrary, Bertipaglia et al. [37] found no differences between pelleted and non-pelleted barley after 24 h of incubation. Similar results were reported by Krieg et al. [38] in cows by incubating barley for 24 h. Another factor that can influence this parameter is the method used to grind the grains Gimeno et al. [39]. These authors reported that the variation between the results concerning rumen degradability might be partly due to the particle size of the material. In the article published by Micek et al. [40], five winter cultivars and four spring barley cultivars were evaluated. These authors reported that, on average, the degradability was high for all cultivars, exceeding 81%. However, differences between cultivars can be more or less important and, as reported by McAllister et al. [41], structural components within the endosperm, rather than the protein matrix and properties of the starch granules themselves, are responsible for the differences in rumen digestion of barley. Thanks to its starch fermentation rate faster than corn, barley also provides a more synchronous release of energy and nitrogen (N), thus improving the assimilation of microbial nutrients. Consequently, feeding barley can reduce the need for protected protein sources [42]. Cereal blends offer advantages in feeding beef and dairy cattle [43]. This is due to their greater extent and fermentation speed than rumen starch [44,45]. Such blends can alleviate rumen acidosis that usually occurs by feeding highly fermentable grains, such as barley. The mixing of barley and corn prior to processing/flaking did not compromise the performance of the cattle herds [46]. In grazing Jersey cows, replacing 50% of corn with barley in concentrates increased milk production, suggesting positive associative effects of corn and barley [43]. More data on feeding combinations of different grains are needed before clear recommendations can be offered to the global ruminant industries. The addition of xylanase-based fibrolytic enzymes to high concentrate diets (e.g., 950 g of barley/kg dry matter—DM) improved feed efficiency with no effect on daily gain and feed intake [47]. Due to their inability to properly chew and break huskies, whole barley cannot be fed to large ruminants [48]. As a result, barley is commonly rolled, tempered, steamed, ground, toasted or pelleted [42]. While milling is the most common and preferred technique for processing barley for dairy cows in Iran [42,49], tempering, dry rolling, and steamrolling are common in North America, Australia, and Western Europe [50,51]. Tempering involves adding water for 24 h before rolling to increase the moisture content of the barley up to 180–200 g/kg. Tempering results in fewer fine particles than dry lamination [52], thus reducing the risk of rumen acidosis. As a result, the starch fermentation rate can decrease, reducing the risks associated with a greatly decreased rumen pH. As such, tempered barley, compared to dry rolled barley, improved milk yield by 5%, feed efficiency by 10% and apparent dry matter digestibility, neutral detergent fiber—NDF; detergent fiber acid -ADF; crude protein—CP; starch of 6, 15, 12, 10 and 4%, respectively [53].

Table 2. Protein degradability of raw and treated barley grains.

	a, %	b, %	c, %/h	ED, %	Species	Source
Barley ground	46.4	47.4	-	81.0	Bovine	Micek et al. [40]
Barley ground	44.3	50	-	84.4	Bovine	Micek et al. [40]
Barley ground	34.2	59.7	-	81.1	Bovine	Micek et al. [40]
Barley ground	39.1	56.6	-	75.7	Bovine	Micek et al. [40]
Barley ground	37.9	57	-	75.9	Bovine	Micek et al. [40]
Barley ground	41.4	53.4	-	84.6	Bovine	Micek et al. [40]
Barley ground	44.6	51.6	-	87.4	Bovine	Micek et al. [40]
Barley ground	38.8	57.1	-	82.2	Bovine	Micek et al. [40]
Barley ground	49	47.5	-	65.3	Bovine	Micek et al. [40]
Barley ground	12.6	84.9	11.2	67.9	Buffalo	Infascelli et al. [54]
Barley ground	-	-	-	68.9	Buffalo	ASPA [55]
Barley ground	54.8	29.1	0.13	75.6	Goats	Wang et al. [56]
Barley crushed	22.4	76.6	3.4	49.3	Buffalo	Infascelli et al. [54]
Barley ground	30.9	-	-	82.3	Bovine	Nedelkov [57]
Barley pelleted	23.8	-	-	79.2	Bovine	Nedelkov [57]

a: rapidly soluble fraction (%), b: potentially degradable fraction (%), c: degradation rates (%/h), ED: effective degradability, -: data not reported.

4.2. Corn

Corn is the most widely used energy source as a concentrate and as silage in ruminant feed; thus, few studies have investigated its protein degradability, but most of the literature focused on the degradability of dry matter. As depicted in Table 3, Infascelli et al. [54] reported higher protein degradability for flaked than raw corn grains in buffalo, mainly due to the increase in the potentially degradable fraction (b). The nutritive value of corn for ruminants is mainly determined by the starch content and rumen degradation. However, due to the high percentage in many diets, corn can also significantly contribute to the animal's protein intake, although the total CP content in corn is relatively low. As a result of many different corn farming programs, the variation of corn genotypes for livestock nutrition is steadily increasing. Differences can also be observed for CP degradation with rumen degradability values ranging from 28.9 to 52.6% for ground maize [58] according to genotype and treatments (ground, small or large cracked). Despite the genotype, a higher protein degradability was found for ground corn, mainly with small cracking. It is, therefore, necessary to investigate the variation in CP and starch degradation of a wide range of maize genotypes in the rumen and to develop simple, rapid, and accurate methods to predict these variations for use in plant breeding and livestock industry.

Both fast and slow fermentation of starch and CP in the rumen are associated with positive and negative effects on the physiological state of the animal. Thus, balancing diets with grains to facilitate high microbial protein synthesis in the rumen and to provide the optimum level of UDP and starch-bypass to the duodenum is the main focus in feeding ruminants, especially those reared for the consumption of dairy products.

Table 3. Protein degradability of raw and treated corn grains.

	a, %	b, %	c, %/h	ED, %	Species	Source
Corn ground	23.5	42.9	5.72	44.5	Buffalo	Infascelli et al. [54]
Corn ground	-	-	-	41.4	Buffalo	ASPA [55]
Corn ground	-	-	-	50.9	Bovine	ASPA [55]
Corn ground	24.5	36.7	4.00	40.8	Goats	Wang et al. [56]
Corn flaked	25.7	73.3	4.34	56.4	Buffalo	Infascelli et al. [54]
Corn ground	-	-	-	52.6	Bovine	Ramos et al. [58]
Corn ground	-	-	-	51.5	Bovine	Ramos et al. [58]
Corn ground	-	-	-	42.4	Bovine	Ramos et al. [58]
Corn ground	-	-	-	47.2	Bovine	Ramos et al. [58]
Corn ground	-	-	-	35.4	Bovine	Ramos et al. [58]
Corn ground	-	-	-	45.1	Bovine	Ramos et al. [58]
Corn cracked large	-	-	-	35.4	Bovine	Ramos et al. [58]
Corn cracked large	-	-	-	37.7	Bovine	Ramos et al. [58]
Corn cracked large	-	-	-	31.8	Bovine	Ramos et al. [58]
Corn cracked large	-	-	-	35.2	Bovine	Ramos et al. [58]
Corn cracked large	-	-	-	28.9	Bovine	Ramos et al. [58]
Corn cracked large	-	-	-	30.7	Bovine	Ramos et al. [58]
Corn cracked small	-	-	-	42.2	Bovine	Ramos et al. [58]
Corn cracked small	-	-	-	43.4	Bovine	Ramos et al. [58]
Corn cracked small	-	-	-	39.1	Bovine	Ramos et al. [58]
Corn cracked small	-	-	-	40.8	Bovine	Ramos et al. [58]
Corn cracked small	-	-	-	36	Bovine	Ramos et al. [58]
Corn cracked small	-	-	-	39.5	Bovine	Ramos et al. [58]

a: rapidly soluble fraction (%), b: potentially degradable fraction (%), c: degradation rates (%/h), ED: effective degradability, -: data not reported.

4.3. Oats

Among the cereals, oats have rather high concentrations of CP [59] and crude fat [60,61]. The oat shell (*Avena sativa* L.) constitutes from 28 to 32% of the grain (on a dry matter basis), and due to the presence of lignin–carbohydrate/phenolic–carbohydrate complexes, the shells have a very low degradability in the rumen [62]. Therefore, due to the low concentrations of CP and crude fat in the hull [63], husking could be a potential processing method to increase the CP and crude fat content in the oat grain. The synthesized microbial proteins are not sufficient to meet the protein needs in high-yielding dairy cows [64]. Therefore, the application of heat treatment (e.g., roasting) could be a possible way to reduce CP rumen degradation [65]. The husking of cereals is a practical tool to increase the digestible diet energy for dairy cows without altering the forage-concentrate ratio [66]. Table 4 shows oat protein degradability. The decortication determines modifications of protein content as well as their degradability in different animal species. After removing the hull, there were no alterations in the protein content, but the NDF content decreased, and the starch content increased. Previous studies have also shown that the hull of oats consists mainly of low digestible cell walls [60], and the fat and protein in the grain are mostly stored with the starch mass throughout the endosperm [67]. Therefore, decortication exposes the digestible semolina to rumen fermentation. Furthermore, roasting, a commonly used practice, lowered the rumen degradability of hulled grain, and a similar result was reported for barley by McNiven et al. [68]. Rumen protein degradation profiles for roasted oats fit more poorly with the exponential function used to describe degradation due to a very large increase in degradability from 0 to 2 h of incubation time. Anyway, roasted oats show lower effective degradability than raw grain [69]. The availability of fast-fermenting carbohydrates along with adequate degradable protein [70] increased microbial synthesis or microbial efficiency. Therefore, the greater microbial efficiency of protein synthesis due to decortication could be explained by greater availability of starch as an energy source for rumen microbes.

Table 4. Protein degradability of raw and treated oat grains.

	a, %	b, %	c, %/h	ED, %	Species	Source
Oat ground	76.9	15.4	4.4	89.9	Bovine	Panah et al. [69]
Oat ground	-	-	-	86.1	Bovine	ASPA [55]
Oat roasted	38.1	47.8	8.0	59.5	Bovine	Panah et al. [69]
Oat dehulled	75.1	19.8	5.8	92.2	Bovine	Panah et al. [69]
Oat dehulled	54.2	31.9	11.4	75.0	Buffalo	Infascelli et al. [54]
Oat dehulled, crushed	67.3	30.2	3.5	78.4	Buffalo	Infascelli et al. [54]
Oat dehulled, toasted	39.4	51.4	4.0	57.6	Bovine	Panah et al. [69]

a: rapidly soluble fraction (%), b: potentially degradable fraction (%), c: degradation rates (%/h), ED: effective degradability, -: data not reported.

4.4. Wheat

As shown in Table 5, the grinding increased the protein rumen degradability of wheat, as reported by Pan et al. [71]. The physical characteristics and nutritional content of wheat can vary greatly due to the different types of wheat: soft, hard, and growing conditions. Other factors affected this parameter as animal species—lower effective degradability in sheep and goats than in bovine and buffalo [55,56]—and wheat variety—soft wheat showed higher degradability than hard wheat in sheep while lower in buffalo and bovine. Differences in rumen degradation were also shown for wheat genotypes [72], suggesting that the genetic modification of cereal grains by breeding might have altered the nutritive value, leading to possible changes after the current feed table values were obtained. The mentioned studies also indicated variation between the different genotypes of a single-grain species, but available data are mostly based on studies that utilized small sample sizes. The manufacturing process is critical in determining the quality of the grain. Rumen microbes or host enzymes poorly digest whole grain because of the high resistance of the seed coat. Therefore, wheat grains must be processed in order to break up the seed coat. Optimal treatment can increase wheat digestibility from about 60% to over 90%. Indeed, accurate processing is fundamental for optimal results, over-processing itself may cause digestive disorders, and other factors such as stone hardness and uniformity can significantly affect the value of the grain [73].

Table 5. Protein degradability of raw and treated wheat grains.

	a, %	b, %	c, %/h	ED, %	Species	Source
Wheat raw	33.3	66.4	5.0	65.9	Goats	Wang et al. [56]
Wheat ground	11.1	82.0	2.7	78.4	Bovine	Benninghoff et al. [74]
Wheat pelleted	15.2	83.0	2.8	83.3	Bovine	Pan et al. [71]
Wheat pelleted	20.4	78.6	2.6	82.8	Bovine	Pan et al. [71]
Hard wheat ground	-	-	-	82.8	Buffalo	ASPA [55]
Hard wheat ground	-	-	-	55.1	Sheep	ASPA [55]
Soft wheat ground	-	-	-	77.0	Buffalo	ASPA [55]
Soft wheat ground	-	-	-	71.2	Bovine	ASPA [55]
Soft wheat ground	-	-	-	70.8	Sheep	ASPA [55]

a: rapidly soluble fraction (%), b: potentially degradable fraction (%), c: degradation rates (%/h), ED: effective degradability, -: data not reported.

4.5. Faba Bean

The disappearance of feed proteins is an essential factor in assessing the value of feed proteins according to the systems for evaluating ruminant feeds [75,76]. Furthermore, the benefit of any feed protein in ruminants depends on the digestion of proteins in the small intestine [68,77]. Concerning legume grains, variable values have been reported both for the protein content [78–80] and rumen degradability [78,80,81]. Several treatments have been used to reduce the protein degradability of legume grains. Heat treatment is one of the ways to reduce rumen degradation [82]. Faba beans have a good protein content, but their use in dairy cow feeding is limited since crude protein (CP) is fast degraded in the rumen resulting in an imbalance between feed breakdown and microbial protein synthesis. Therefore, these seeds are not suitable to be used in an unprocessed form in ruminant diets, causing an unnecessary Nitrogen-loss from the rumen [82]. Its efficacy is a function of time of exposure and temperature [83]; moreover, particle size and moisture during processing can also affect heating effects. Decreasing rumen protein degradation should result in increased intestinal availability of protein. The usefulness of heat treatment to improve protein bypass is widely accepted, but optimal heating conditions for each legume seed have not been determined. Importantly, overheating above may overprotect the protein in a way that it is neither fermented in the rumen nor digested in the small intestine; thus, the optimal temperature is critical [83]. The reduced degradability of proteins after heat treatment has been attributed to the formation of Maillard products from reducing sugars and amino acids and crosslinking between and within proteins [84]. Literature on the effects of pressurized steam treatments without additional shear forces on protein degradability of faba beans is limited to the results of Aguilera et al. [78]. Pressure roasting for three minutes at 132 °C further increased the protein undegradable fraction compared to autoclaving for 30 min at 120 °C. Similarly, Goelema et al. [21] found an increase in protein undegradable fraction after toasting faba bean grains. As reported by Infascelli et al. [54] in buffalo, crushing faba bean grains resulted in halving the protein's effective degradability, with a huge decrease in the rapidly soluble fraction (a) (Table 6). Instead, Hosking [85] found a high difference in protein degradation in raw and ground faba beans in sheep.

Table 6. Protein degradability of raw and treated faba bean grains.

	a, %	b, %	c %/h	ED, %	Species	Source
Faba bean ground	20.2	78.8	10.7	70.3	Buffalo	Infascelli et al. [54]
Faba bean ground	-	-	-	90.1	Buffalo	ASPA [55]
Faba bean ground	-	-	-	86.3	Sheep	ASPA [55]
Faba bean ground	33.1	66.2	8.6	85.7	Sheep	Aguilera et al. [78]
Faba bean	76.0	22.0	12.4	91.0	Sheep	Hosking [85]
Faba bean raw	35.0	64.0	11.0	79.0	Sheep	Hosking [85]
Faba bean ground	79.3	18.2	9.9	91.4	Buffalo	Infascelli et al. [54]
Faba bean ground	70.2	27.8	10.6	89.0	Sheep	Infascelli et al. [54]
Faba bean ground	64.2	34.0	7.4	82.7	Cattle	Vérité et al. [86]
Faba bean crushed	23.6	38.6	7.9	45.4	Buffalo	Infascelli et al. [54]

a: rapidly soluble fraction (%), b: potentially degradable fraction (%), c: degradation rates (%/h), ED: effective degradability, -: data not reported.

4.6. Soybean

Protein degradability of raw and treated soybean is reported in Table 7. Being the most used source of protein in ruminant feeding, several data are available in the literature if compared to other feeds. Whole soybean, which contains 40% of crude protein (CP) and 17% of fat, is an interesting ingredient as a source of protein and energy to be included in ruminant rations, but its protein is highly degradable in the rumen [87]. The soybean proteins are rich in lysine, methionine, valine, and isoleucine, constituting the first, second, and third amino acids limiting the production of milk. For many years, various physical and chemical methods have been studied to reduce the degradability of rumen proteins and increase the supply of amino acids to the intestine. Heat treatments appear to be more effective than chemical ones in protecting proteins from rumen degradation [17]. As reported by ASPA Commissions [55], the roasting treatment negatively affect the rumen protein degradability. Regardless of species, soybean meal all showed the highest digestibility, at levels ranging from 70 to 89.7% ED. It is interesting to underline the percentage of variability between soy flakes and soybean meal found in the buffalo species (52 vs. 89.7% ED). Extrusion [83,88] and roasting [89] caused an increased flow of total amino acids in the intestine by minimizing the activity of anti-nutritional factors [90]. Data reported in the literature regarding the effect of treatments on milk production in response to heat-treated soybeans were obtained from Schingoethe et al. [91] and Kim et al. [92], but other studies [93] showed no improvement. In addition, Nowak et al. [94] tested the effects of extrusion on soybeans at three temperatures (145, 155, and 165 °C) and found a significant reduction of the rapidly soluble fraction and of the protein's effective degradability with all the treatments. The reduction of the soluble fraction by heat treatment is in agreement with others [95]. Van Soest [96] reported that true rapidly soluble protein fractions denatured at low heat inputs and became intermediate or slow degradation fractions based on the level of heat inputs, while slowly degradable protein fractions responded to higher heat temperatures.

Various sources [76,97] state that 75–80% of the protein is degraded in the rumen, which limits its inclusion in diets for high-yield ruminants. Different temperature effects between 145 and 165 °C from 33 to 37%. The maximum heat input (165 °C extrusions) can penetrate the soybean, denature the proteins or form protein–carbohydrate complexes and may be more effective in altering and reducing the rumen disappearance of the nylon bag. According to Mir et al. [98], soy protein is less readily denatured by heat than rapeseed protein. Van Soest [96] suggested that an optimal heat input depends on many factors: moisture content, carbohydrate content and composition, protein content, and presence of sulfites, and therefore, optimal heat treatment parameters vary from one dietary protein to another. Aldrich et al. [99] observed when the extrusion temperature increased (104, 140, and 160 °C), the degradable fraction measured in in situ studies decreased (45.7, 36.7, and 30.1% ED, respectively). Oria et al. [100] found that soybean extrusion at a high temperature (160 °C) did not affect bacterial synthesis because it did not adversely affect the digestion of organic matter or the availability of N for rumen microbes. Heating the soy to such a temperature increased the digestion of amino acids in the small intestine (except methionine and glycine). Stern et al. [83] showed that heat treatment of soybeans by extrusion at 149 °C reduced the rumen degradability of proteins compared to untreated soybeans, while extrusion at a lower temperature (132 °C) was not advantageous for the reduction of the rumen degradability of proteins. Aldrich et al. [90] reported that soybean extrusion at 116, 138, and 160 °C reduced the disappearance of rumen DM after 16 h of incubation from 70 to 56.3%, respectively. Another effect that could improve rumen digestibility is the destruction of anti-nutritional factors. Indeed, as reported by Mir et al. [98], an increase in effective protein degradability was observed when soybeans were heated to 110 °C for two hours. Oria et al. [100] concluded that extruding soybeans at 116 or 138 °C might not be sufficient to protect soybean proteins from rumen degradation. Data from Faldet and Satter [101] demonstrated lower values for the degradation kinetics of roasted soybeans. Lykos and Varga [89] observed no significant effect of roasting broken soy at 144 °C and a significant decrease in the protein degradability of ground and roasted soybeans at the same temperature. Heating soy to an optimum temperature can protect against microbial degradation in the rumen and also make proteins in the intestine indigestible due to the Maillard reaction between sugars and proteins. Comparing the EDP data, high variability was observed between different species and whiting some species, and this is probably ascribable not only to the experimental condition but to the differences in the treatments that affect the protein degradability.

Table 7. Protein degradability of raw and treated soybean.

	a, %	b, %	c, %/h	ED, %	Species	Source
Soybean ground	38.2	7.00	30.3	57.5	Buffalo	Infascelli et al. [54]
Soybean ground	-	-	-	39.6	Bovine	ASPA [55]
Soybean ground	20.08	8.4	16.06	-	Bovine	Akbarian et al. [102]
Soybean raw	55.6	22.9	5.0	-	Goats	Wang et al. [56]
Soybean raw	57.4	3.9	50.9	-	Sheep	Canbolat et al. [103]
Soybean milled	-	-	-	85.6	Bovine	ASPA [55]
Soybean meal	16.5	83.5	7.2	67.3	Bovine	Nedelkov [57]
Soybean meal	-	-	-	72.9	Bovine	ASPA [55]
Soybean meal	63.2	6.4	57.4	-	Sheep	Canbolat et al. [103]
Soybean meal	-	-	-	70.0	Sheep	ASPA [55]
Soybean meal	-	-	-	89.7	Buffalo	ASPA [55]
Soybean roasted	-	-	-	30.4	Bovine	ASPA [55]
Soybean roasted	34.66	6.1	13.13	-	Bovine	Akbarian et al. [102]
Soybean roasted	47.4	4.8	46.4	-	Sheep	Canbolat et al. [103]
Soybean roasted, milled	-	-	-	72.4	Bovine	ASPA [55]
Soybean flaked	-	-	-	55.8	Bovine	ASPA [55]
Soybean flaked	-	-	-	66.7	Sheep	ASPA [55]
Soybean flaked	35.3	2.3	34.1	52.0	Buffalo	Infascelli et al. [54]
Soybean flaked	-	-	-	62.8	Buffalo	ASPA [55]
Soybean flaked, milled	-	-	-	69.4	Bovine	ASPA [55]
Soybean extruded	-	-	-	60.8	Sheep	ASPA [55]
Soybean extruded, milled	-	-	-	57.6	Bovine	ASPA [55]
Soybean electronbeamirradiated	25.26	13.3	19.69	-	Bovine	Akbarian et al. [102]

a: the rapidly soluble fraction (%), b: the potentially degradable fraction (%), c: degradation rates (%/h), EDP: effective degradability of protein, -: data not reported.

5. Conclusions

On the basis of the analyzed literature, feed processing highly affects the rumen degradability of proteins, at least when measured by the in situ method. Despite the fact that the considerable variation of results reported by different authors, also within similar animal species such as bovine, ovine, or buffalo, either physical or heat treatments or a combination of both seems to increase the protein rumen undegradable fraction, but further studies are needed in order to support this result. Nevertheless, particularly the extrusion process does not seem to affect bacterial synthesis since it does not decrease the digestion of organic matter. Finally, it has to be underlined that, either for cereals or legumes, the differences in the effective degradability are not always attributable to the same fraction (rapidly soluble or potentially degradable fraction) or to the degradation rate.

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