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Review article

Operational conditions and potential benefits of grains micronization for ruminant: A review

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ABSTRACT

As a nutritionist mission to increase energetic value of grains for animal especially in major grain importer countries, this study has focused on the micronization process and reviewed relevant literature with emphasis on operational conditions and potential benefits for ruminant. Despite simplicity of the system compartments, success in this thermal technology, requires optimization of six important sub-processes. However, because of variation in size and capacity of the different system used for micronization of various grains, no conclusive operational conditions were given which means for every micronizer-flaker machine and grain an optimization is compulsory. In livestock farms and feed plants which have access to natural gas, using micronization method for processing of the seeds has at least two nutritional benefits: it reduces ruminal starch fermentation rate that may also decrease acidosis risk and second, it increases small intestine digestion of starch and protein. Cost benefit studies and evaluation of micronization of grains on milk yield and composition still need further investigations.

1. Introduction

Today animal husbandry is more dependent on grains due to inadequate global availability of grasses and forage in one hand and economically unprofitable importing forage from other locations because of high transportation costs on the other hand (Mupondwa et al., 2012). Consequently, processing of the grains is more pronounced for obtaining maximum energetic value of them especially in countries which processing costs is economically reasonable.

Mechanical processing of the grains such as grinding or dry rolling do not guarantee efficient and healthy digestion of starch in the gastrointestinal tract specially in those containing resistance starch (e.g., corn grain) therefore, thermal treatment methods should be used to complete mechanical processes for maximizing nutrients utilization by ruminal microbes and host animal as well (Ebrahimi, 2020). Micronization is a fast (30–90 s) thermal treatment through using infrared radiation (IR) (Aboud et al., 2019) and has great potential of application in feed industry because of the simplicity of construction and operation (Fasina et al., 1999). However, as Loy and Lundy (2019) stated, compare to other thermal methods, a few recent studies have been conducted on the efficiency of this process.

Generally, heat treatment consists of starch gelatinization and protein denaturation which both may alter digestion site of starch

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Table 1
Companies active in the micronization industry.

Row	Name of company	Country of manufacturer	Since	Products	Consumers	Site address
1	I'Anson quality feeds	UK	1900	Micronized-flaked barley and maize	All animals (Ruminants, equine, poultry and pet)	https://www.ianson.co.uk
2	Jones Feed Mills Ltd	North America	1930	Micronized flaked soybean, corn, barley, wheat and oat	All Livestock and Pig	https://www.jfm.ca/specialty-feeds
3	Villamayor	Spain	1934	Micronized flour	Human	https://www.harinerasvillamayor.com/en/special-flour
4	Charnwood milling	UK	1960	Micronized linseed, soya bean, wheat meal and hampseed meal	Horse, Poultry, wild bird, Rabite, Fish and Ruminants	https://www.charnwoodmilling.co.uk/index.html
5	Virbac	Australia	1968	Micronized corn	Horse	https://au.virbac.com/health-care/horse-nutrition/complete-feed-for-horses
6	Micronizing Company (UK) Ltd	UK	1971	Micronized cereal flakes (barley and corn), soya, oil seed, linseed, pea and Cocoa bean	Human,Ruminants, Horse, Poultry, Pig and Pet	http://www.micronizing.com
7	Masham micronized feeds	UK	1974	Micronized-flaked barley and maize	All animals (Ruminants and Non-ruminants)	http://www.mmfeeds.com
8	Eobank	Australia	1978	Micronized flaked barley, maize, lupin, tic bean, beet,	Horse	https://www.robankfeeds.com.au
9	Micronized Food Products	UK	over 30 years ago	Micronized (flake, whole, meal) barley, wheat, maize, peas, beans, rice, linseed and soya	Human, Livestock, Pet, Poultry and wild Bird	https://www.micronizedfoodproducts.co.uk
10	InfraReady Products Limited, Saskatoon, SK	Canada	1994	Micronized grains, legumes and oil seeds	Human	http://www.infrareadyproducts.com
11	Capstone. HORSE FEED	South Africa	2004	Micronized maize and barley	Horse	https://www.capstonehorsefeed.com/micronization
12	Mi-Feed	Australia	n.f.	Concentrate mixture with micronized grains	All livestock classes	https://www.mi-feed.com.au
13	Morton nutrition	Australia	n.f.	Micronized lupin, maize, barley, naked oat,	Horse	https://mortonnutrition.com.au
14	Faravadaneh Ferdowsi Mashhad	Iran	2018	Concentrate mixture with micronized grains	All livestock classes	https://faravardaneh.com/

and protein in the ruminant. Severe heating may reduce nutrients digestibility of micronized grains (Shiau and Yang, 1982) therefore; standardized operational conditions are necessary for popularization of this method. Although steam-flaking of grains has been reviewed and major standard parameters have been summarized (Zinn et al., 2002) but for micronization there is a need for similar regularization. Thus, the first objective of this review was to achieve the mentioned situation. At present, manufacturing and use of this technology is well adopted in feed industry (Table 1) but most of commercialized micronizer machines are appointed in equine feed industry. It is because of the great animal responses in terms of health and performance and/or higher net margin in horse feed manufacturing compare to other species. The second objective of the present study was to explore prospective profits of micronization process for using it in ruminant feed industry too.

2. Fundamental of technology and operational conditions for various grains

Briefly, micronization is a process in which materials are exposed to IR, a region of the electromagnetic radiation spectrum where wavelengths range from about 700 nanometers to one millimeter. There are three spectral ranges of IR radiation as follow: near-IR (NIR: 0.75–1.4 μm), mid-IR radiation (MIR: >1.4–3 μm), and far-IR radiation (FIR: >3–100 μm). The wavelength ranges 2.5–100 μm and above 100 μm create changes in vibrational and rotational states of atoms and molecules, respectively (Krishnamurthy et al., 2008). In general, the substances absorb FIR energy most efficiently through the mechanism of changes in molecular vibrational state, which can lead to radiative heating. Throughout the mid and far IR spectral regions, water exhibits strong absorption and weak scattering of radiation. Penetration of IR in the substances results to vibration of water molecules in frequency of 8.8×10^7 to 1.7×10^8 H.Z. Water and organic compounds such as proteins, which are the main components of food, absorb FIR energy at wavelengths greater than 2.5 μm (Table 2). Absorption spectra of food components overlap with one another in the spectral regions (Aboud et al., 2019).

Penetration and reflection capacity of feedstuffs increase as the wavelength of the radiation decreases therefore, despite the NIR has a higher penetrating capability than the FIR, the heating effects are almost similar because of body reflection. The radiation absorption of foodstuffs depends mainly on the water content, thickness, and physicochemical nature of the product.

Energy coming out of an IR emitter is composed of different wavelengths. The wavelength at which the maximum radiation occurs

Table 2
Absorption wavelength of major food components.

	Absorption wavelengths
Amino acids, Polypeptides, Proteins and Nucleic acids	3–4 and 6–9 μm
Lipids	3–4, 6 and 9–10 μm
Sugar	3 and 7–10 μm
Water	2.7–3.3, 4.7, 6 and 15.3 μm

is determined by the temperature of the heater therefore, required temperature of IR heater needed for a desired spectral distribution can be estimated by following equation (Modest, 1993):

$$\lambda \max = \frac{2898}{T}$$

Where T is the source temperature in Kelvin (K) and λmax is the peak wavelength (Aboud et al., 2019).

Infrared radiant energy can be generated from any object or material at temperature above absolute zero. The quality and intensity of radiation are related to the temperature of the radiator by the Stefan–Boltzmann law, which states that the energy emitted by a radiator roughly depends on the fourth power of its absolute temperature. Color can be used as a good indicator of heat output and the best radiation heat transfer efficiency occurs when the heater glows red (Das and Das, 2011).

The emissivity of any surface or heater varies with temperature, wavelength, and direction of emitted radiation. Shorter-wavelength emitters such as tungsten filament operate at temperatures above 2000 °C, medium-wavelength emitters like quartz tube operate at around 700–1150 °C and long-wavelength emitters just as ceramic operate at below 800 °C. Emitters may use electricity to generate radiant heat however, large scale IR sources consumes a very high electricity which is not possible to be supplied within industrial sectors. In the gas fired IR emitters which are more popular, combustion of the air and fuel stream takes place on the ceramic burner surface, which raises the surface temperature to about 1000–1200 °C, develops power density (the amount of power per square meter that the emitter is capable of delivering per second) of about 120 kW/m^2 and emits radiation in the wavelength of 1.6–10 μm (Das and Das, 2011).

Diagrammatic structure of the micronizer machine was illustrated in many publications (Fasina et al., 1999; Cinq-Mars et al., 2003; Wiriyaumpaiwong et al., 2004; Syrovatka, 2014; Pathiratne et al., 2015) and it is not going to be re-drawn again. Simply, grains are heated while horizontally moving under infrared emitter using a vibratory conveyer. The vibration of the conveyor rotates the grains and thereby surface of grains exposed to same heat. Prior to heating, other necessary components such as screening portion, damping section and appropriate feeder must be installed. Flaking machine and further suitable cooling system are also key compartments of a micronization system that are generally less presented in the literature.

Some studies have used same protocol for different grains e.g. Douglas et al. (1991) micronized corn and for high or low tannin sorghum similar protocol was followed as: tap water was added in a horizontal mixture for increasing grains moisture content to 180 g/kg and further tempered overnight. The tempered grains further infrared heated to 150 °C for 3 min. Infrared radiated grains were immediately flaked and ground and included in the diet of broilers. Rosenfeld and Austbø (2009) added 80–100 g/kg water to barley, maize and wheat and then cooked them for 45 s at temperature of 112–115 °C which were later flaked for studying gastro-intestinal retention time in horse. They also micronized oat, barley and corn by moisturizing (level not expressed) and heating for 45 s at temperature of 100 °C. All grains were further flaked for studying small intestine and total tract digestibility in horse. McAllister and Sultana (2011) micronized whole wheat, barley and corn grains for 60 s to obtain internal kernel temperature of 100 °C. These authors used water to increase moisture content to 150 g/kg which was reduced to 70–90 g/kg post micronization. Serna-Saldivar (2016) simplified general operational conditions for micronizing of grains as final surface temperature and moisture to 135°C and below 70 g/kg, respectively without any specifications in the initial moisture of the substrate. He stated that appropriate time for micronizing must be controlled in such a way that the grain exits the micronizer before eversion or popping. The author also documented that flaking is a necessary post-micronizing process and standardizes an ideal density of 0.312 kg/L for micronized flaked grains. In the steam-flaking technology, it is well distinguished that steaming time is different for barley and is shorter than corn (Zinn et al., 2002) because barley contained rapidly fermentable starch and has smaller size than corn grain. Therefore using similar micronization time for grains that are different in nature by some researchers is not appropriate. Unklesbay et al. (1983) used this technology for baking of potato and tomato. Because of the large sizes of the substrates, the duration of radiant heating were 41 and 11 min and temperature of micronizer chamber also were 341 and 371℃ for potato and tomato, respectively. Therefore, cooking conditions seem to be substrate dependent.

Following is attempted to describe operational conditions for different substances, however in some manuscripts similar styles for expression of important parameters such as temperature have not been reported. For instance, sometimes temperature of chamber was expressed and in some other studies surface temperature of grains while exiting from micronizer was considered and even in few of them there was term" micronization temperature" without specifying exact place of temperature such as micronizer tunnel, inside or surface of the grains.

2.1. Maize grain

For the purpose of increasing storage time of maize flour, infrared radiant energy was used for micronizing maize grain in two studies. Žilić et al. (2010) micronized three types of corn grains (white, yellow and red corn) for duration of 40 s at 140ºC. Deepa and Umesh Hebbar (2017) described that maize grain with initial moisture of 110–120 g/kg were soaked in water for 4 h to achieve 250 g/kg final moisture and further was micronized by quartz Near Infra-Red (NIR) system at a chamber temperature of 200ºC for 4 min Vervuert et al. (2004) steamed corn grain and then micronized at relatively high temperature (300 °C) for 30 s without further flaking for a feeding trial on horse.

2.2. *Wheat grain*

Zarkadas and Wiseman (2002) examined micronization of wheat grain at chamber temperature of 200ºC for 10, 13 and 35 s without additional water enhancement. They also tested two steeping times of 2 and 12 h at durations of 10 and 35 s for the purpose of feeding of piglets. Final temperature of the seeds surface was ranged between 85 and 110ºC in their study. Niu et al. (2003) increased initial moisture of wheat to 200 g/kg by tempering for 2 h and then grains were micronized at three temperatures of 90, 105 and 120 °C.

2.3. *Barley grain*

A more operational conditions details were given by Fasina et al. (1999) where barley grains with initial moisture of 122 and 133 g/kg were micronized using laboratory-scale infrared system. Deionized water was added to whole barley 24 h before starting the process and stored in air-tight container to achieve 192–265 g/kg final moisture. The surface temperature of grains while exiting micronizer could be adjusted to desired temperature of 115, 135 and 150 °C when initial moisture was 133 g/kg (control), however three levels of temperature of the grains with 192 g/kg moisture at the time of micronizing were relatively lower (105, 115 and 135 °C). Because of the highest level of moisture in third treatment (265 g/kg), only two surface temperatures of 105 and 115 °C could be achieved. They used flow rate of sample entering vibratory conveyor via the vibratory feeder for adjusting surface temperature at exiting. Uniform infrared energy emitting on all surfaces of the seeds was also guaranteed by presence of an electrical vibratory conveyor. Zarkadas and Wiseman (2002) used IR for heat treatment of barley grain. The micronizer, temperature and duration of treatment were similar to those of described for wheat grain (Zarkadas and Wiseman, 2001). Emami et al. (2010) increased moisture content of barley grains by adding deionized water for 3 h prior to the micronization. They aimed the moisture content of 115 g/kg post-micronization and to achieve this, grain surface temperatures were reached to 100, 120 and 140 °C in the grains which had moisture content of 170, 310 and 410 g/kg, respectively. Fattah et al. (2013) investigated the effect of micronization of barley grains on protein hydrophobicity, in vitro protein degradability, degradation characteristics of protein and starch and its feeding effect on ruminal pH of sheep. The grain was micronized at different times of 60, 90, 120 and 150 s in chamber at temperature of 220ºC. The temperature of micronized grains at exiting was between 110 and 120ºC. After processing, grain was cooled at room temperature. No information about the flow rate of the barley and initial moisture were provided by the authors however, they concluded that 90 s time was high enough and considered as optimum time for barley micronization. In a recent study by Bai et al. (2018) on hull-less barley grain, two moisture contents of original (86 g/kg) and increased by tempering with distilled water for 1 h (200 g/kg) were micronized using laboratory scale micronizer to reach a surface temperature of 115 and 135ºC. They mentioned that micronizer burner was located 19 cm above conveyer heated grain was further ground to produce fine flour for later experiments.

2.4. *Sorghum grain*

Croka and Wagner (1975a) expressed micronization degree by specifying three densities of 412, 322 and 232 g/L micronized sorghum grain. Decreased density of micronized sorghum was an indication of greater gelatinization which occurred by increasing thermal treatment during micronization. In an in vivo trial, the above authors (Croka and Wagner, 1975b) described that sorghum grains were cleaned before processing and then micronized on a vibratory steel table. The micronizer consisted of eight gas-fired infrared generators (generating 50,000 BTU or 1055.07 J) which were hanged from 15 cm above the table as a heat source. The micronized sorghum grains were immediately rolled between two 21.6 × 76.2 cm rollers. Shiau and Yang (1982) micronized sorghum grain in three temperatures of 102, 250 and 282 °C for 20–25 s without increasing initial moisture content of raw grain (110.5 g/kg) that caused reduction of moisture level to 100.7, 61 and 57.1 g/kg by increasing processing temperature. They specified that infrared emitter was located at 15.24 cm above conveyer.

3. Grains physicochemical changes after micronization

3.1. *Kernel hardness*

McAllister and Sultana (2011) evaluated the effect of micronization on three varieties of wheat included, Sceptre, Laura and Kansas. Micronization decreased kernel hardness in Sceptre and increased in Laura and Kansas.

3.2. *Microstructural changes in grains*

Fasina et al. (1999) using scanning electronic microscope observed that starch protein granules which were within 2–25 μm diameters in un-treated barley, swelled up to 50 μm in micronized grain.

3.3. Water absorption and starch gelatinization

Based on Fasina et al. (1999), infrared heating reduced kernel density from 802.1 in un-processed to 302.5 kg/m^3 in micronized barley grain which was along with increased water absorption (up to two fold). They also found that 0.934 of starch was gelatinized as a consequence of micronization. Kokić et al. (2013) also observed an increase of 45.34% and 63.58% in water absorption and gelatinized starch, respectively when they micronized corn grain at 125 ºC. When starch gelatinization occurs as a result of heat treatment, molecular orderliness within the starch granule disrupts which resulted in greater starch digestibility and in vivo glycemic index (Wang and Copeland, 2013). Experiments conducted by Zarkadas and Wiseman (2001) indicated that 0.086, 0.067 and 0.465 of wheat starch gelatinized at processing time of 10, 13 and 35 s, respectively. Zarkadas and Wiseman (2002) reported that proportion of gelatinized barley starch increased from zero in raw barley grain to 0.374, 0.348 and 0.371, respectively when grain was heated for 10, 13 and 35 s by micronizer. These authors demonstrated that steeping of barley grain and increasing moisture content of the seeds to 160–170 g/kg increased gelatinized starch to 0.596 within 35 s. Similarly, Fasina et al. (1999) found greatest gelatinization at initial moisture of 265 g/kg. Emami et al. (2010) also reported that starch gelatinization was increased when barley grains were micronized at higher moisture content and surface temperature. McAllister and Sultana (2011) found that starch gelatinization was 0.721, 0.647 and 0.496 when Sceptre, Laura and Kansas varieties of wheat were micronized at similar conditions, respectively. In contrast, Vervuert et al. (2004) found that only 0.27 of starch was gelatinized post micronization process.

3.4. Chemical composition

No influence of micronization on chemical composition (starch, protein, total dietary fiber, ash and fat) of barley grain was found (Fasina et al., 1999). Similarly, Zarkadas and Wiseman (2002) also found that gross energy, crude protein, total fat, ether extract and ADF did not change by micronization nevertheless total starch content increased by 13.47% and 9.09% when barley grain was exposed to IR for 10 and 35 s, respectively or it decreased by 3.9% in treatment processed for 13 s compared to raw barley. For wheat grain, it was found that the amount of starch, nitrogen and ether extract were not affected by micronization (Zarkadas and Wiseman, 2001). Niu et al. (2003) also reported no effects of micronization on total and gelatinized starch when wheat were micronized for feeding to the broilers. In contrast, micronization of Sceptre, Laura and Kansas wheat grains resulted in decrease of 2.67%, 3.4% and 2.3% in starch, an increase of 19.81%, 23.21% and 9.3% in NDF and 2.05%, 2.36% and 8.09% increase in CP content, respectively (McAllister and Sultana, 2011).

Regarding effects of micronization on fiber fractions, Douglas et al. (1991) micronized corn grain which resulted in reducing ADF and NDF content by 45% and 50% compare to un-heated grain, respectively. Micronization of wheat grain also reduced ADF content by 39.39%, 12.12% and 36.36% when seeds were micronized at 10, 13 and 35 s compare to raw substrate, respectively (Zarkadas and Wiseman, 2001). Žilić et al. (2010) demonstrated that micronization reduced cellulose by 36.99%, 38.77% and 2.12% in white, red and yellow maize flour, respectively. Similarly, Srivastava and Vasishtha (2013) found that cellulose and hemicellulose decreased after cooking of lentil by 16.7% and 50%, respectively. However, Chang and Morris (1990) observed that thermal processing such as autoclaving (121 °C for 15 min and 100 °C for 30 min) and microwave heating (700 Watts, 2450 MHz, 5 and 10 min and optimum ratio of water to fiber was 3:1) did not change insoluble fiber and total fiber of ground corn.

No effect on protein content of micronized sorghum was found, however there was a reduction of lysine by 17%, 25% and 33% at processing temperature of, 102 °C, 250 °C and 282 °C (Shiau and Yang, 1982). Likewise, lysine content was reduced by 25% after micronizing corn grain compare to un-treated grain (Douglas et al., 1991). This destruction of lysine may happen when maillard reaction occurs (Hedegaard and Skibsted, 2013). Comparison of three types of maize flour obtained from micronized grains by Žilić et al. (2010) showed that micronization caused a reduction of crude protein in red corn (4.15%) and ash content in red and yellow corn by 15.0% and 16.08%, respectively. Micronization altered various fractions of protein so that the amount of albumin, globulin and α-zein were lowered in micronized ones by 43.15%, 52.26% and 27.13%, respectively but G3-glotelin increased in all of them by 8.46% on average (Žilić et al., 2010). Bai et al. (2018) however found no effect of micronization on crude protein content and amino acid profile of hull-less barley at two moisture contents of 86 and 200 g/kg and surface temperatures of 115 and 135 °C were applied for processing.

Beta carotene which was present only in yellow and red corn, after the thermal process decreased by 23.02% and 8.33%, respectively. Peroxidase, tryptophan and various forms of tocopherols were also reduced by 60%, 46.97% and 36.86% in the flour samples as a consequence micronization, respectively (Žilić et al., 2010). Deepa and Umesh Hebbar (2017) reported that micronization process reduced lipase activity by 84% and completely deactivated peroxidase in the finely ground (390–475 mm) micronized maize grain, thereby reduced free fatty acid production and their oxidation during storage compared to raw flour. There are also evidences that show micronization was able to reduce tannin level by 26.79% and 16.67% in high and low tannin sorghum compared to raw seed, respectively (Douglas et al., 1991). Recent study confirmed that as total phenolics, condensed tannins, trypsin and chymotrypsin inhibitor activity in the hull-less barley were significantly decreased by micronization (Bai et al., 2018). As two non-grain plant items, micronization of potato and tomato for 41 and 11 min resulted in a weight loss of 17.92% and 16.89% in potato and tomato, respectively (Unklesbay et al., 1983). Relative to raw materials, IR significantly decreased protein content of potato by 9.86% without affecting vitamin C however beta carotene (vitamin A) was increased in baked tomato halves about three folds compared to un-processed one. Phosphor was also significantly decreased (17%) with micronization in the cooked potato.

3.5. *In vitro protein solubility*

Fasina et al. (1999) indicated a significantly reduced in vitro protein solubility in the micronized barley grain. Similarly, Niu et al. (2003) observed a decrease in soluble protein of micronized wheat when compared with raw grain. Fattah et al. (2013) estimated surface hydrophobicity of isolated barley protein and they found that micronization of this grain for 90 and 120 s resulted in enhancing surface hydrophobicity of protein (which is negatively correlated with its solubility) by 24% and 46%, respectively. Shiau and Yang (1982) also found reduction of 9.79%, 18.54% and 25.18% in protein solubility of sorghum when it was micronized at 102, 250 and 282 °C, respectively.

4. *In vitro* enzymatic digestibility

Croka and Wagner (1975a) evaluated in vitro dry matter disappearance and gas production of dry rolled and micronized sorghum at three different densities of 412, 322 and 232 g/L. Micronization of sorghum significantly increased both in vitro disappearance of dry matter and gas production compared to dry rolled grain and reducing the density linearly improved above parameters as degree of starch gelatinization (mg maltose/g grain) increased from 15 in dry rolled grain to 40, 64 and 105 by reducing grain density, respectively. Shiau and Yang (1982), found similar finding when in vitro enzymatic starch availability was tested for raw and micronized sorghum at 102 and 250 °C but under the severe micronizing temperature (282 °C), a reduction of starch availability was found compared to lower temperatures that indicated sensitivity of micronization to the processing temperature. *In vitro* starch digestibility of corn showed 74.16%, 59.46%, 41.67%, 26.09% and 20.62% improvement in micronized corn compare to raw one during 2, 4, 8, 12 and 16 h incubation times, respectively. Similarly, in vitro starch digestibility of high tannin sorghum were enhanced by 51.89%, 35.89%, 25.84%, 19.87% and 16.29% in high tannin and by 57.49%, 36.83%, 29.33%, 19.03% and 14.07% in low tannin sorghum compare to corresponding controls after 2, 4, 8, 12 and 16 h enzymatic incubations, respectively (Douglas et al., 1991). Emami et al. (2010) using in vitro enzymatic starch digestibility method concluded that micronization was not an effective process for reducing starch digestibility in barley. In their study, barley was ground to obtain flour passing 425 μm sieve for determination of in vitro starch digestibility. Findings of McAllister and Sultana (2011) was opposite between in vitro and in situ experiment in which in vitro rumen starch digestion in micronized wheat was greater than control grain throughout 48 h incubation. The author argued that because substrate used for in vitro experiment was finely ground (finer than that of in situ tests), integrity of protein matrix disrupted and gelatinized starch exposed to microbial digestion resulting higher starch digestion compared with un-heated treatment. Surprisingly, Bai et al. (2018) observed that in vitro enzymatic protein digestibility of micronized hull-less barley was significantly increased compared with un-heated one but it should be highlighted that they used fine flour of micronized seed for in vitro test.

5. Micronized grains as ruminant feed

In the Table 3, we listed most relevant papers cited in this review which evidenced some findings for using micronized-flaked grains as ruminant feeds. McAllister and Sultana (2011) performed 96 h in situ experiment on micronized barley and they found that although micronization had little effect on rapidly soluble fraction of protein, it reduced this parameter in starch by 66.18%. Authors also reported that protein disappearance was reduced from 632 g/kg in un-treated barley to 487 g/kg in the micronized treatment and slowly degradable fraction of protein was reduced from 529 to 383 g/kg. However, starch disappearance in the above incubation time was even increased by 2.1 units in treated one compare to control which was along with increasing slowly degradable fraction of starch from 675 in raw grain to 734 g/kg in micronized barley. Despite this, rate of slowly starch degradation was reduced from 6.8% to 5.5%/h in micronized barley.

In situ study conducted by Fattah et al. (2013) showed that soluble fraction of protein in micronized grains were reduced 22%, 36%, 55% and 54% in the treatments which were micronized during 60, 90, 120 and 150 s, respectively compared to untreated barley. They reported that slowly degradable fraction of protein was increased in micronized treatments up to 120 s and further decreased when

Table 3
Literature cited in the current review with findings relevant to use of grains micronization in the ruminant nutrition.

Reference	Title
Croka and Wanger (1975)	Micronized Sorghum Grain. 1. Influence on feedlot performance of cattle
Croka and Wanger (1975)	Micronized Sorghum Grain. II. Influence on in vitro digestibility, in vitro gas production and gelatinization
Fasina et al. (1998)	Infrared heating of hulless and pearled barley
Cenkowski et al. (2007)	Mathematical modeling of heat and mass transfer during continuous infrared micronization
Emami et al. (2010)	Impact of micronization on rapidly digestible, slowly digestible, and resistant starch concentrations in normal, high-amylose, and waxy barley
McAllister and Sultana (2011)	Effects of micronization on the in situ and in vitro digestion of cereal grains
Fattah et al. (2012)	Degradation characteristics of infrared processed barley grain and its feeding effects on ruminal pH of sheep
Kokic et al. (2013)	Influence of thermal treatments on starch gelatinization and in vitro organic matter digestibility of corn
Nixdorff et al. (2020)	Comparison of the effects of dry rolling, temper rolling, and steam flaking barley grain on dry matter intake, growth, and carcass characteristics of finishing beef steers
Malekkhahi et al. (2021)	Effects of ground, steam-flaked, and super-conditioned corn grain on production performance and total-tract digestibility of dairy cows

barley was processed for 150 s. Micronization of barley grain caused an decrease in the rate of protein degradation however, no difference was found between duration of 120 and 150 s. Regarding starch degradation, the authors found that similar to protein, there was a reduction in soluble fraction and increase in slowly degradation fraction by increasing the time of thermal treatment. Micronization of barley for 60 and 90 s decreased degradation rate of starch by 24% and 55%, respectively compared to untreated grains. The sheep fed with 400 g/kg forage hay and 600 g/kg micronized barley for 60, 90, 120 and 150 s had ruminal pH of 5.7, 5.95, 5.9 and 5.85 respectively which were all greater than that of untreated barley (pH=5.5). In the above study, micronization of barley grain for 60 and 90 s increased in vitro small intestinal digestibility of rumen un-degradable crude protein by 12% and 22% compared to un-treated barley which showed micronization could alter site of barley protein digestion from rumen to small intestine.

In situ incubation (96 h) of raw and micronized corn grains by McAllister and Sultana (2011) indicated that disappearance of protein and starch reduced from 0.416 and 0.461 in control to 0.399 and 0.424 in radiated grains, respectively. Micronization reduced rapidly soluble fractions of both protein (166 vs154 g/kg) and starch (56 vs 38 g/kg) but it caused an increase in slowly degradable fraction of starch (403 vs 580 g/kg) in radiated treatment compared to raw grains. However, slowly degradable fraction of protein was reduced as a result of micronization (492 vs 433 g/kg). Because of the increased slowly degradable fraction of starch in a relatively slower rate (1.9 vs 5.7%/h) in micronized corn compared to un-processed corn in this study, it was concluded that micronization is effective method to modulate the rate of acid production during corn grain fermentation in the rumen.

Despite 31% increase in slowly degradable fraction of starch which was occurred in micronized wheat grain, overall influence on in situ dry matter disappearance was − 12.57% because soluble fraction of protein, starch and slowly degradable of protein were reduced by 5.55%, 72.56% and 21% in micronized grain compared to control, respectively (McAllister and Sultana, 2011).

As described in this study, soluble fraction of starch was reduced in all types of grains because of micronization. There was an evidence that showed within desirable infrared processing time (60–120 s) rumen un-degradable crude protein of barley could be digested in the small intestine with greater extent compare to non-processed grains. This event may release gelatinized starch which was escaped from the rumen (because of reduced rumen degradation rate) resulting greater starch digestion in the small intestine and further lesser starch entering to the large intestine for further hindgut fermentation (Fig. 1). Therefore, it could be hypothesized that micronization of grains had at least two benefits for ruminant: first reduces ruminal starch fermentation rate that may also decrease acidosis risk and second, it increases small intestine digestion of starch. The later decreases the quantity of starch degradation in the large intestine which is more favorable for slowly degradable grains such as corn. A key point for the above conclusion is particle size of micronized grains entering to the rumen as McAllister and Sultana (2011) found endosperm protein that can act as physical barrier to protect starch granules from microbial attack fails when wheat particle size was reduced below 1 mm.

Most cited paper that used micronized grain as a ruminant diet ingredient is Croka and Wagner's research (1975b) who fed micronized sorghum (at level of 800 g/kg DM basis) to the feedlot cattle. The main outcome of that study was reducing feed intake in animal fed micronized grains compare to one consuming dry rolled one but because all groups had similar weight gain, it improved feed efficiency by 18.78% than control treatment when micronized flaked sorghum with 322 g/L density was fed to animals. In the above experiment, no effect of micronization was found on rumen pH however there was a significant decrease in molar proportions of acetic and isovaleric acid which was along with an increase in propionate percentage. Nixdorff et al. (2020) observed improving feed efficiency when steam flaked barley (flake density of 450 g/L) was fed to finishing beef steers. Because monogastric animals also showed similar reduction in feed intake when broilers were fed with micronized wheat (Niu et al., 2003), we suggest two possible reasons for improving feed efficiency in animal fed micronized-flaked grains: firstly, infrared radiated grains absorbed more water (Fasina et al., 1999) and had greater viscosity (Niu et al., 2003) therefore, exhibited slower passage rate in digestive tract of horse (Rosenfeld and Austbø, 2009). Welch (1986) reported that increasing water holding capacity in a feed caused an increase in specific gravity of it. The author indicated that increasing specific gravity up to 1.17 can reduce outflow rate from the rumen and interestingly rumen fluid was capable to enhance specific gravity more and faster than plain water. Based on the above documents it can be hypothesized that micronized-flaked materials may absorb rumen fluid and obtain higher specific gravity that would result more retention in the rumen with increased rumination chance (Seo et al., 2009). Secondly, in the absence of sedimentation, high proportion

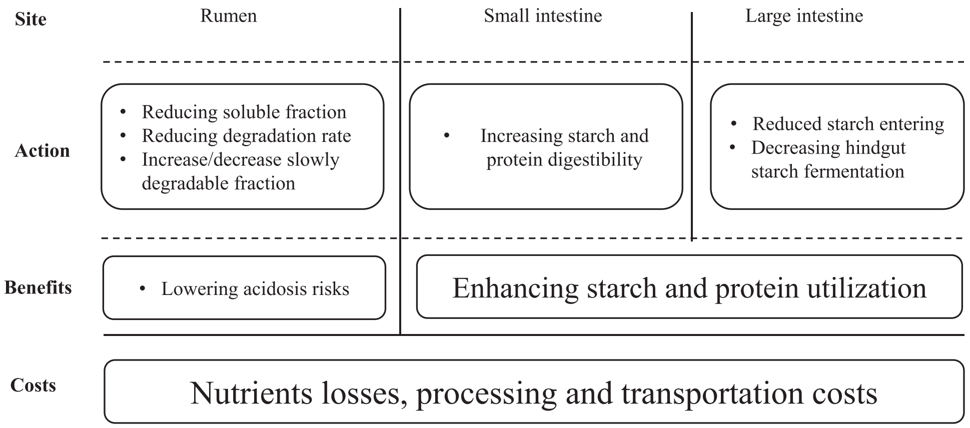

Fig. 1. Proposed costs and benefits items of grains micronization for ruminant.

of particles within size of 1–10 mm may escape reticulo-rumen after eating without rumination (Kaske et al., 1992). It was also found that in the flaked barley grains with flake density of 470 g/L, 95.85% of particles were between 4 and 8 mm (Johnson et al., 2020). Seo et al. (2009) described that small particles may sediment in the ventral and cranial parts of the rumen (escapable phase) near to reticulo-omasum orifice with high probability of leaving and moving to the omasum. These un-ruminated particles are crushed between omasum laminae by strong contractions (McBride et al., 1984). Unlike forage particles, if un-fermented micronized- flaked grains reaches to the small intestine with smaller size (by rumination or omasum contractions), they have great potential of digestion by pancreatic amylase. Conclusively, shifting starch digestion site from rumen to small intestine may results greater glycemic response in the plasma and higher blood glucose may regulate feed intake (Fisher, 2002).

6. Cost benefit of micronized grains as ruminant feed

Micronizer systems work with gas which is economically explainable where there is natural gas resources however, energy cost limits utilization of this technology worldwide. Unlike pelleting technology, major factor for un-popularization of flaking based methods is decreasing bulk density and increasing transportation cost, easily up to two folds of un-processed grain. This challenge might be solved by manufacturing small unit micronizer -flaker for in farm grain processing or processing in the nearby feed plant. Commercialization of micronization is already occurred as listed in Table 1 and it's successfulness in ruminant nutrition would be possible if improvement in animal performance and health overcome to above main costs plus losses in nutrients which occur during cooking (Fig. 1).

7. General considerations on micronization process with focus on ruminant as end users

Apart from the type of grain and as illustrated in Fig. 2, micronization process generally involves six important sub-process. For successful application in diet of ruminant, following technical stages pre, during and post-micronization were summarized:

7.1. *Tempering*

Increasing moisture of the grains (to about 200 g/kg) by adding tap or distilled water was essential stage for enhancing heat transfer inside the grain mass. Although the amount of added water depends on the initial moisture and independent of grain type but, damping duration may vary as seed size and fiber content. Lowering tempering time by using steam or pressurized water might be desirable which probably requires higher technology than conventional water addition. Cenkowski et al. (2004) developed and validated a mathematical model that showed pea seeds at 290 g/kg moisture content could reach to greater temperature than seeds with 195 g/kg moisture at exiting of micronizer while processing time was similar. There must be proper arrangement for uniform water distribution and absorption among the grains during this sub-process. Furthermore, shortening damping duration reduces risk of mold growth and activity inside the grain mass.

7.2. *Feeding the micronizer*

Single layer of grains on the conveyer should have enough porosity for obtaining targeted temperature. Among reviewed papers, only Syrovatka (2014) determined that optimal micronization process takes place in granular layer porosity of 0.5–0.75 apart from the type of grain. Therefore, an appropriate feeder must be located before micronizer for controlling inlet flow rate which itself depends on the conveyer area.

7.3. *Vibration while heating*

All surfaces of the grain must receive uniform IR to achieve a high degree of micronization. This might be guaranteed by suitable electro-mechanical vibrator placed below and throughout the conveyer. Porosity of granular grains layer below emitter is also

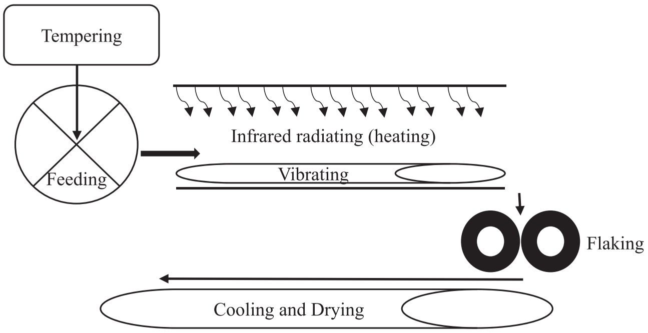

Fig. 2. Six important sub-process involved in the grains micronization.

influenced by vibration power and speed.

7.4. Infrared heating

This sub-process may refer to the main stage of whole micronization process. For each micronizer system, heat penetration into the grain depends on factors such as heating duration or conveyer speed, type of emitter (temperature at burner and amount of energy emitted), distance between burner and conveyer, isolation of system, and type of materials used for conveyer. Therefore it seems that in the majority of publications, full description of operational conditions were not provided. A general rule for the amount of heating could be increasing grain temperature to obtain cooked substances before burning and Maillard reaction occurring.

7.5. Flaking

Thermal processing itself increases ruminal and post-ruminal digestibility. Theurer et al. (1999) documented that the net energy for lactation (NE_L) of steam-flaked corn is about 20% greater than the NE_L for un-heated corn. They believed this was because of greater dietary starch fermented in the rumen and increased digestibility of dietary starch fraction reaching to the small intestine. Makizadeh et al. (2020) also argued that greater growth performance of calves fed steam-flaked corn compared to ground fed group was because of higher starch available in the rumen, small intestine or both. Micronization process involves IR heating of whole grains. To make gelatinized starch accessible for enzymatic hydrolysis, an appropriate physical treatment is required. This could be achieved by either grinding or flaking. There are evidences that flaking might be a better post-heating process as in a recent study, when corn grain was steamed, ground and fed to the lactating dairy cows at the level of 310 g/kg DM, it decreased ruminal pH and milk fat compare to the group fed steam-flaked corn grain despite gelatinized starch was not significantly different in both ones (Malekkhahi et al., 2021). One of the perquisites for using flaking strategy is the density of flake which is a very critical factor for regulating ruminal fermentation (Zinn, 1990; Plascencia and Zinn, 1996). It was found that reducing flake density increased rumen fermentation of corn (Gutierrez et al., 2018) and barley (Nixdorff et al., 2020). Another term for using heat treated flaked grains in the diet of ruminant is that total quantity of rapid-fermentable starch should be balanced as Malekkhahi et al. (2021) used corn as sole grain source in the diet.

As explained earlier, micronization process may reduce ruminal fermentation of starch. Main mechanism for this event is protein denaturation which generally happens by heating (Eckhoff, 2004). Denaturation temperatures of albumins, globulins, glutelins and prolamins extracted from soybean seeds were estimated by 90.62, 81.68, 83.05 and 80.75 °C (Makeri et al., 2017). Thus, it is possible that under IR heating and while temperature can go easily to 100 °C, denaturation of maize grain proteins occurs. Therefore, endosperm protein may act as a physical barrier for protecting starch granules from ruminal microbial attack as long as physical processing does not fragmentize it (McAllister and Sultana, 2011).

An advantage of flaked corn is that it may increase physically effective NDF in TMR and enhance rumination as explained by Savari et al. (2018). When steam-flaked corn with a flake density of 390 g/L was incorporated in lactating dairy cow diet at the level of 245 g/kg DM, it increased physically effective NDF from 242.4 g/kg DM in TMR containing ground corn grain to 282.9 g/kg in the similar formulation having steam-flaked corn (Savari et al., 2018). Cows that received steam-flaked corn grain had significantly longer rumination time (min/kg DMI) than those consumed.

The main objective of flaking barley and wheat is to optimize rumen fermentation by preventing fine particles formation during grinding. Practically, increasing moisture and moderate heating with shorter duration (compare to corn and sorghum) might be enough to obtain durable flake (Ebrahimi, 2020). López-Soto et al. (2014) demonstrated that energy value of steam-flaked barley increased by 8% when fed to the lactating dairy cows. These authors conclude that ruminal fermentation of steam-flaked barley was a function of flake density and similarly Nixdorff et al. (2020) found for optimum ruminal digestion, flake density of steam-flaked barley should not to be below 450 g/L for using in finishing cattle diet. In contrast, Soltani et al. (2009) did not find any advantages of using steam-flaked barley over grinding when fed to the lactating dairy cows. Unfortunately, scientific comparison between micronized-flaked and steam-flaked of specific grain with the same origin are lacked and needs further investigations.

In some reviewed papers which did not aim flaking step, targeted final moisture in the grain was below 10%. We believe that obtaining flaked grain with desirable density and formidability may not be feasible with such a level of moisture and therefore, moisture level in the cooked seeds should be enough for producing flaked grain with minimum floury materials. However for further long time storage, moisture content must reduce below 130 g/kg to avoid mold growth development (Ziegler et al., 2021).

7.6. Cooling and drying

Wang et al. (2015) documented that at moisture content below 200 g/kg starch retrogradation is not a major threat for gelatinized grains starch but they have also mentioned that under the 80 °C, about half of maximum starch retrogradation could be occurred within just 3.4 min and was independent of moisture level in the grain. Therefore, micronized and flaked grains as end product of micronization process and must be cooled and dried to avoid starch retrogradation and mold growth during storage.

8. Conclusion

For those countries which have natural gas resources, using micronized-flaked grains has advantage over ground form as digestibility of the starch and protein would increase without adverse effects on rumen health. To avoid un-controlled rumen fermentation of micronized grains, flaking is mandatory post-micronization process but optimum flake density may differ between rapid and slow fermentable grains. Micronization may control degradation rate of grains in the rumen by helping endosperm protein to act as physical barrier for protecting starch granules from ruminal microbial attack. Therefore, it could be used even for processing rapid-fermentable grains such as wheat and barley. On the other hand, for any micronization machine and types of grains, there could be specific operational standards which are not generalized and might be find out or set up by system manufacturer. There is also a need for further research to evaluate any increases in energetic value of micronized grains as ruminant ration ingredient.

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CRediT authorship contribution statement

Hanieh Sajjadi: Writing – original draft. **Seyed Hadi Ebrahimi**: Supervision. **Seyed Alireza Vakili**: Resources. **Abbas Rohani**: Methodology. **Mohammad Reza Golzarian**: Conceptualization. **Vahideh Heidaraian Miri**: Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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