RECENT ADVANCES / CURRENT UNDERSTANDING OF FACTORS IMPACTING BARLEY UTILIZATION BY RUMINANTS

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INTRODUCTION

Barley grain is the principal source of energy in the diets of feedlot and dairy cattle in western Canada; finishing diets used in commercial feedlots in this area typically contain more than 85% barley grain on a dry matter basis. In order for cattle to digest barley grain, the protective outer layers of the kernel must be broken or damaged to expose the nutritious, starch-rich components of the endosperm. These internal components are subsequently digested by enzymes produced by microorganisms inhabiting the rumen and/or by the animal itself, in the small intestine. Mastication alone is known to be insufficient for damaging whole barley kernels to the extent necessary for efficient digestion. Therefore, barley grains must be damaged mechanically prior to feeding. In discussing barley grain digestion by cattle, a combination of physical, microbiological, biochemical and physiological processes must be considered. Ruminal microbes typically digest over 80% of the starch in barley grain, but this can vary depending primarily on the degree to which the grain has been processed. Understanding this interaction between grain processing and the microbial mechanisms of barley grain degradation is essential to optimizing cereal grain digestion by ruminants

BARLEY GRAIN STRUCTURE

Barley possesses a thick, multilayered pericarp which surrounds the germ and endosperm. In hulled varieties, the pericarp is surrounded by a fibrous husk (Figure 1). These outer structures account for 5 to 15% of the total kernel, and are extremely resistant to microbial digestion. The pericarp and husk are composed of about 90% fibre (Hoseney, 1986), and their feed value is likely equivalent to that of barley straw.

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Endosperm is by far the predominant component of the cereal kernel, accounting for about 80% of the total kernel weight (McMasters et al., 1971). The endosperm comprises cell walls surrounding starch granules embedded in a protein matrix. In barley, cell walls in the endosperm contain large amounts of β-glucan. This is not readily digestible by monogastric animals, but in ruminants it is easily degraded by enzymes (i.e., β-glucanases) produced by ruminal microorganisms (McAllister et al., 1990b). Unlike corn and sorghum, the endosperm in barley is homogeneous throughout, and the starch granules are loosely associated with the protein matrix (Evers and Bechtel, 1988).

Starch is the principal carbohydrate in cereal endosperm. It is composed of linear (amylose) and branched (amylopectin) glucose polymers (French, 1973). The glucose units in amylose are linked by α-(1,4)- bonds; in amylopectin, α-(1,6)- linkages are present at branching points. Unlike cellulose, in which the glucose monomers are linked by β-(1,4)- bonds, the α-(1,4)- linkages in starch can be hydrolysed by enzymes produced in the small intestine. Thus, starch escaping digestion in the rumen remains potentially digestible in the small intestine. The degree of branching (i.e., the ratio of amylopectin to amylose) of the starch varies among barley cultivars. For example, waxy barley varieties contain little or no amylose. Digestibility of starch by monogastric animals is inversely related to its amylose content (less branching = lower digestibility). In ruminants, barley starch is readily digestible upon exposure to the rumen microbial population; the extent of starch digestibility reflects more the degree of access of the rumen microorganisms to the starch than its ratio of amylose to amylopectin.

The second internal component of barley, the germ, accounts for 2.5 to 3.5% of the volume of barley and wheat kernels, and 10 to 14% of corn kernel volume (Hoseney, 1986). In corn, the germ contains 20% protein, whereas in barley and wheat, this figure is about 25% (McMasters et al., 1971).

DIGESTION OF BARLEY BY MICROORGANISMS IN THE RUMEN

The ruminal microflora is concentrated, and exceedingly diverse. One millilitre of ruminal fluid contains 10 million to 10 billion bacteria, 100,000 to 1 million protozoa and 1,000 to 10,000 fungi. Over 200 species of bacteria, 100 species of protozoa and 8 species of fungi have been described, and additional microbial species undoubtedly remain to be isolated. Molecular ecological research suggests that a clear majority of the bacteria in the rumen are not yet identified (Whitford et al., 1997).

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Because of their numerical predominance and metabolic diversity, the ruminal bacteria are believed to be responsible for the majority of barley starch digestion in the rumen (Cheng et al., 1991). The principal starch-digesting bacteria in the rumen are *Streptococcus bovis*, *Ruminobacter amylophilus*, *Prevotella ruminicola*, *Butyrivibrio fibrisolvens*, *Succinomonas amylolytica* and *Selenomonas ruminantium* (Cotta, 1988). Although each can digest starch, these species are individually incapable of producing the variety of enzymes required to digest an entire barley kernel. Rather, barley digestion is accomplished by physiologically complementary bacterial species that associate to form a complex digestive "team" at the exposed surface of the grain (McAllister et al., 1994).

Establishment of the microbial team is sequential, initiated when amylolytic bacteria in the ruminal fluid are attracted to the surface of starch granules, to which they adhere. There the primary colonizers multiply via cell division, and their digestive enzymes release soluble nutrients and form digestive pits on the surface of the granules. In this way, the resulting microcolony generates a surface environment that attracts secondary colonizers from the rumen microbial pool to the digestive site. In time, the surface of the barley grain becomes covered, often completely occluded, by a definitive multi-species microbial population. The entire process of ruminal digestion of the grain, however, is dependent upon the establishment of the primary colony. Factors that alter this sequential development, such as grain processing, can thus profoundly affect both the rate and extent of cereal grain digestion in the rumen.

Two groups of ruminal protozoa, the Holotrichs and the Entodiniomorphs, are also capable of degrading starch (Hungate, 1966). These protozoa readily engulf starch granules, at rates of ingestion inversely related to the size of the granules (Wakita and Hoshino, 1989). Estimates of the proportion of amylolytic activity in the rumen attributable to protozoa have ranged from 20% (Coleman, 1986a) to 45% (Eadie, 1967). Adding concentrate to a high forage diet for ruminants in general initially increases the protozoal population in the rumen (Hynd et al., 1985). Although earlier reports suggested that protozoal populations were greatly reduced or completely eliminated from the rumen when diets comprising 80 to 90% cereal grain were fed (Lyle et al., 1981), our recent research indicates that sizable rumen protozoal populations do persist in cattle fed high-grain finishing diets (Hristov et al., 2001), and that the role of protozoa in grain digestion, particularly in the early stages, is probably greater than was previously thought (Wang et al., unpublished data; Figure 2).

The most significant impact of ruminal protozoa on ruminal grain digestion may arise from their ability to regulate the rate of starch digestion. Up to 36 h

may be required for protozoa to completely metabolize engulfed starch granules (Coleman, 1986b). These microorganisms also reduce the population of amylolytic bacteria in the rumen via predation (Kurihara et al., 1968). These activities both reduce the rate at which barley starch is fermented in the rumen, which in turn moderates the post-feeding drop in ruminal pH (Veira et al., 1983).

Ruminal fungi have also been observed to colonize and degrade structural carbohydrates (Bauchop 1979; Akin et al., 1983). Most commonly studied is the ability of the fungi to digest fibre (Mountfort and Asher, 1985; Lowe et al., 1987; Borneman et al., 1989), but one detailed investigation reported production by *Neocallimastix frontalis* of an endohydrolytic α-amylase that releases maltose, maltotriose and maltotetraose as major starch hydrolysis products (Mountfort and Asher, 1988). In addition, we found *Orpinomyces joyonii*, *Neocallimastix patriciarum*, and *Piromyces communis* to be capable of affecting cereal grain digestion (McAllister et al., 1993). Fungi produce hyphae which have the unique ability to exert a physical force and penetrate recalcitrant plant structures. They are the only organisms in the rumen that have exhibited the ability to penetrate the husk and pericarp of barley grain. The number of fungi present in the bovine rumen remains relatively constant across diets varying widely in composition (e.g., 100% forage to 80% concentrate).

RATE AND EXTENT OF BARLEY GRAIN DIGESTION

By breaching the outermost layers of the barley kernels, processing techniques such as grinding, tempering or rolling all increase the rate and extent of barley starch digestion in the rumen. These outermost layers (i.e., the husk and pericarp) constitute a major barrier to digestive microorganisms. In both hulled and hulless varieties of barley, the pericarp remains virtually uncolonized by ruminal microbes even after 24 h of exposure (Figure 3, Wang et al., 1998). Thus, although hulless varieties contain more starch and less fiber than hulled barleys (Khorasani et al. 2000), these whole kernels are as resistant to microbial attack as their whole, hulled counterparts. Once the pericarp is breached, however, rates of access to the starch granules within are governed by the protein matrix and the endosperm cell walls.

Many of the bacteria capable of digesting starch lack β-glucanases and so are incapable of degrading endosperm cell walls; they depend upon cellulolytic organisms to penetrate this structure and enable access to the starch granules contained therein. Within the endosperm cell, the protein matrix surrounding the granules must also be digested to allow amylolytic attack of the starch. In barley, this matrix is readily penetrated by a variety of proteolytic bacteria, thus cereal

grain digestion proceeds rapidly (McAllister et al., 1990*c*). Conversely, the protein matrix in corn is resistant to proteolytic attack and restricts access of bacterial amylases to the encompassed starch granules. These differences in cereal grain protein matrices exert tremendous influence on the rate and extent of starch digestion. For example, 40% of the starch in processed corn escaped digestion in the rumen whereas the barley or wheat starch reaching the small intestine in cattle was less than 10% of that fed (Ørskov, 1986).

Many plants produce polyphenolic compounds called proanthocyanidins or condensed tannins as a chemical defense against predation by microbes, insects and herbivores (Kumar and Singh, 1984). These compounds form complexes with protein and carbohydrates, and can impede enzyme activity and digestion. The presence of these compounds may serve to slow the rate of starch digestion and avoid excessive acid production. Proanthocyanidins (PA) are normally present in barley grain at concentrations typically less than 0.5% of dry matter (Ekman, 1981; Aastrup et al., 1984) but the nutritive characteristics of PA-free cultivars developed primarily for the brewing industry have also been studied (Newman et al., 1984; Kemalyan et al., 1989). A negative correlation was determined between PA in 11 barley cultivars tested for use as animal feeds and their in vitro digestion by pepsin and pancreatin (Ekman, 1981), and chickens fed PA-free barley varieties gained more quickly than did those fed conventional barley (Newman et al., 1984). Little is known, however, about the effects of PA on digestion of barley grain by ruminal microorganisms.

We recently conducted a study to determine if the PA in barley affect its digestion by ruminal microbes (Wang et al., 1998). In vitro gas production and fermentation products, as well as in vitro and in situ dry matter disappearances were measured on normal barley (var. Harrington) and three PA-free cultivars (Caminant, Ca504316 and Ca802711). The PA in Harrington barley were localized in the pericarp-testa layer of the kernels (Figure 4), and a de-pericarping procedure was used to isolate the pericarp from Harrington barley and to determine the effects of its PA on digestion of the pericarp fraction. As well, polyethylene glycol (PEG) was used to bind and inactivate the PA, to investigate their effects on digestion through selective elimination.

In the PEG-inactivation study, PA significantly reduced ammonia accumulation in in vitro incubations of the pericarp-testa fraction, in which PA present at 9 g/kgDM, but not in incubations of whole rolled grain, in which PA were present at 2 g/kg DM. Barley grain PA were also found not to affect ruminal digestion of the grain, and it was concluded that the concentration of PA in barley is likely too low to affect ruminal digestion. As well, the absence of PA

in the pericarp did not enhance digestibility of the PA-free barley cultivars. Thus, other antimicrobial compounds (e.g., *n*-alkanes, fatty acid esters, lignin) are apparently rendering the pericarp resistant to microbial attack even in the absence of PA. It is only logical that barley plants must preserve the anti-microbial properties of their outer kernel in order to defend against attack by plant pathogens in the field. These same properties make whole barley grain resistant to microbial attack in the rumen.

REGULATION OF BARLEY GRAIN DIGESTION

Barley cultivars differ in their fermentation characteristics. Rates of digestion of ground barley grain among 60 cultivars studied ranged from 20% h^{-1} to 62.4% h^{-1} (Khorasani et al., 2000). Similarly, Lehman et al. (1995) found rates of rumen degradation of 22 cultivars ranged from 25% h^{-1} to 35% h^{-1}. We have observed, however, that when processing was minimal (i.e., kernels cut in half), the rate of digestion of barley was less than 5% h^{-1} (McAllister et al. 1990c). Within a given study, differences in rates of digestion among barley cultivars likely reflect variations in chemical composition, grain structure and response to physical processing. Because the chemical composition and structure of kernels can influence the particle size produced by a particular processing method, it may be impossible to determine the relative contributions of these factors to the fermentation properties of the barley. Barley cultivars with a chemical composition and structure that result in finer particle sizes after processing will naturally be digested more rapidly by microbial populations within the rumen.

As part of the above-mentioned study with Harrington and the three PA-free barley cultivars (Wang et al., 1998), we also examined the effects of different processing methods on digestion of barley by ruminal microbes. Barley kernels were studied whole and as manually dry-rolled, de-hulled, and de-pericarped preparations. The de-pericarping process gave rise to a fraction rich in pericarp-testa, which was also included in the study. In situ dry matter disappearance (ISDMD) from all four cultivars was lower with whole kernels than with any of the preparations (Figure 5). Digestion of de-hulled barley was slower than that of de-pericarped barley initially, but by 48 h there was little difference in ISDMD between the two preparations. Microbial degradation of the pericarp-testa fraction was minimal, even though its particle size was substantially reduced during milling.

This study showed clearly that disruption of the degradation-resistant pericarp is an absolute requirement for microbial digestion of cereal grains. Closer regulation of the rate of digestion of barley in the rumen may be achieved

through a processing method that just "scratches" the kernels to partially remove the pericarp. The degree of mechanical processing required to facilitate digestion, however, is often dependent upon the extent of chewing damage to the kernels. This is illustrated by the fact that unprocessed corn can be fed effectively to ruminants because its pericarp is extensively damaged by chewing both during eating and during rumination (Beauchemin et al., 1993). During eating and rumination of barley, however, chewing damage is much less severe, hence the requirement for processing to achieve efficient digestion in the rumen (Mathison 1996).

Sodium hydroxide or ammonia treatment of barley may enable efficient digestion of this grain by ruminants. Alkali-treatment causes swelling of the husk and pericarp of the kernel, thereby increasing the accessibility of the endosperm to ruminal bacteria (Rode et al. 1986). However, Bradshaw et al. (1996) observed reduced live weight gains among cattle fed ammoniated whole barley as compared to those fed rolled or tempered barley. Although ammoniation did improve the digestibility of ADF in barley grain, it did not overcome the constraints to microbial digestion of whole barley grain.

In some applications it is desirable to slow the rate of fermentation of ground or rolled cereal grains. Chemical treatments have also been assessed for their efficacy in this regard. Fluharty and Loerch (1989) studied the effects of formaldehyde, glyoxal, masonex, propionaldehyde and tannic acid treatments on in vitro DM disappearance from ground corn and found that chemical treatment (other than formaldehyde) did not significantly alter the digestive properties of the corn. In other studies, formaldehyde treatment of barley (to 0.40% (w/w), Van Ramshorst and Thomas, 1988) or corn (0.56%; Oke et al., 1991) nearly doubled the flow of starch to the small intestine. We examined ruminal incubation residues of formaldehyde-treated barley by scanning electron microscopy, and determined that formaldehyde treatment substantially increased the resistance of the protein matrix in the barley endosperm to microbial penetration and adhesion (McAllister et al., 1990a). In the formaldehyde-treated barley, ruminal bacteria gained access to starch granules in the interior of the endosperm cells by digesting through the granules located at the surface of the cells, rather than by digesting the protein matrix as they did in untreated barley. The chemically altered protein matrix slows barley digestion because it delays the formation of the microbial consortium required to digest the endosperm.

Considerable effort has been dedicated to slowing the rate of barley starch digestion by ruminants in order to enhance the flow of starch to the small intestine (Kassem et al. 1987; Van Ramshorst and Thomas 1988; McAllister et al., 1990a).

The hypothesis driving the research is that hydrolysis of starch and subsequent absorption of glucose in the small intestine is energetically more favorable than microbial fermentation of starch in the rumen (Robinson, 1989). However, this strategy is fundamentally flawed because any method that increases the resistance of starch to microbial degradation in the rumen invariably increases its resistance to digestion by mammalian enzymes in the intestine. Consequently, most procedures that have reduced starch digestion in the rumen have also resulted in lower total tract digestion of starch and consequently, no improvement in animal performance (Huhtanen et al. 1985; Peiris et al. 1988; McAllister et al. 1992). Efficient utilization of barley grain by ruminants is dependent on maximizing the capacity of ruminal microorganisms to digest barley in the rumen. Achieving this goal without excessive acid production or development of subclinical or clinical acidosis is likely a more profitable direction for research.

BARLEY PROCESSING – EFFECTS ON MICROBIAL UTILIZATION

Assessing the extent of barley processing

No standards of measurement currently exist for describing the degree to which barley has been, or is to be, processed. Research reports commonly used terms such as 'coarse', 'medium' and 'fine', but these descriptors are relative, and relevant only to treatments within a given study; medium-processed grain in one study may actually be equivalent to coarsely-processed grain in another study. The need for definitive terms by which describe grain processing is obvious. A processing index (PI) has been used in the feed industry to indicate the degree of processing of barley. The PI refers to the bulk density (i.e., volume weight, either as g/L or lb/bu) of the barley after processing expressed as a percentage of its volume weight before processing (Yang et al., 2000). The PI takes into account the fact that more extensive processing will give rise to finer particles. Volume weight will then be lower, and hence, a lower PI. This index, however, is affected by the method of processing, as well as the extent; the values generated can differ substantially between dry-rolling, where particles tend to be smaller and more discrete, and temper- or steam-rolling, where fractured particles are more likely to adhere to one another prior to being ingestion. The method of processing should always be considered in defining the optimal PI for barley. Additional factors, such as the forage:concentrate ratio of the diet and/or the type of livestock being fed (e.g., calves, beef cattle, dairy cows), will also influence the optimal PI for a given situation. For example, the optimal PI for feedlot cattle fed dry-rolled barley was proposed to lie between 80 and 85% (from Hironaka et al., 1992), whereas optimal PI for dairy cattle fed steam-rolled barley was recommended as 62 to 65% (Yang et al., 2000).

Dry-rolling vs. temper-rolling

In dry rolling, air-dried barley grain (moisture content typically about 10% moisture) is fed directly through a roller. The extent of kernel damage depends upon the characteristics of the kernel and the setting of the roller. In temper-rolling, the grain is soaked for 12 to 24 h to bring its moisture level to between 18 and 20% prior to rolling. Tempering grain reduces production of fines during rolling and increases the uniformity of particle size. Because the rate of microbial digestion is closely related to digestible surface area, fewer fines will moderate the rate of barley digestion in the rumen. In addition, there is evidence that temper-rolling reduces energy costs by about 11.3% as compared with dry-rolling (Combs and Hinman, 1985). Tempering followed by rolling is rapidly becoming the predominant barley processing method used in Alberta. Animal responses in growth studies comparing temper- rolling and dry-rolling, however, have been less clear. The observable benefits of temper-rolling may in some cases have been diminished by such factors as the consistency of roller settings, changes in the kernel uniformity during the experiment, and small numbers of animals involved (10 to 15 animals per pen). Tempering barley produces particles small enough to be efficiently digested by ruminal microorganisms, but not so fine as to provoke excessive acid production and predispose cattle to digestive disturbances. Reduced incidence of such disturbances is more readily detected in commercial operations (10,000 to 25,000 head) than on a research scale (50 to 200 head).

At present, our research team is evaluating the inclusion of a surfactant (AgriChem, Inc., Anoka, MN) in the water used for tempering feed barley. The surfactant was found to increase the rate at which water penetrates the kernels, which reduced the time required for tempering. As well, including surfactant in the tempering process produced more uniform, slightly smaller particles, with only a slight increase in fines (Table 1). Roller sizes were set to yield a PI of approximately 70% with tempered barley (denoted 'moist setting'), and 80% with dry-rolled barley ('dry setting'). Tempered barley processed at the dry roller setting yielded a particle size distribution similar to that obtained at the moist roller setting. In contrast, processing the dry barley at the moist roller setting dramatically reduced the PI and caused a substantial increase in the amount of fine particles produced. Cattle fed the tempered barley exhibited higher DM intake and average daily gain, and improved feed efficiency as compared to cattle fed the dry-rolled barley, irrespective of the roller setting ('moist' vs 'dry'). These results suggest that particle sizes produced from tempered barley will remain acceptable over a range of roller settings whereas minor alterations in roller distance can have major impact on the distribution of particle sizes produced from dry-rolled barley. Including the surfactant during tempering further improved the

Table 1. Effect of roller setting and tempering, with and without surfactant[z], on processing characteristics of barley grain and on performance of steers fed the barley during backgrounding and finishing

	Dry roller setting			Moist roller setting			
	Dry	T	T+S	Dry	T	T+S	SEM[y]
Processing characteristics							
Volume weight, g/L	516.3*a*	497.4*a*	490.4*ab*	425.9*c*	449.9*bc*	451.7*bc*	14.84
Processing index (PI)[x]	80.86*a*	78.69*a*	78.28*a*	67.21*b*	71.25*b*	71.86*b*	2.199
Whole kernels, %	11.08*b*	12.42*ab*	15.82*a*	2.92*d*	4.99*cd*	5.58*c*	0.415
Kernel thickness, mm	2.23*a*	2.24*a*	2.21*a*	1.98*b*	2.00*b*	1.98*b*	0.029
Distribution of particles, %[w]							
4.75 mm	0.28*c*	2.66*b*	2.08*b*	0.75*c*	5.69*a*	4.85*a*	0.428
3.35 mm	37.62*b*	61.81*a*	61.67*a*	32.74*b*	62.51*a*	61.44*a*	2.776
2.36 mm	39.35*a*	29.91*b*	29.91*b*	34.66*ab*	23.79*c*	25.30*bc*	1.956
1.70 mm	14.35*b*	3.16*c*	3.06*c*	20.23*a*	5.01*c*	4.98*c*	1.645
< 1.70 mm	8.37*a*	2.42*b*	2.84*b*	11.58*a*	2.96*b*	3.41*b*	1.712
Animal performance							
Average daily gain, kg	0.96*b*	1.1*c*	1.1*c*	0.81*a*	1.1*c*	1.1*c*	0.04
DM intake, kg/d	7.7*b*	8.3*d*	8.1*cd*	6.5*a*	7.6*b*	7.8*bc*	0.04
Feed efficiency, gain/feed	0.13*c*	0.13*c*	0.14*b*	0.13*c*	0.14*b*	0.15*a*	0.01

a-d: Within a row, means followed by different letters differ ($P < 0.05$).
[z]T: barley tempered to 20% moisture prior to rolling; T+S: 60 ppm GrainPrep® added to barley during tempering.
[y]Standard error of the mean ($n = 23$).
[x]Expressed as volume weight after processing/volume weight prior to processing (Yang et al., 2000).
[w]Particle sizes are reported as the mesh size of the sieve upon which particles were retained. Thus, the particles reported as <1.70 mm are those that passed through the 1.70-mm screen.

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feed efficiency of steers fed temper-rolled grain. The potential time savings in tempering and processing, and possible improvements in animal performance, suggest that there is a value in including surfactants in the tempering process.

Developing an automated procedure by which to produce uniform particle size

The kernel size of barley obviously affects selection of an optimal roller setting, distribution of particle sizes produced, and ultimately, the microbial digestion of barley grain. At present, barley is marketed primarily on the basis of bushel weight. Although the average kernel size is usually larger in barley with a higher bushel weight, bushel weight itself does not give any indication of kernel uniformity. In fact, barley with a light bushel weight is commonly blended with heavier bushel weight barley to create more marketable, mid-weight barley. Although blending produces what is perceived as a more acceptable product (higher bushel weight), it actually reduces the kernel uniformity and makes optimal processing extremely difficult (Figure 6). Roller placements selected for larger kernels allow passage of smaller kernels processed inadequately for efficient digestion; rolling to accommodate the smaller kernels will over-process the larger ones, causing shattering and production of fines which could promote digestive disturbances.

Significant quantities of whole, undigested barley kernels were present in the feces of over 25% of the feedlot cattle sampled in a recent survey conducted in southern Alberta (McAllister et al., unpublished data), even though the processing procedure used on the barley they were fed was perceived as optimal. This problem undoubtedly arose at least in part from the inability of the feed processing settings to accommodate variations in kernel uniformity. Hinman et al. (1995) also reported reduced growth performance by cattle fed blended barley, as compared to those fed uniform high- or low bushel weight barley processed according to kernel size. Those observations together with our own recent findings lead us to propose that determinations of the market value of barley should include kernel uniformity in addition to bushel weight.

Consistent achievement of a defined particle size when processing feed barley is complicated greatly by the high degree of variability of barley type and variety, kernel weight, kernel plumpness and moisture content. Some of these characteristics can vary even between truckloads, requiring that roller settings be adjusted to accommodate barley from different sources. Consequently, processing parameters are often set arbitrarily and fine-tuned by visual assessment - a time consuming, labour intensive, and often haphazard (as the characteristics of incoming barley change) process. A number of feedlot operators have

identified maintaining proper processing of barley grain as the greatest challenge in quality control during diet preparation.

Recent technological developments based upon the relationships between particle size, moisture content, and electrical conductivity may make it possible to automate barley processing to consistently produce a defined optimal particle size. These measurements are used presently to monitor bushel weight and moisture level of barley grain prior to its arrival at the roller. We are currently involved in a cooperative research project that has revealed a potentially strong relationship between bushel weight and particle size of processed barley grain. On this basis, post-processing particle size could be monitored using a system similar to those currently in use pre-processing. Establishing communication between the pre- and post-rolling sensors, and linking the information to hydraulically controlled rollers may allow automatic adjustments to rollers for consistent production of a defined optimal particle size. A system such as that is under investigation as part of the cooperative project, and may represent the next major advancement in processing barley grain for optimal microbial digestion.

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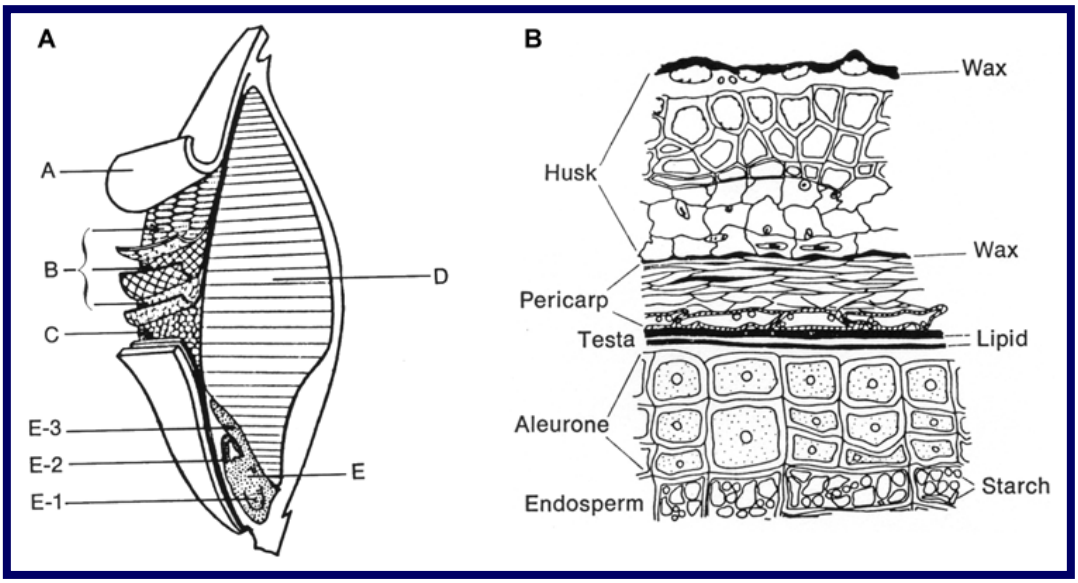

Figure 1. Diagrams of (A) a typical barley kernel and (B) a transverse section of the outer layers of barley kernel showing the relationship of the pericarp-testa to adjacent structures. In Figure 1A, labels are: A: husk; B: pericarp and testa; C: aleurone layer; D: endosperm; E: embryo (germ): 1-rootlets, 2-acrospire and 3-scutellum (Broderick et al., 1977).

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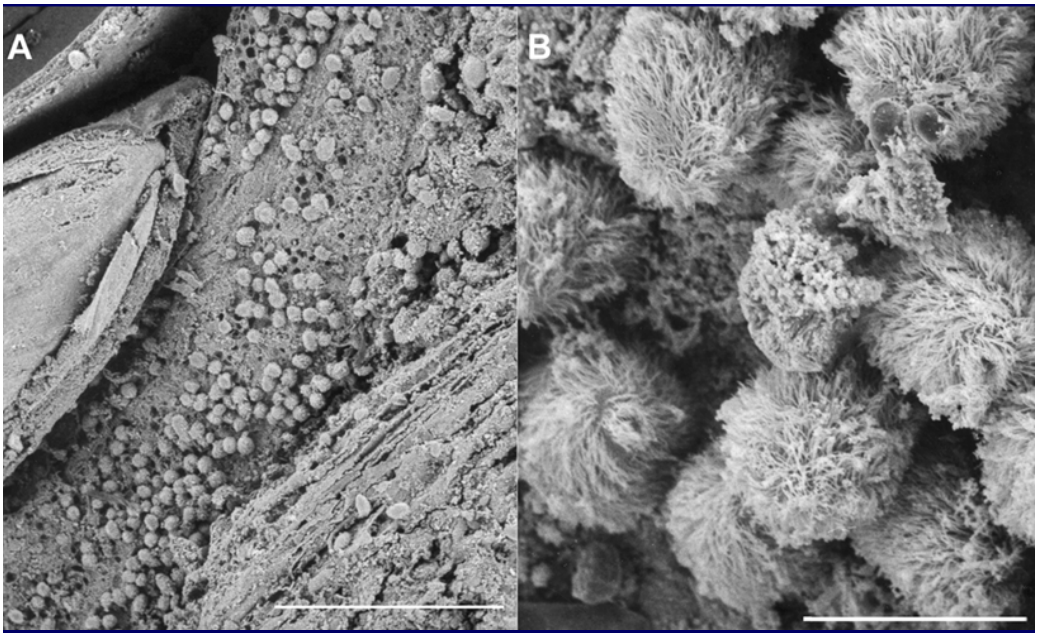

Figure 2. Scanning electron micrographs ground corn incubated for 30 min in the rumen of a cow fed an early lactation diet. (A) The endosperm has been colonized by numerous protozoa. (B) Higher magnification of (A). The protozoa are heavily ciliated. Bar in (A) = 600 μm; in (B) = 50 μm.

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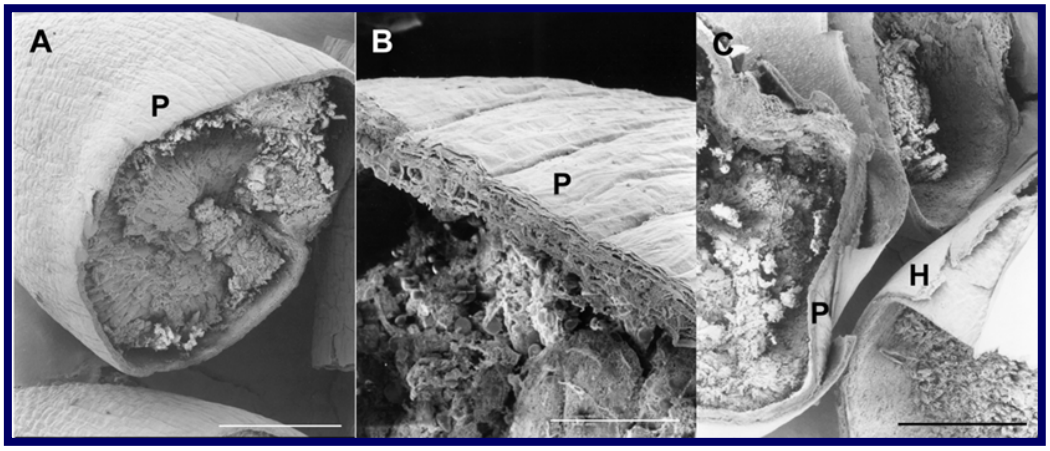

Figure 3. Scanning electron micrographs of (A, B) hulless and (C) hulled barley incubated in nylon bags in the rumen for 24 h. Microbial colonization and degradation of the endosperm is progressing, whereas the pericarp (P) and hull (H) are virtually uncolonized. Bars in (A) and (C) = 1 mm; in (B) = 130 μm.

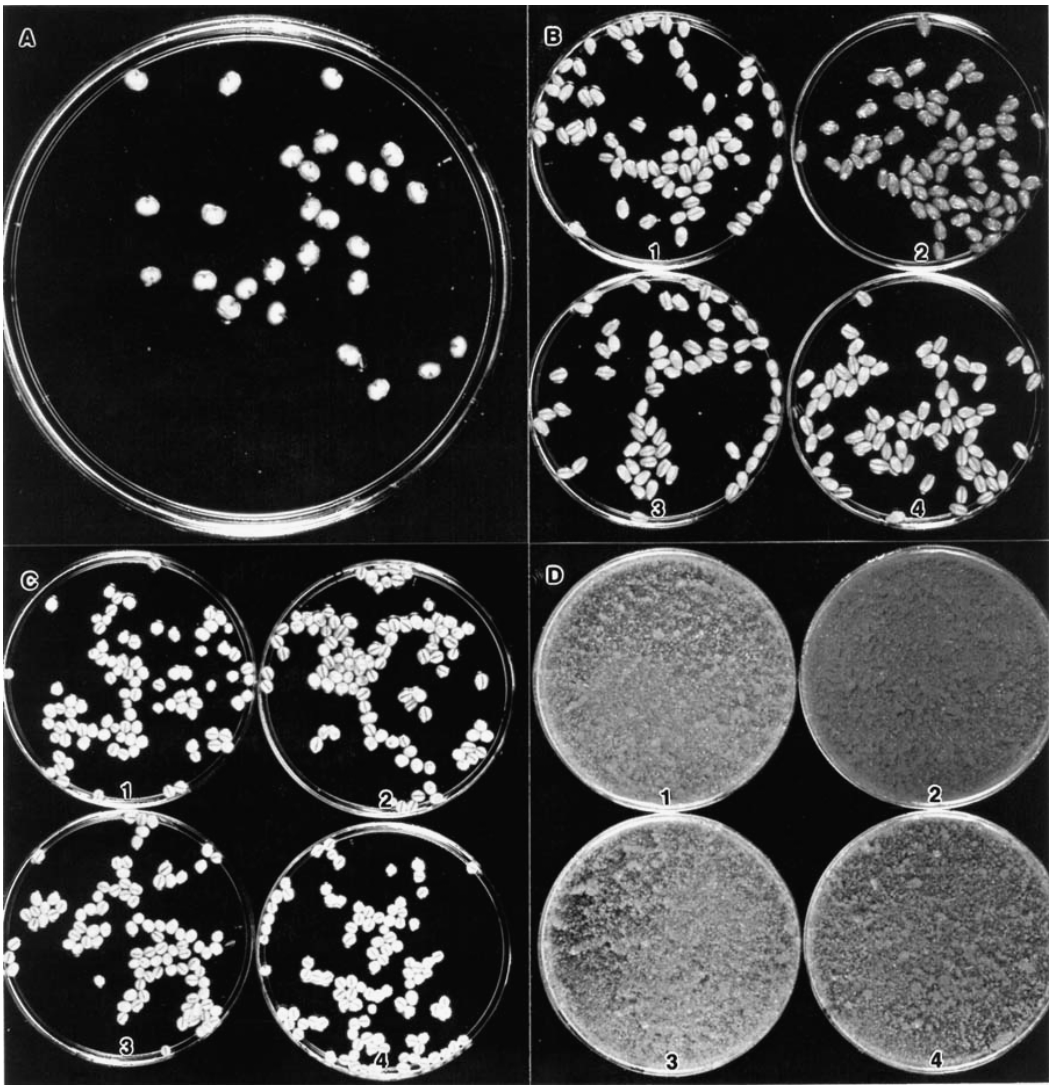

Figure 4. Preparations of Harrington and three proanthocyanidin-free barley lines treated with vanillin-HCl, which reacts with proanthocyanidins to produce a vibrant red product. (A) Transverse, 2–mm sections of whole Harrington barley kernels. Proanthocyanidins are visible as a faint ring underlying the surface of the kernels. In (B), (C) and (D) the dishes labelled 1, 2, 3 and 4 contain Caminant, Harrington, Ca5043 and Ca802711 respectively. (B) Dehulled kernels. Harrington barley is distinguishable from the other three lines by the heavier deposition of color. (C) Barley kernels with the pericarp removed. Harrington is considerably less distinct from the other three lines. (D) Pericarp-testa fraction generated during removal of pericarp for (C). The deep red color of pericarp-testa from Harrington barley (dish 2) is evident as a darker image. Proanthocyanidins were localized in the pericarp-testa layer of Harrington barley, but not in the proanthocyanidin-free lines.

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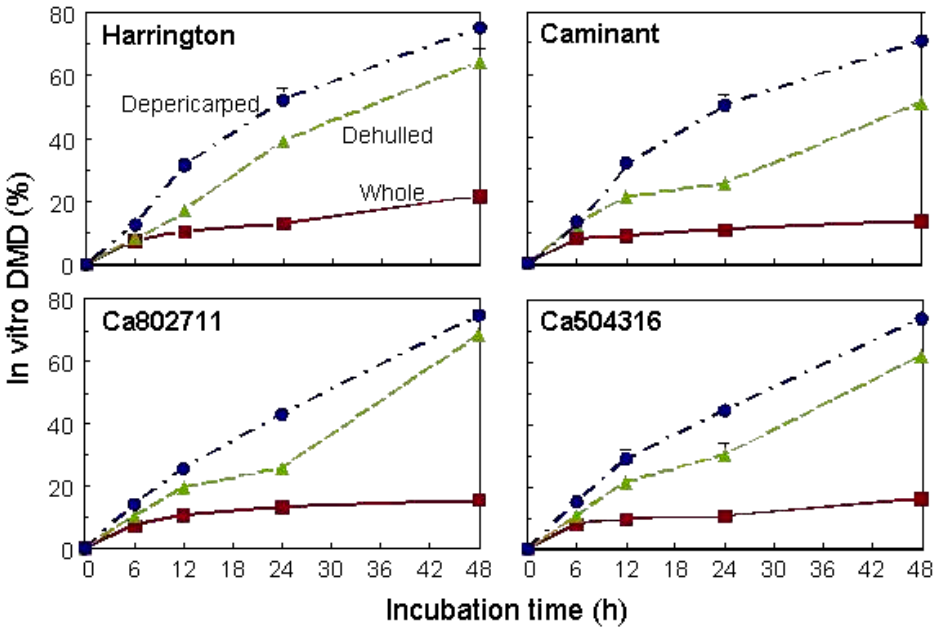

Figure 5. *In situ* dry matter disappearance (% of initial) from Harrington barley and three proanthocyanidin-free lines, each studied whole and after dehulling, de-pericarping and dry-rolling the kernels. The pericarp-testa fractions produced during de-pericarping were also included in the incubation.

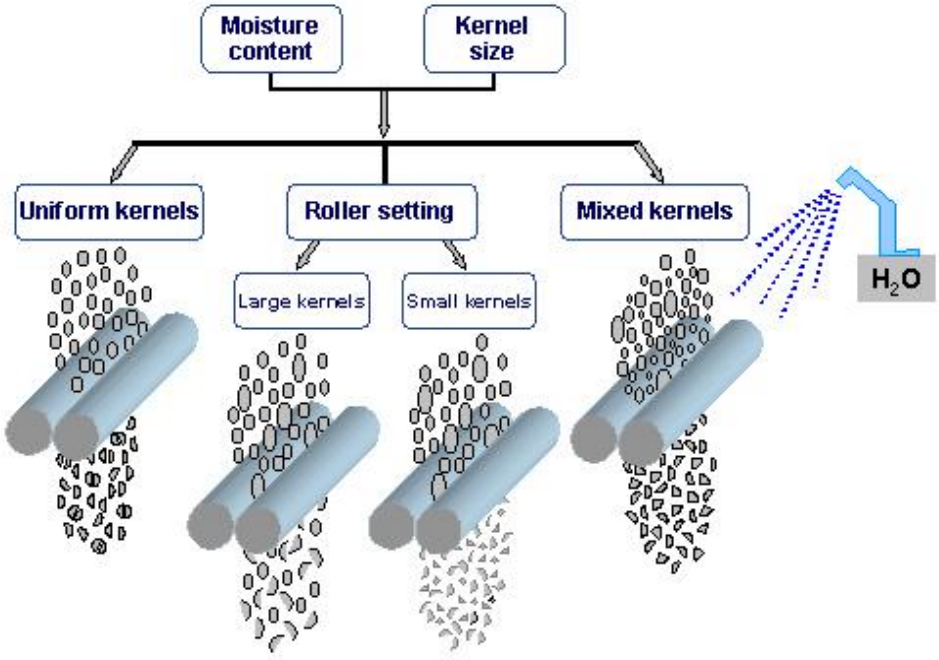

Figure 6. Schematic representation of the effect of kernel uniformity on the outcome of processing by rolling. Roller settings are selected after consideration of kernel size and moisture content. Uniform kernel-size barley is evenly processed, as roller settings are appropriate for the majority of kernels in the lot. When kernel size is not uniform, roller settings may be selected to be optimal either for the larger kernels in the lot, or for the smaller kernels. In the former case, larger kernels are processed as desired, but the smaller kernels are inadequately processed, or may escape processing. In the latter case, the smaller kernels are adequately processed, but the larger kernels are overprocessed, causing fracturing and production of fines. We have found that increasing the moisture content of non-uniform barley prior to rolling will improve the processed product by reducing the generation of fine particles.

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