INTRODUCTION

The corn wet milling process involves fractionation of the kernel to extract its constituents as valuable products like starch, purified glucose and dextrose, high fructose corn syrup, etc., as well as coproducts like corn gluten feed, corn gluten meal, and germ (Rausch et al., 2019). Starch is the primary product and is used to make products such as sweeteners, alcohol for fuel, etc. In 2019, around 29.23 million tons of corn were processed for food and industrial use by wet milling (USDA ERS, 2020) out of the total 360 million metric tons produced in the United States of America (USDA, 2020). [Correction added on 13 April 2021, after first online publication: The quantity of corn corrected from 172 million to 29.23 million and total amount produced corrected from 3.5 billion to 360 million metric.

During the same period (2018–2019), the United States exported 52.5 million tons of corn worth 9.58 billion USD (US Grains Council, 2019) to countries like Mexico, Japan, Columbia, and Taiwan, a major portion of which is utilized for wet milling. Starch yield is a major factor contributing to profitability for end-users of this corn. However, a concern
for wet millers is broken corn and foreign material (BCFM %) in import shipments. Long-distance transport involves several handling steps like mixing, storing, loading and unloading, and transferring, which lead to changes in corn quality (Hill et al., 1979). These changes result in economic loss for the grain merchandisers as well as end-users.

Different geography, climatic conditions, and corn genetic varieties are the major factors affecting the physical properties and endosperm hardness of corn produced in different international markets. Corn endosperm hardness is an indicator of quality as well as of ease of starch extractability. The hardness of endosperm is related to endosperm structure, composition, structure of granules, and protein distribution. Hard endosperm corn has more (3.3 times) zein protein than soft endosperm corn (Dombrink-Kurtzman & Bietz, 1993), whereas soft endosperm corn is known to have higher physiologically active proteins (albumin + globulin) compared to storage proteins (prolamin + glutelin) (Landry & Delhaye, 2007). Increased hardness leads to desirable qualities for storage, handling, and transport; however, it negatively impacts starch extractability (Dombrink-Kurtzman & Knutson, 1997).

US corn has been bred for more than half a century for higher starch yield, and so, US commodity corn is generally of a softer endosperm compared to commodity corn from South America. Due to the US midwestern weather, there is a short harvest window. Thus, the corn harvest moisture content is typically higher than 13% (moisture content required for safe long storage). In order to store and export corn as well as to achieve adequate starch recovery, artificial drying after harvest is needed, which leads to stress cracks (Kirleis & Stroshine, 1990; Peplinski et al., 1989). US commodity corn, generally having softer endosperm, is susceptible to breakage due to stress cracks during transport and shipping to international markets (Hill et al., 1979; Paulsen et al., 1989). On the other hand, corn originating in South America (Brazil and Argentina) is generally hard endosperm and is field dried to lower moisture content prior to harvest. Due to gentler, natural drying, it does not suffer from stress cracks.

Corn wet millers import commodity corn from United States, South America, and other geographies. Due to higher amount of broken corn and dust, the US commodity corn is perceived as inferior compared to South American commodity corn which is ideal for storage and transport (Paulsen et al., 1989). Broken corn and dust create cleaning and transportation issues for wet millers (Watson, 1988); thus, South American commodity corn is preferred over US corn by international importers of corn for wet milling based on physical quality of shipped corn. However, wet milling process economics depend largely on wet mill starch yield and hence on the wet milling characteristics of corn. Every percent increase in starch yield, over a year, can result in a substantial additional revenue for a corn wet milling plant.

Corn genetics, geographical factors like weather patterns and location (Singh et al., 1996), as well as postharvest practices and grain maturity (Jennings et al., 2002) are known to affect the physical properties, but they also affect the wet milling characteristics or millability of corn, primarily the wet milling yield. The wet mill yield, especially the starch yield, should be the primary basis for choosing corn for wet milling and not just the physical characteristics. Laboratory wet milling studies are carried out to determine the wet milling characteristics of obtained commodity corn (Singh & Eckhoff, 1996). The objective of this study was to evaluate the millability of corn originating from different parts of the world and received at processing plants post transport in different international corn wet milling markets.

2  │ MATERIALS AND METHODS

2.1  │ Corn procurement

Corn samples from Argentina, Brazil, and the United States were acquired from arrival port terminals in Colombia, Taiwan, and Tunisia. Three trucks per shipment vessel (single ship) arriving at the starch plant destination were sampled and then mixed in a 5-gallon plastic bucket for each sample. The mixed samples were air shipped to the University of Illinois, under APHIS (Animal and Plant Health Inspection Service, USDA) permit, in double-sealed plastic bags. All samples were from 2018 corn crop. The received corn samples were then cleaned by sieving over a 12/64 in (4.8 mm) round hole sieve to remove and quantify broken corn and foreign material (BCFM). Cleaned samples were packaged in plastic bags and stored at 4 °C until further processing.

2.2  │ Analytical procedures

Commodity corn samples were analyzed for their chemical composition, BCFM, test weight, and hardness, to observe physical properties of corn which affect the decision of international buyers of corn. A Boerner divider was used to get exact representative samples of all the commodity corn being studied. Corn chemical composition and BCFM were analyzed by an analytical laboratory (Illinois Crop Improvement Association, Champaign, IL). Corn chemical composition of all samples was determined by near-infrared transmittance (Foss GrainSpec, Foss Food Technology) according to a previously reported method (Singh and Graeber, 2005), and BCFM was determined using Grain Inspection, Packers, and Stockyards Administration (GIPSA) method (USDA GIPSA, 2004). The coefficient of variance (COV) for corn compositional analysis was below 0.93% and for BCFM was below 10% for the analytical laboratory. Grain hardness as a
measure of kernel density was measured by the floaters test (Wichser, 1961), for which a sodium nitrate solution with a specific gravity of 1.275 was used. Sample test weights were also determined using GIPSA test weight method (USDA GIPSA, 2004). Moisture content of the corn was determined by drying the samples in hot air oven at 105°C for 72 h (AACCI, 2017, Approved method 44-15.02). For wet milling experiments, all solid loadings were referenced to the moisture content analyzed.

### 2.3 | Wet milling

Corn samples were fractionated into starch, protein, germ fiber, and solubles. All experiments were performed in triplicates. Laboratory-scale 100 g wet milling procedure developed by Eckhoff et al., (1996) was carried out with minor changes made to suit the requirements and improve the efficiency of the process. Wet mill fraction yields were reported as a percentage of dry weight of fraction, of the total corn on a dry basis. Moisture content of the fractions was determined using a two-stage convection oven method (AACCI, 2017, Approved method 44-18).

Laboratory wet milling (100-g procedure) consists of five major steps, involving (a) steeping by soaking the grain in acidified water and sulfur dioxide under controlled temperature conditions. Steeping softens the grain kernel texture and breaks the protein matrix, aiding in easier separation of the corn components in the process. (b) Steeping is followed by a coarse grinding step to separate the germ from the rest of the kernel. (c) The coarse fiber and germ are separated using a sieve, and the starch and gluten are washed off using water. (d) A second sieving step using a finer sieve is carried out to separate the fine fiber from the components after a second grinding step, and starch and gluten are similarly washed off. (e) Starch is separated from the gluten protein via a tabling step based on a density difference in the components.

Slight changes were made to the earlier method established for the washing and separation steps to increase precision. Steeping was carried out at 52°C in an incubator for 48 hr. The first grinding step was carried out at 5,000 rpm for 3 min, followed by increasing blender speed to 6,500 rpm and then 7,500 rpm for a minute each. Pulsing the control for equal distribution of steeped corn slurry in the blender and an equivalent separation of all corn kernels was shown to help in this step. For the germ and coarse fiber washing step, the slurry on top of the sieve was squeezed using a spatula to remove the starch while the other material was retained. Wash water was used to wash off any residual starch and gluten that may be stuck to the fiber, on the sieve, the blender, or on the spatula. For the second grind and washing step, the decanted water was then passed over the sieve to wash the slurry while ensuring uniform dispersion of solids using spatula to break the clumps of fiber.

### 2.4 | Protein extraction

Ground corn samples were defatted using hexane, followed by extraction of each fraction in separate solvent (Ramchandran et al., 2018). During defatting, sample was homogenized by shaking in an incubator at 300 rpm for 2 hr, vortexing the tubes at regular intervals. The homogenized mixture was then centrifuged at 3,234 g for 15 min, and the supernatant fraction containing fat was discarded. The sample was air-dried by leaving it overnight under a fume hood to remove residual hexane. Samples were kept at 4°C to prevent the denaturation of proteins.

Protein fractions were extracted sequentially from the defatted sample by washing and centrifugation method. The extraction media were added in the ratio of 10 ml per gram sample. Supernatant obtained from each extraction step was dialyzed against cold deionized water at 4°C in a porous membrane tubing with a molecular weight cutoff 3.5 kDa. The water was kept agitated using magnetic stir bars and was replaced at regular intervals to ensure dialysis of salts and ions in the supernatant. After dialyzing the samples for 4 days, the samples were taken out in pre-weighed cans and left to dry completely. The total protein fraction per weight of corn sample taken was weighed and noted.
2.5 | Data analysis

Wet milling fraction yields were each calculated after two-stage drying, and the mass balance was calculated as the total of these yields compared to total sample taken on dry basis. Percentage recovery of the different fractions was calculated. All the laboratory wet milling experiments, corn analytical procedures, and protein extractions were done in triplicates. The percentage yield of the different fractions on dry basis as well as the data collected for the physical properties of the corn samples was then compared using an ANOVA test in R (R Core Team, 2020) to determine significant difference in means. Statistical significance was 5% ($p < .05$).

3 | RESULTS AND DISCUSSION

3.1 | Wet mill starch yield

Corn starch yield is the most important factor to consider for end-users and importers of corn for wet milling. The 100 g laboratory wet milling experiments showed that the starch yield of the US commodity corn sample (68–70% w/w) was significantly higher than the South American commodity corn (64–66% w/w) (Figure 1). Millability of the corn samples is different and is dependent upon genetics, agronomic conditions, and postharvest practices (Hill et al., 1979; Jennings et al., 2002); hence, despite having a similar percentage of starch content (Table 2, NIR chemical composition), the starch yield obtained from wet milling varied. These results are indicative of the higher millability of soft endosperm corn exported from the United States.

### Table 1: Physical properties of commodity corn

<table>
<thead>
<tr>
<th>Sample</th>
<th>Floatation index</th>
<th>BCFM (%)</th>
<th>Test weight (lb/bu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>US Colombia</td>
<td>80.00 ± 1.41</td>
<td>0.4</td>
<td>58.44 ± 0.47</td>
</tr>
<tr>
<td>B Colombia</td>
<td>49.67 ± 2.49</td>
<td>1.4</td>
<td>61.20 ± 0.41</td>
</tr>
<tr>
<td>A Colombia</td>
<td>47.33 ± 4.11</td>
<td>0.8</td>
<td>60.45 ± 0.42</td>
</tr>
<tr>
<td>US Taiwan</td>
<td>81.67 ± 2.87</td>
<td>3.4</td>
<td>56.09 ± 0.28</td>
</tr>
<tr>
<td>B Taiwan</td>
<td>58.33 ± 2.05</td>
<td>0.6</td>
<td>60.62 ± 0.32</td>
</tr>
<tr>
<td>US Tunisia</td>
<td>80.00 ± 1.7</td>
<td>1.6</td>
<td>58.94 ± 0.41</td>
</tr>
<tr>
<td>B Tunisia</td>
<td>49.67 ± 1.41</td>
<td>1.4</td>
<td>59.38 ± 0.30</td>
</tr>
<tr>
<td>A Tunisia</td>
<td>47.33 ± 5.31</td>
<td>1.1</td>
<td>60.05 ± 0.13</td>
</tr>
</tbody>
</table>

Note: US, B, A—Corn exported from the United States of America, Brazil, and Argentina, respectively, to countries of export.

### Table 2: Chemical composition of export corn

<table>
<thead>
<tr>
<th>Sample</th>
<th>MC%</th>
<th>Starch%</th>
<th>Oil%</th>
<th>Protein%</th>
</tr>
</thead>
<tbody>
<tr>
<td>US Colombia</td>
<td>14.3</td>
<td>72</td>
<td>4.1</td>
<td>8.3</td>
</tr>
<tr>
<td>B Colombia</td>
<td>10.8</td>
<td>71.1</td>
<td>4.8</td>
<td>9.3</td>
</tr>
<tr>
<td>A Colombia</td>
<td>12.2</td>
<td>72.3</td>
<td>4.4</td>
<td>8.7</td>
</tr>
<tr>
<td>US Taiwan</td>
<td>13.9</td>
<td>71.5</td>
<td>4.3</td>
<td>8.2</td>
</tr>
<tr>
<td>B Taiwan</td>
<td>11.9</td>
<td>71.7</td>
<td>4.8</td>
<td>8.7</td>
</tr>
<tr>
<td>US Tunisia</td>
<td>13.5</td>
<td>72.4</td>
<td>3.9</td>
<td>8.5</td>
</tr>
<tr>
<td>B Tunisia</td>
<td>13</td>
<td>72.2</td>
<td>4.5</td>
<td>8.2</td>
</tr>
<tr>
<td>A Tunisia</td>
<td>12.1</td>
<td>72.1</td>
<td>3.9</td>
<td>8.7</td>
</tr>
</tbody>
</table>

Note: % dry basis.

### Table 3: Protein fractions from commodity corn

<table>
<thead>
<tr>
<th>Sample</th>
<th>Physiologically active protein content (g)</th>
<th>Storage protein content (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>US Colombia</td>
<td>0.33 ± 0.016</td>
<td>0.35 ± 0.008</td>
</tr>
<tr>
<td>B Colombia</td>
<td>0.32 ± 0.011</td>
<td>0.32 ± 0.004</td>
</tr>
<tr>
<td>A Colombia</td>
<td>0.36 ± 0.028</td>
<td>0.40 ± 0.013</td>
</tr>
<tr>
<td>US Taiwan</td>
<td>0.33 ± 0.005</td>
<td>0.39 ± 0.037</td>
</tr>
<tr>
<td>B Taiwan</td>
<td>0.37 ± 0.004</td>
<td>0.34 ± 0.002</td>
</tr>
<tr>
<td>US Tunisia</td>
<td>0.36 ± 0.008</td>
<td>0.36 ± 0.023</td>
</tr>
<tr>
<td>B Tunisia</td>
<td>0.41 ± 0.066</td>
<td>0.37 ± 0.022</td>
</tr>
<tr>
<td>A Tunisia</td>
<td>0.30 ± 0.021</td>
<td>0.41 ± 0.030</td>
</tr>
</tbody>
</table>

Note: Protein content in g extracted per 5 g of ground corn sample. Physiologically active protein are albumin and globulin extracted in water and NaCl solution respectively and storage proteins are prolamin and glutelin extracted in ethanol and NaOH solution. US, B, A—Corn exported from the United States of America, Brazil, and Argentina, respectively, to countries of export.
samples recorded. Artificial drying at high temperatures is also a factor that contributes to a greater number of floaters (Kirleis & Stroshine, 1990). The BCFM in US commodity corn imported by all three countries ranged from 0.4 to 3.4, and was higher as compared to other corn samples from different countries of origin imported by the same country. The US corn also shows a lower test weight across all the end-use countries (Colombia, Taiwan, and Tunisia), indicating that the samples were artificially dried (Gunasekaran & Paulsen, 1985; Kirleis & Stroshine, 1990) at high temperatures. Test weight is a measure of kernel density as well, and factors like moisture content, shape, BCFM, artificial drying, and handling also affect the packaging and weight of a bushel of corn (Pomeranz et al., 1986).

The observed physical properties of corn compared to the starch yield show a striking trend that while US corn has low density and is prone to stress cracks and breakage, it shows a higher starch yield compared to the corn from South America (Figure 1). Since US commodity corn is shown to have softer endosperm compared to South American commodity corn, it can be concluded that the hardness of the endosperm is negatively correlated to the millability of corn.

### 3.3 Chemical composition analysis

A chemical composition analysis of all the corn samples was carried out in order to determine if the difference in wet mill starch yield was due to difference in starch content. The chemical composition of all the corn samples was found to be similar (Table 2). The starch content, which is the major product extracted by wet milling, was approximately 72% for all the commodity corn samples regardless of the export destination and country of origin. Thus, the chemical composition of corn does not seem to be a factor that would help approximate wet mill yield. Wet millers who import international commodity corn tend to choose samples based on physical appearance as there is no discernable difference in the chemical composition of the corn.

### 3.4 Protein fraction analysis

The US commodity corn has a soft endosperm and high starch yield as seen from recorded data. Major four protein fractions (albumin, globulin, prolamin, and glutelin) were separately extracted for all samples, and recovered protein...
was weighed (Table 3). Corn protein composition and distribution affect endosperm hardness and physical properties. Alcohol soluble zein protein (prolamin) is found in protein bodies which are larger and more abundant in hard endosperm corn as compared to those in soft endosperm corn (Dombrink- Kurtzman & Bietz, 1993; Giuberti et al., 2014). The protein matrix of corn is closely related to the intertwined starch matrix and affects starch release and recovery and hence, millability (Christianson, 1970). Base soluble glutelin protein is only extractable after disulfide bond cleavage, indicating presence in corn endosperm as a three-dimensional network crosslinked by these bonds, (Nielsen et al., 1970) and is a distinct protein system. No clear trend in the physiologically active proteins and storage proteins in samples was observed in this study. Commodity corn is a mixture of several different corn varieties, and the observed data for protein fractions in corn do not correspond with earlier studies which were conducted with isogenic hybrids (Dombrink-Kurtzman & Bietz, 1993; Landry & Delhaye, 2007) correlating endosperm hardness to protein content.

### 3.5 Wet milling fraction yields

The yields of other components from the wet milling experiments, germ, gluten, fiber, and steep water (Figures 2 and 3) were also recorded. Around 99% total recovery of solids was ensured for every wet milling experiment. Protein content in the gluten was recovered, and oil content in the germ was also estimated and compared. Percentage recovery recorded was similar to earlier studies carried out with 100 g scale laboratory wet milling (Eckhoff et al., 1996).

The recovered germ was ground and analyzed for oil content which was also consistently about 50% by weight on a dry basis for all the corn samples imported to all three countries. The germ contributed to around 5–6% of the total solids recovered. Germ recovery was higher for US corn exported to Colombia and Tunisia and comparable to corn exported to Taiwan. Previous studies have also shown higher germ recoveries from wet milling with soft endosperm corn, in comparison to hard endosperm corn (Khullar et al., 2011).
The recovered gluten was around 4.5–6% (w/w) of the total corn undergoing wet milling. The protein content in the gluten recovered after tabling was approximately 50% on dry basis for all the corn samples investigated. The coarse fiber and fine fiber fractions, which were combined, formed a major portion of the recovered material and were significantly lower for the US corn (13–15% w/w) compared to the South American samples (18–20% w/w). This can be attributed to the unrecovered starch, in hard endosperm samples with lower millability, which is measured with the fiber, increasing the fiber fraction.

The rest of the material separated was made up by the recovered steep water solids. According to prior research on BCFM and steep water characteristics (Wang & Eckhoff, 2000), soft endosperm corn dried at higher temperatures is likely to release a higher amount of soluble solids and proteins into the steep water. Thus, soft endosperm corn is expected to give lower gluten yield compared to hard endosperm corn. However, there was no significant difference observed in the gluten recovery and the steep water solids from different samples.

3.6 Economic impact and value proposition

US commodity corn has a significantly higher starch yield and hence better millability than the South American commodity corn. For an increase in every one percent of extracted starch yield from wet milling, the economic return is expected to be around 4–6 cents per bushel depending on the sales price of product and plant capacity (Paulsen et al., 2003). The increase in value for using the US commodity corn, which has 4 to 6 percent higher starch yield compared to the other samples analyzed, is in multitudes for a large-scale wet milling plant. For a wet milling processing plant with a capacity of 100,000 bushels a day (Ramirez et al., 2008) operating for 330 days a year, the increase in revenue will be approximately 1.65 million USD for an increase in starch yield by 1 percent. Since the starch yield with US corn is 4–6% higher than South American corn, it implies that a wet milling plant operating with US corn as raw material will provide an additional revenue of 6.5–9 million USD/yr. Economic return will also depend on efficiency of wet milling and starch recovery. Higher revenue from starch justifies adding additional unit operations to remove BCFM for separate processing and/or better handling during transportation to minimize breakage of soft endosperm corn samples. US commodity corn offers better value proposition for importers of corn for wet milling.

4 CONCLUSION

Higher starch yield of 68 to 70 percent from US corn can result in a positive economic impact for importers of corn for wet milling when compared to corn imported from South America. Soft endosperm corn is shown to be superior for corn wet milling owing to a floury starch that is easier to recover in wet milling process. Despite the challenges posed by the physical nature of the soft endosperm corn, which results in higher breakage during transport, higher extractable starch is obtained from soft endosperm corn in wet milling process. An efficient wet milling process utilizing the soft endosperm US corn will result in an increase in revenue by 6.5–9 million USD a year over a plant using hard endosperm corn from other geographical locations.

ACKNOWLEDGMENTS

This work was funded by the US Grains Council and the US Department of Agriculture, Foreign Agriculture Service.

ORCID

Gitanshu Bhatia https://orcid.org/0000-0002-7669-1739
Vijay Singh https://orcid.org/0000-0003-4349-8681

REFERENCES


How to cite this article: Bhatia G, Juneja A, Bekal S, Singh V. *Wet milling characteristics of export commodity corn originating from different international geographical locations*. *Cereal Chem.*. 2021;00:1–8. [https://doi.org/10.1002/cche.10423](https://doi.org/10.1002/cche.10423)