AgriEngineering

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Adaptation of Conventional Wheat Flour Mill to Refine Sorghum, Corn, and Cowpea

Michael Joseph [1,*], Sajid Alavi [2], Akinbode A. Adedeji [3,*], Lijia Zhu [2], Jeff Gwirtz [4] and Shawn Thiele [2]

[1] Prestage Department of Poultry Science, North Carolina State University, Raleigh, NC 27695, USA
[2] Department of Grain Science and Industry, Kansas State University, 201 Shellenberger Hall, Manhattan, KS 66502, USA; salavi@ksu.edu (S.A.); lijiazhu1012@gmail.com (L.Z.); smt9999@ksu.edu (S.T.)
[3] Department of Biosystems and Agricultural Engineering, University of Kentucky, 128 C E Barnhart Building, Lexington, KY 40546, USA
[4] JAG Services Inc., 5000 Clinton Parkway, Lawrence, KS 66047, USA; jeff@jagsi.com
* Correspondence: mvjoseph@ncsu.edu (M.J.); akinbode.adedeji@uky.edu (A.A.A.); Tel.: +1-919-515-2493 (M.J.); +1-859-218-4355 (A.A.A.)

Abstract: This study evaluated the refinement of sorghum, corn, and cowpea grains using the processing steps and equipment originally designed for wheat milling that consists of a conventional gradual reduction system. The need to mill these grains resulted from a desire to produce alternative ingredients for developing new fortified blended extruded foods used for food aid programming. Milling of white sorghum grain resulted in a crude protein content of 7.4% (wb) for both whole and coarse-milled flour. The crude protein content in whole fine-milled sorghum was 6.8% (wb), which was significantly lower than that of whole coarse flour at 9.3% (wb). A decrease in the ash content of sorghum flour correlates with the decortication process. However, degermed corn, fine and coarse, had significantly different crude protein content of 6.0 ± 0.2% (wb) and 7.7 ± 0.06% (wb), respectively. Degerming of corn improved the quality of corn flour (fine and coarse) by reducing the crude fat content from 3.3 ± 0.18% (wb) to 1.2 ± 0.02% (wb) and 0.6 ± 0.13% (wb), respectively. This helped increase the starch content from 60.1 ± 0.28% (wb) in raw corn to 74.7 ± 0.93% (wb) and 71.8 ± 0.00% (wb) in degermed fine and coarse corn flour, respectively. Cowpea milling did not produce differences in the milling stream outputs when the crude fat and crude protein were compared. Whole flour from the grains had higher milling yields than decorticated flour. This study demonstrated that a mill dedicated to wheat size reduction can be adapted to refine other grains to high quality.

Keywords: milling; sorghum; cowpea; corn; proximate content; whole flours; fortified blended foods

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Citation: Joseph, M.; Alavi, S.; Adedeji, A.A.; Zhu, L.; Gwirtz, J.; Thiele, S. Adaptation of Conventional Wheat Flour Mill to Refine Sorghum, Corn, and Cowpea. *AgriEngineering* **2024**, *6*, 1959–1971. https://doi.org/10.3390/agriengineering6030114

Academic Editor: Pankaj B. Pathare

Received: 4 May 2024
Revised: 8 June 2024
Accepted: 18 June 2024
Published: 24 June 2024

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1. Introduction

Milling is a very important unit operation in grain processing. It allows the disruption of the structural integrity of grain in order to separate its constituent into fractions with increased functionality and nutritional quality. For example, the degerming process separates the oil-rich germ from the main constituent of the grain, the endosperm, which is rich in starch and protein. Oil is extracted from the germ for different food and industrial applications, while the endosperm is further milled into different particle sizes (coarse, medium, or fine) for all kinds of uses. Most mills are designed primarily for common grains like wheat. The adaptation of a particular mill designated for a grain to process other grains like cowpea, sorghum, and corn is usually challenging, and the functionality and nutritional quality of the end fractions are unpredictable.

Common food aid products are made from staple grains like corn and soy (a corn-soy blend that needs to be ground [1,2]. The USAID report on improving the quality of food aid strongly recommended that these products be developed with ingredients common in regions where they are mostly served to help local economies grow, reduce cost and

time of supply, and decrease the chance of rejection of the food due to concerns around GMOs that corn-soy blends are made from [2]. Food aid is an effective mechanism used by governments and humanitarian organizations to fight food insecurity and to restore health of millions of people suffering from chronic and hidden hunger in many developing economies [3]. They are also the most preferred commodities for food aid, either as staple grain or as part of specially formulated foods, along with legumes such as soybean to supplement essential amino acids [4,5]. In the past decade, there has been a renewed focus on increasing the effectiveness of food aid and maximizing nutritional impact [6]. One major step in this direction is to increase the flexibility of programming, take into account the availability of commodities, and explore alternative cereals such as sorghum and millets, as well as legumes such as cowpeas [2].

Sorghum is a drought-tolerant crop and can also withstand significant heat stress. This makes it particularly suited as a long-term, sustainable staple that can withstand climatic vagaries. It is priced competitively with other food aid grains and is nutritionally equivalent if processed properly [7]. Furthermore, it is not part of a range of crops in the food supply that are genetically modified organisms (GMO) and restricted by several countries around the world, especially in places where food aids are served. Cowpea is a legume crop that is also non-GMO. It can be used in specially formulated food aid products such as fortified cereal-legume blends (also known as fortified blended foods or FBFs) to deliver greater and higher quality protein to supplement the lysine-deficient cereal [8].

Like corn, both sorghum and cowpea are also grown and consumed in many parts of Africa, where a lot of food aid is provided [7–9]. These crops are well suited for local and regional procurement of food aid, which is another key trend for making food aid programming cost-effective and timely while strengthening agriculture and food markets in developing countries [10]. For effective use of these crops in food aid products such as FBFs, in-country production of flour, grits, and meals is needed at an industrial scale. However, milling these grains typically requires techniques that are either specialized or rely on the unorganized sector, making them uneconomical and/or infeasible [9,11–14]. The development of simple flowsheets that can allow the use of existing in-country flour milling capacity and the design of other scalable techniques for large-scale processing of corn, sorghum, and cowpeas are some ways to address this unique challenge. This is the primary focus of this study.

Milling of various grains is a topic that has been well researched using various methods and with the aim of optimizing yields, characterization of physicochemical properties of flours, or evaluation of the quality of end products such as bread and porridge [15–22]. Most of the studies on sorghum milling were based on the use of hammer mills or lab-scale mills. There has been only one study that showed sorghum fractionation using a pilot-scale wheat mill [23]. While corn is normally wet milled to produce starch, oil, and by-products like corn gluten meal [24], dry milling of corn is executed by using a stone mill, hammer mill, or stationary roller mill for producing corn products for human consumption or for production of ethanol [25]. Cowpea milling has also mainly been executed using hammer and pin mills in addition to the wet milling process [20]. Therefore, this study is the first to develop a process for dehulling and milling of cowpeas by adapting a conventional gradual reduction roller mill designed to produce wheat flour. The authors also reported simplified milling flows for decortication and particle size reduction of corn and sorghum on the same pilot-scale wheat milling system to obtain coarse and fine dehulled (in the case of corn, also degermed) flours. Hammer milling of corn and sorghum and subsequent grading for producing coarse and fine whole flours is also described. The various milling fractions were analyzed for proximate composition. The yield and particle size distribution of end products were also characterized. The overall aim was to develop protocols that can be easily scaled up to industrial production of milled corn, sorghum, and cowpea for food aid applications, using available infrastructure in developing countries.

2. Materials and Methods

2.1. Materials

Whole white sorghum (variety Fontanelle 4525) was procured from Nu Life Market, Scott City, KS, USA. Yellow dent corn was procured from Agronomy Foundation Seed, Kansas State University, Manhattan, KS, USA. Cowpea (variety number 8046) was obtained from LPD Enterprises LLC (Olathe, KS, USA).

2.2. Milling of Dehulled Sorghum and Degermed Corn

Whole sorghum and corn grains were milled to produce dehulled sorghum flour and degermed corn flour, respectively, using a conventional wheat flour mill (Hal Ross Flour Mill, Kansas State University, Manhattan, KS, USA). This pilot-scale gradual reduction Buhler roller milling system was operated at a throughput of 0.27 kg/s (or 1000 kg/h) of whole grain. Prior to milling, both sorghum and corn grains were subjected to conditioning and post-conditioning processes (Figure 1). The sorghum grain with an initial moisture content of 7% (wb) was conditioned by adding a measured quantity of water (27 mL/s or 100 L/h) to obtain a moisture of 15.5% (wb) and storing it in a tempering bin for 24 h. The tempering moisture and time were determined based on requirements for hard wheat. For conditioning of corn having an initial moisture content of 10.5% (wb), water at the rate of 1.25 mL/s (or 4.5 L/h) was added right before the peeler with minimal tempering time (30 s). After tempering, both grains were taken through a post-conditioning process wherein they passed through an abrasive peeler, followed by a scourer, and then through an aspirator. The peeler was used to remove the maximum seed coat, and the throughs or peelings were discarded. The peeler conditions were the same for sorghum and corn, and the removals were not quantified. The scourer helped remove surface contamination from the grains, such as fines, dust including sand, clods of soil, and insects and their fragments. The aspirator, attached to the end of the scourer, separated any detached hull particles or any other remaining surface contaminants neatly from the grain. Cleaned grain was collected from the bottom of the aspirator and put into the 1 BK (first break) bin for milling.

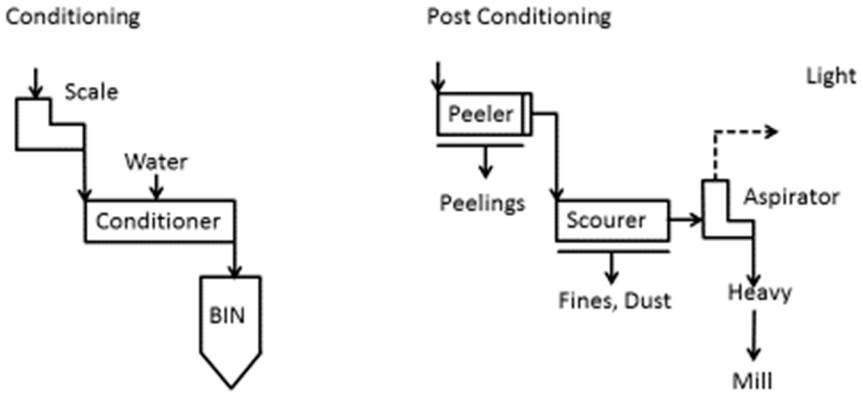


Figure 1. Conditioning and post-conditioning flow before sorghum and corn milling.

The mill flows for both corn and sorghum were the same, as shown in Figure 2. The milling steps were designed to obtain two fractions, fine flour (−315 µm) and coarse meal (+315 µm). The grain went through five break rolls (1 BK to 5 BK), three purifiers (P-1 to P-3), four reduction rolls (1 Siz, 2 Siz, QU, and 1T), and a bran duster (BD). Some roll stands of the mill were bypassed and not used, as only two particle-size fractions of flour were required. The roll details, including grinding action, are provided on the flowsheet. The differential speeds of the corrugated rolls were 2.5:1, and the roll disposition of dull-to-dull and the smooth rolls were 1.25:1. The goal of the breaking system was to remove the endosperm from the bran, with each roll having successively finer corrugations and set to maximize pure endosperm. Cleaned grain was fed to the 1 BK corrugated rolls, spaced at 1.25 mm, for initial coarse splitting. The broken grains and some separated bran were then

sent to a vibrating sifter with screens of increasing fineness from top to bottom, allowing the finer flour to sift to the bottom and the coarse bran to be removed from the top. Cutting of the bran is common for a small-sized grain such as sorghum, resulting in a mixture of endosperm and bran in released middlings. These were sent to the purifiers, where a controlled flow of air lifted off the fragmented bran particles and at the same time, a bolting cloth separated endosperm fractions by size and quality. The overs (+600 µm) were collected above nylon sieves of 32 grid gauze (GG), and fines (−315 µm) were the products that passed through sieves of 54 GG. The purified middlings were sent to the reduction rolls, while the coarser fraction was carried to 2 BK rolls (spaced closer together at 0.5 mm). The process repeated itself through 3 BK. After 3 BK and its sieving and reduction, the decorticated sorghum flour was collected from the patent screw (fine flour) and semolina screw (coarse meal). The overtails from the quality rolls (QU) fed the 4 BK, followed by sieving and size reduction at 5 BK and QU. Finally, the 5 BK produced flour, which passed through the 315 µm sieve, and the overtails were collected as feed and bran.

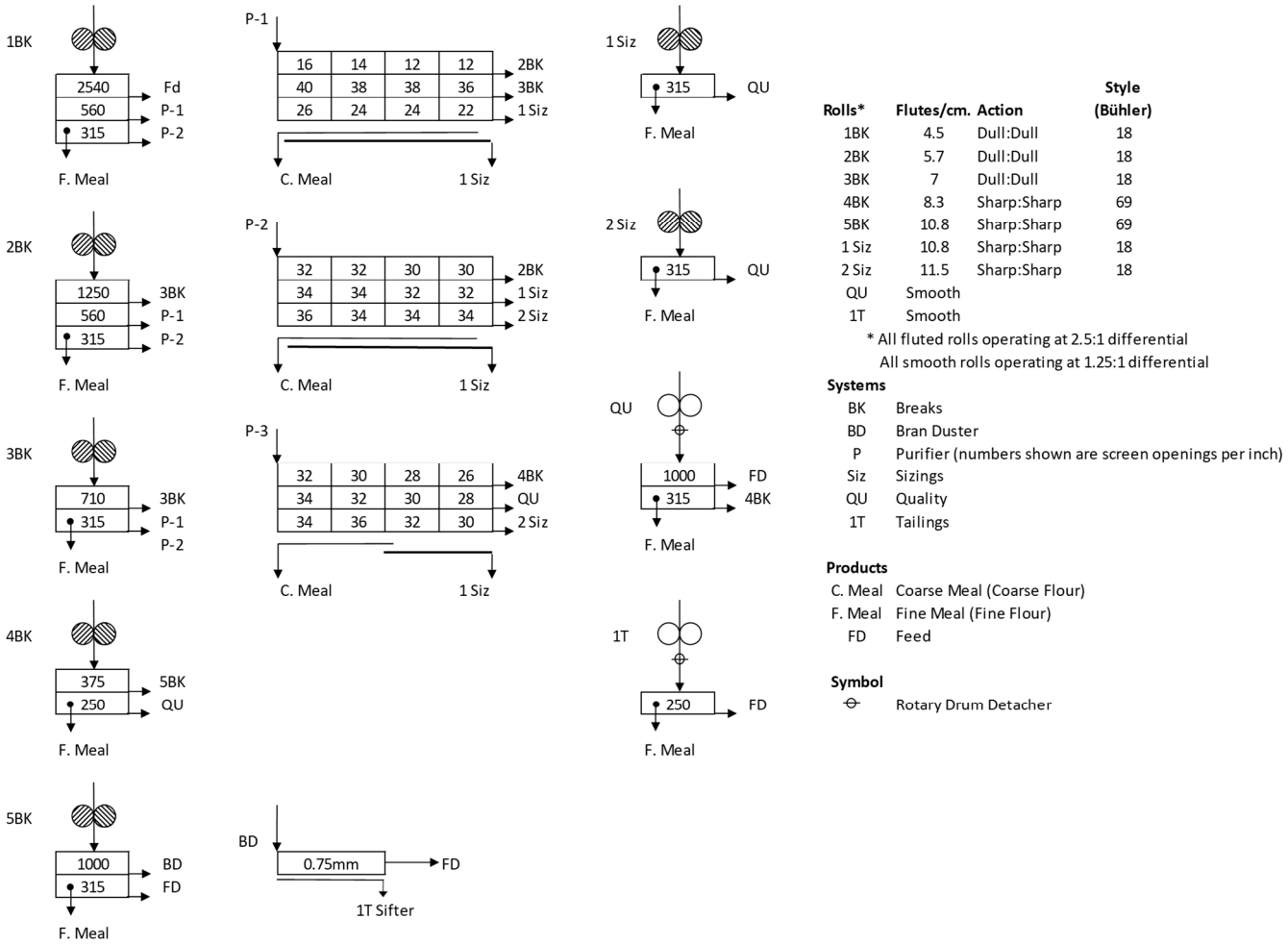


Figure 2. Milling flow chart for producing decorticated sorghum and corn flour.

2.3. Milling of Whole Sorghum and Whole Corn

The milling for obtaining whole fine (−315 µm) and coarse (+315 µm) flour fractions from sorghum and corn grain without dehulling was also carried out in the Hal Ross facility using an 18-7-301 model pilot scale Circ-U-Flow hammermill (Schutte Buffalo, Buffalo, NY, USA) having a width of 177.8 mm and rated tip speed of 85.85 m/s (or 16,900 feet/minute). A pictorial representation of the same is provided in Figure 3. Cleaned grain was fed to the hammer mill fitted with an 1190 µm (or 3/64 inch) screen. The product was caught by the hammer rotors, and the particle size was reduced till it passed through the screen.

This flour was sifted on a vibrating sieve assembly. The overs (+315 µm) on the sieve were collected as whole coarse flour or meal, and the throughs as whole fine flour.

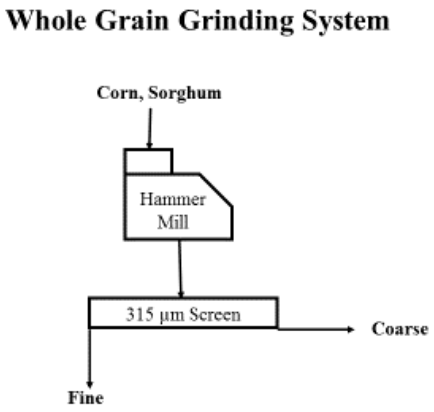


Figure 3. Milling system for production of whole sorghum and whole corn.

2.4. Milling of Cowpea

Cowpea was milled using the same conventional pilot-scale roller wheat milling system described before. The grain was subjected to a cleaning process by passing it through a screener/aspirator to remove fines, brokens, and black eyes of cowpeas. After the first cleaning, the grain was stored in 'dirty' bins, which are used for incoming raw material, and was passed through a combination cleaner wherein the screener removed the remaining fines and the aspirator removed any light impurities. After the second cleaning, cowpeas were placed in tempering bins just for storage. The grain, at an initial moisture content of 8.42% (wb), was not tempered because water addition led to cowpea fractions becoming sticky and it hindered the flow of material. From the temper bins, the grains were subject to peeling, followed by aspiration to remove fines and brokens, and then finally stored in the 1 BK bin till actual milling started.

The milling flow (Figure 4a) was very different than sorghum and corn, and fewer rolls were used because only one particle size of the flour was targeted (−315 µm). The cleaned grain from the 1BK bins was fed to 1/2 BK double-high corrugated rolls rotating at different speeds for initial coarse splitting. The broken grains were then sent to a vibrating sifter having screens of increasing fineness from top to bottom (1041 µm, 500 µm, and 315 µm), as shown in Figure 4a. The +1041 µm particles or scalp, which contained mainly bran, were sent to feed. The −1041 µm to +500 µm particles collected on top of the 500 µm screen were sent to the purifier for further separation of bran and endosperm. The −500 µm to +315 µm fraction was also sent to the purifier. The −315 µm particles from 1/2 BK rolls were collected as flour. The throughs from the purifiers were sent to middlings reduction rolls (1/2 M), and the output from there was passed through a sifter having a 315 µm screen. Maximum flour was collected as throughs from this sifter while the overs were directed to the feed stream.

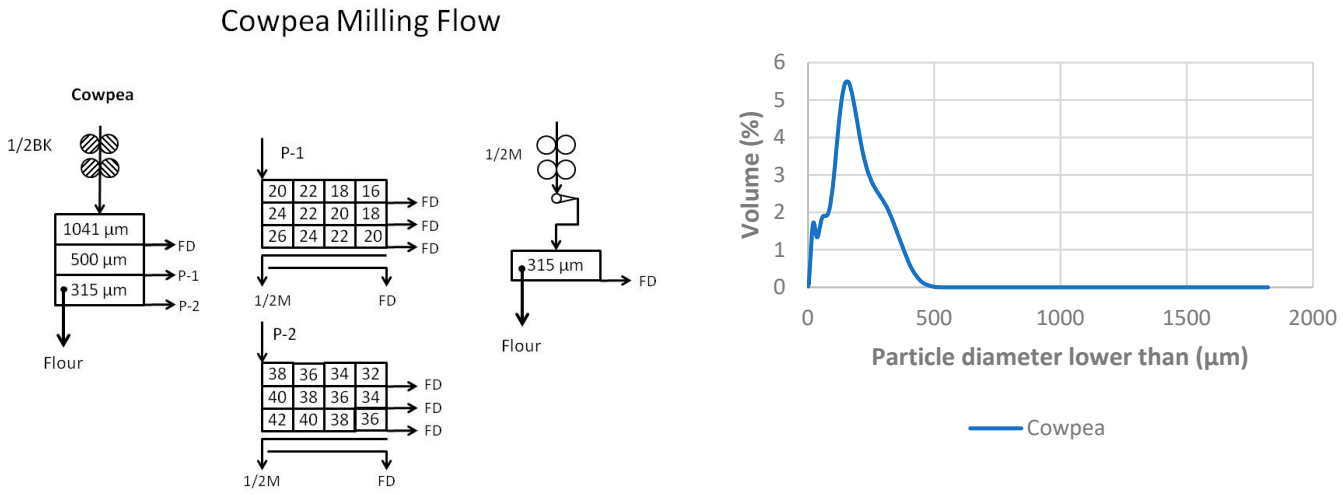
2.5. Particle Size Analysis

The particle size distribution of milled products was determined using a laser diffraction particle size analyzer (LSTM 13320, Beckman-Coulter, Inc., Miami, FL, USA) following the protocol for the equipment. Each sample was tested in duplicate.

2.6. Proximate Composition

The proximate composition of raw grains and their milled components was determined using standard methods. This included the determination of moisture (135 °C for 2 h; AACC 44-19.01, 2010 [26]), crude protein (based on nitrogen by combustion, 6.25× Nitrogen %, AOAC 920.176 [27]), crude fat (petroleum ether extract method; AOCS Ba 3-38 [28]), ash (600 °C for 2 h; AOAC 942.05 [27]), crude fiber (ceramic fiber filter method;

AOAC 962.09 [27]); and total starch (glucoamylase method; AOAC 979.10 [27]). Protein, starch, fat, ash, and crude fiber contents were reported on a dry basis (% db) from replicates.



(**a**) (**b**)

Figure 4. (**a**) Flowchart for milling of decorticated cowpea; (**b**) Particle size distribution of decorticated cowpea.

2.7. Statistical Analysis

Duplicate results for each test parameter were analyzed ($p \leq 0.05$) using a one-way analysis of variance (ANOVA). Tukey's post hoc means separation test at a 5% level of significance was used to determine significant differences. Statistical analyses were performed with SAS® statistical software (version 9.2, SAS Institute Inc., Cary, NC, USA) using PROC GLM.

3. Results and Discussion

3.1. Sorghum Milling

Proximate analysis of whole sorghum grain is given in Table 1, which was consistent with the ranges for protein (7.3–15.6%), fiber (1.2–6.6%), fat (0.5–5.2%), ash (1.1–2.5%) and starch (55.6–75.2%) reported in the literature, although the composition can vary widely with variety and other factors [29]. Proximate analysis data for different fractions of sorghum obtained after roller milling are also presented in Table 1. The endosperm makes up the bulk of the sorghum grain, typically accounting for 84–90% of its weight, while the pericarp (3–6%) and germ (5–10%) are the other major components [29]. Roughly half of the fiber in the sorghum grain is present in the pericarp [30]. Therefore, its efficient removal should lead to a substantial decrease in the fiber content of the resultant flour. This was indeed the case as crude fiber content of 0.4% in dehulled fine flour (−315 µm) and coarse meal (+315 µm) was significantly lower than that of whole grain (1.9%). The germ has been reported to contain the majority of lipids (76.2%) and ash (69%) present in the grain [29]. The significantly higher content of crude fat (3.9–4.1%) and ash (1.7–1.8%) in the non-endosperm fractions, as compared to the whole grain (3.2% and 0.6%, respectively), point to the removal of a substantial part of the germ during milling. The significantly lower crude fat content (1.7% and 0.5%, respectively) of the dehulled fine flour and coarse meal, as compared to the whole grain, was also consistent with this result. The protein content in the dehulled fractions was not significantly different than the whole grain, as has been reported previously for laboratory and industrial-scale roller milling of sorghum [30]. The protein recovery was 97.1 and 96.3% in dehulled fine flour and coarse meal, respectively, relative to whole sorghum grain. It was comparable to the protein recovery in milled sorghum, as reported by [31]. However, their study used stone and disc

mills for decortication and milling. The starch content increased significantly from 61.8% in whole grain to 69.8% and 72.3% in dehulled fine flour and coarse meal, respectively. Sorghum endosperm is reported to typically contain 81.3 to 83.0% starch [29]. However, the starch content of the dehulled fractions was similar to that reported for abrasion-milled Fontanelle sorghum varieties [32] and within the range reported for various roller-milled sorghum flour varieties by [33], although on the lower end. The low ash content in the final flours is an indicator that the milling process was able to separate the endosperm from the pericarp and germ [34]. Therefore, these proximate analysis data confirmed that the pilot-scale roller milling method used in this study was effective in removing significant portions of germ and pericarp and purifying the endosperm from whole sorghum.

Table 1. Proximate analysis of sorghum milling streams.

Product	Milling Streams	Crude Protein (%)	Crude Fiber (%)	Crude Fat (%)	Ash (%)	Starch (%)
Whole Grain	**Before milling**	**7.6 ± 0.2 ^{a}**	**1.9 ± 0.1 ^{aci}**	**3.2 ± 0.2 ^{a}**	**0.6 ± 0.0 ^{agj}**	**61.8 ± 0.6 ^{a}**
Dehulled Sorghum (roller milled)	Flour from 2 M	12.3 ± 0.3 ^{b}	1.3 ± 0.1 ^{ae}	3.9 ± 0.1 ^{d}	1.8 ± 0.1 ^{d}	58.6 ± 0.1 ^{dg}
	Hulls from Peeler	7.8 ± 0.3 ^{a}	2.0 ± 0.2 ^{ci}	4.1 ± 0.0 ^{d}	1.7 ± 0.0 ^{d}	57.0 ± 0.0 ^{d}
	Semolina/Grits	7.3 ± 0.3 ^{a}	1.0 ± 0.0 ^{degj}	0.5 ± 0.0 ^{c}	0.3 ± 0.0 ^{ch}	70.5 ± 0.3 ^{bc}
	Dehulled fine (−315 µm)	**7.4 ± 0.1 ^{a}**	**0.4 ± 0.1 ^{b}**	**1.7 ± 0.0 ^{b}**	**0.7 ± 0.0 ^{abf}**	**69.8 ± 0.4 ^{beh}**
	Dehulled coarse (+315 µm)	**7.3 ± 0.2 ^{a}**	**0.4 ± 0.1 ^{bd}**	**0.5 ± 0.2 ^{c}**	**0.3 ± 0.0 ^{c}**	**72.3 ± 0.4 ^{c}**
Whole Sorghum (hammer milled)	**Whole fine (−315 µm)**	**6.8 ± 0.1 ^{a}**	**1.6 ± 0.1 ^{acg}**	**3.0 ± 0.1 ^{a}**	**1.3 ± 0.0 ^{e}**	**68.0 ± 0.8 ^{e}**
	Whole coarse (+315 µm)	**9.3 ± 0.3 ^{c}**	**3.1 ± 0.1 ^{f}**	**3.0 ± 0.1 ^{a}**	**1.3 ± 0.0 ^{e}**	**57.3 ± 0.6 ^{d}**

Data for whole grain and final products are in bold font. Means in the same column not having the same subscript are significantly different at $p < 0.05$.

Proximate analysis data for whole sorghum flour (−315 µm) and meal (+315 µm) obtained from hammer milling are also provided in Table 1. There was no significant difference in fat and ash content in the two fractions, but the coarser hammer-milled fraction had significantly higher ($p < 0.05$) protein and fiber and significantly lower ($p < 0.05$) starch content. Bran fragments are typically larger in size and, thus, more likely to get retained on the 315 µm screen [35]. In addition, the lesser degree of milling for larger-sized particles in the meal could have removed less bran. The coarser meal also likely had a higher proportion of the hard, corneous (or vitreous) part of the endosperm that contains greater protein and less starch as compared to the floury endosperm [29,30]. These factors could have contributed to the difference in composition between the coarse and fine fractions of hammer-milled whole sorghum. These results are consistent with the findings of [36], who reported a reduction in fiber and protein content and an increase in starch content in the lower particle size fraction (−250 µm) of milled whole sorghum obtained after sieving.

3.2. Cowpea Milling

A proximate analysis of whole cowpea and its various milled fractions is shown in Table 2. Mill by-product screening (mentioned as hulls from mill by-products) removes the unwanted outer shell/seed coat of cowpea, which is a low protein-containing component of the seed. Therefore, the lower protein content in that fraction was able to demonstrate the efficacy of peeling, which could efficiently remove just the seed coat without taking away parts of endosperm with it that is rich in protein. It was observed that the protein content of different fractions was not significantly different ($p < 0.5$) except for the fraction from the mill by-product screen. Most of the germs were removed during the peeling process, as evidenced by the increase in the fat content of peelings relative to the raw cowpea. The fiber content in the peeler screenings and mill by-product screens was found to be exceptionally high at 10.0% and 22.0%, respectively. These fractions had significantly higher ($p < 0.05$) fiber content than other fractions of cowpea, which indicated efficient removal of seed

coat from the endosperm of the grain. The milling removed the germ effectively, as can be observed from the significantly high ($p < 0.05$) fat content of 1.7% in the peeler screens and subsequently significantly lower ($p < 0.05$) fat content of 0.7% in the mill by-product screen as compared to all other fractions of cowpea. Ash content was lowest in the mill by-product screen, and it was significantly different from other fractions of the cowpea milling stream. The starch content increased significantly ($p < 0.05$) after decortication of cowpea grain.

Table 2. Proximate analysis of cowpea milling streams.

Product	Milling Streams	Crude Protein (%)	Crude Fiber (%)	Crude Fat (%)	Ash (%)	Starch (%)
Whole Cowpea	Before milling	25.0 ± 0.4^{a}	2.2 ± 0.2^{a}	1.2 ± 0.1^{a}	3.1 ± 0.2^{a}	36.2 ± 0.1^{a}
Dehulled Cowpea (roller milled)	Hulls from peeler	25.2 ± 0.2^{a}	10.0 ± 0.2^{b}	1.7 ± 0.0^{b}	3.5 ± 0.2^{a}	18.9 ± 0.4^{b}
	Hulls from mill by-products	21.1 ± 0.2^{b}	22.0 ± 0.2^{c}	0.7 ± 0.1^{c}	5.1 ± 0.3^{a}	9.8 ± 0.1^{c}
	Peeled cowpea to 1/2 BK	25.9 ± 0.0^{a}	1.6 ± 0.4^{a}	1.1 ± 0.1^{a}	2.6 ± 0.1^{a}	38.0 ± 0.6^{d}
	Flour from 1/2 M flour	26.0 ± 1.0^{a}	1.1 ± 0.4^{a}	1.3 ± 0.1^{a}	2.8 ± 0.0^{a}	43.5 ± 0.0^{e}
	Ground stock to 1/2 M sifter	25.7 ± 0.5^{a}	1.7 ± 0.2^{a}	1.1 ± 0.1^{a}	2.7 ± 0.3^{a}	42.1 ± 0.1^{f}
	Flour from 1/2 BK	$\mathbf{26.1 \pm 0.3^{a}}$	$\mathbf{1.1 \pm 0.1^{a}}$	$\mathbf{1.1 \pm 0.1^{a}}$	$\mathbf{3.1 \pm 0.0^{a}}$	$\mathbf{40.7 \pm 0.0^{g}}$

Data for whole grain and final product are in bold font. BK = Break rolls, M = Middlings, Values in the same column not sharing the same subscript are significantly different at $p < 0.05$.

Milling did not affect the overall nutritional composition of cowpea flour largely, but it did reduce the fiber content [37]. It was reported by Ward et al. [38] that the moisture, fat, protein, ash, and total carbohydrate composition of cowpeas were not affected by milling and particle size. The particle size distribution of the milled cowpea flour (Figure 4b) showed that the milling method was efficient. This was due to the majority of the flour particles being found to be below the target particle size of −315 µm. The roller mills help produce flours within a small range of particle size distribution. Reichert, Lorer, and Youngs [39] observed that upon dehulling of brown and white varieties of cowpea on barley de-Awner, the seed coat had the least amount of protein and fat and the highest amount of ash and fiber when compared to others. The current observations in this study are in accordance with the above findings and clearly established that cowpea flour with low fiber and fat content could be produced on wheat flour roller mills. The fat and starch content of cowpea flour increased with a decrease in particle size in the cowpea milling study conducted by Kerr, Ward, and McWatters [40]. They attributed the higher starch content in finer particle-sized flour to the occurrence of a greater degradation of starch when passing through smaller sieves (and presumably higher shear conditions due to passage through restricted sieve openings) that facilitate higher starch extraction.

3.3. Corn Milling

The proximate composition of different milled fractions of corn is shown in Table 3. The average protein content in the degermed fine (6.0%) and coarse corn (7.7%) are significantly ($p < 0.05$) different. The M-2 (stream), where the fine flour is collected through a screw conveyor, had a significantly higher ($p < 0.05$) protein content (9.5%) than the degermed fine and coarse fractions as the protein matrix surrounds the endosperm, which is primarily starch [9]. A study by Shevkani et al. [41] showed the composition of corn grits from three successive reductions in dry milling, and they found similar protein, lipid, and carbohydrate content between the fine (<300 µm) and medium-coarse (300–500 µm) fractions. The flour stream from patent screw, raw corn, and corn meal had lower protein content as compared to other streams, and it clearly indicated that milling could remove the seed coat and would discard it through the corn meal stream. It can be observed from the table that milling was able to reduce the fiber content in degermed fractions of corn flour significantly ($p < 0.05$) from the raw maize stream, which carried most of the hull and germ.

Similarly, fat and ash were also reduced in the degermed fractions. Degerming and seed coat removal significantly increased ($p < 0.05$) the starch content of the corn flour fractions.

Table 3. Proximate analysis of corn milling streams.

Product	Milling Streams	Crude Protein (%)	Crude Fiber (%)	Crude Fat (%)	Ash (%)	Starch (%)
Corn	Raw corn	7.8 ± 0.03^{c}	1.9 ± 0.20^{b}	3.3 ± 0.18^{c}	1.2 ± 0.07^{ac}	60.1 ± 0.28^{c}
	M-2 Stream clear	9.5 ± 0.20^{ad}	0.5 ± 0.08^{a}	2.0 ± 0.19^{a}	1.0 ± 0.04^{a}	67.5 ± 0.07^{a}
	Flour from Patent screw	6.1 ± 0.20^{b}	0.7 ± 0.21^{a}	0.6 ± 0.08^{b}	0.3 ± 0.03^{b}	75.5 ± 1.20^{b}
	Coarse meal from purifiers	7.9 ± 0.05^{c}	0.1 ± 0.06^{a}	0.4 ± 0.15^{b}	0.2 ± 0.04^{b}	74.5 ± 0.57^{b}
	Degermed fine	6.0 ± 0.20^{b}	0.2 ± 0.03^{a}	1.2 ± 0.02^{d}	0.3 ± 0.05^{b}	74.7 ± 0.93^{b}
	Degermed coarse	7.7 ± 0.06^{c}	0.2 ± 0.03^{a}	0.6 ± 0.13^{b}	0.3 ± 0.02^{b}	71.8 ± 0.00^{b}
	Whole Corn (+315 µm)	9.9 ± 0.04^{a}	3.4 ± 0.36^{c}	2.5 ± 0.09^{a}	1.3 ± 0.10^{c}	54.6 ± 1.77^{d}
	Whole Corn (−315 µm)	9.1 ± 0.08^{d}	2.0 ± 0.15^{b}	3.1 ± 0.02^{c}	1.4 ± 0.11^{cd}	63.2 ± 0.07^{c}

Whole corn fractions are the output after hammer milling; values in the same column for respective grains not sharing the same subscript are significantly different at $p < 0.05$.

The whole corn fractions (coarse and fine) had different proximate contents as well. The coarse fraction had a significantly higher ($p < 0.05$) content of protein and fiber as compared to whole fine corn flour. Fat, ash, and starch contents were found to be higher in the fine fraction of whole corn than in whole coarse corn. A study conducted by Bookwalter et al. [42] characterized different fractions of dry milled high lysine corn and ordinary dent corn, and they found that fat and ash content were higher in lower particle-sized corn fractions in both cases, and protein and fiber were higher in coarser fractions.

3.4. Flour Yield and Particle Size

This study was not optimized for yield but rather simple flows using minimal processing technologies. The effort was to establish methodologies for milling sorghum, corn, and cowpea in a simple way using a wheat flour mill. The flour yield was calculated by dividing the mill fraction of interest by the total native feed (dirty feed) to the mill. The yield of useful flour fractions of sorghum, corn, and cowpea is listed in Table 4. The yield for decorticated sorghum flour was 68.4%, and for whole sorghum was 88%. Anderson [43] reported a 66% yield of white sorghum flour produced on a wheat mill, whereas Alvarenga et al. [44] reported an average yield of 69.16% when red sorghum was milled using a roller wheat flour mill. Yoganandan et al. [45] found the white sorghum milled on a laboratory-scale roller mill had yields ranging from 57.91 to 62.08% for different tempering conditions. Sorghum grits, which were tempered at 16% moisture, had yields of 76–79% [15]. They further found an increase in yield as the tempering time increased from 2 h to 8 h. FAO [46] reported the yield for whole sorghum flour to be around 90%. The particle size of decorticated sorghum fine and coarse was 202.93 µm and 518.43 µm, respectively. The particle size of whole sorghum fine and coarse was 407.33 µm and 459.07 µm, respectively. It is interesting to note that whole flour had higher particle size for fine flour and lower particle size for coarse flour compared to decorticated flour. This could be attributed to the difference in milling methods. Hammer milling produced flours of one variety, which were segregated into fine and coarse over a 315 µm sieve. The larger particle size of the whole fine flour than the screen size could be due to the fact that the hammer mills are not perfectly sealed systems at the seams holding the sieves. Further, cellulose-containing materials, when ground, have greater length than their diameter. Moreover, the forces propelling (hammer) or sucking/blowing (air) material through a screen would facilitate the movement of elongated particles through the hammer mill screen nearly perpendicular to the screen surface. With the particles' long axis parallel to airflow and perpendicular to the hammer mill screen opening, the orientation offers the least resistance to airflow through the screen. Also, the diagonal length of the sieves would be 445.48 µm (by Pythagorean theorem), which is clearly enough for a particle with a diameter of more than 315 µm to

pass through. The gradual milling of decorticated flour might have produced much smaller particles due to gradual size reduction, and that passed through the sieve horizontally as it has only gravitational force acting most of the time when passing through the sifter.

Table 4. Milling yield and average particle size of flour fractions of sorghum, corn, and cowpea.

Flours	Yield (%)	Average Particle Size (μm)
Decorticated sorghum—fine	68.40	202.93 ± 2.17
Decorticated sorghum—coarse	68.40	518.43 ± 0.67
Whole sorghum—fine	88.00	407.33 ± 9.57
Whole sorghum—coarse	88.00	459.07 ± 4.29
Degermed corn—fine	67.00	93.79 ± 0.74
Degermed corn—coarse	66.66	491.09 ± 2.13
Whole corn—fine	86.95	197.56 ± 0.34
Whole corn—coarse	86.95	439.10 ± 0.95
Cowpea	86.00	124.57 ± 0.82

The yield of degermed corn flour—fine and coarse was 67.00% and 66.66%, respectively. The whole corn flour yield for fine and coarse was the same at 86.95%. The yield of corn endosperm products falls in the range of 65–70% [47]. Rausch et al. [48]) reported an average yield (on a dry basis) of 39.16% for large grits, 25.25% small grits, and 13.81% fines, along with 14.29% germ and 6.83% pericarp fractions for corn fractions. They added that the yield of corn components during milling is dependent on the type of hybrid corn being milled. Manay and Sadaksharaswamy [49] also reported a yield of around 75% of endospermic corn fractions during dry milling. The average particle size of degermed corn flour—fine and coarse they reported were 93.79 μm and 491.09 μm, respectively. The particle size of whole corn flour—fine and coarse was observed as 197.56 μm and 439.10 μm, respectively. Wingfield [50] subdivided corn meal into categories of coarse meal (1190–730 μm), medium meal (730–420 μm), and fine meal or cones (420–212 μm). So, the coarser particle flour was in the medium meal category, and the fine particle flour was in the flour category. The standards for maize, as stipulated by Title 21 (Part 137) of the U.S. Code of Federal Regulations (USCFR) of 2023, are different from the above sub-divisions of corn meal. According to the USCFR, the standards for corn products listed are white corn flour (137.211—not less than 98% passes through No. 50 sieve (300 μm) and not less than 50% passes through No. 70 (212 μm) woven-wire cloth) [51], yellow corn flour (137.215—not less than 98% passes through No. 50 sieve (300 μm) and not less than 50% passes through No. 70 (212 μm) woven-wire cloth) [52], white corn meal (137.250—not less than 95% passes through No. 12 sieve (1.7 mm) and not less than 45% passes through No. 25 (71 μm), but not more than 35% pass through No. 72 grit gauze (224 μm) [53], enriched corn meal (137.260—meets the standards of white corn meal and other meals defined in CFR) [54], degermed white corn meal (137.265—not less than 95% passes through No. 20 sieve (850 μm) and not less than 45% passes through No. 25 (710 μm), but not more than 25% pass through No. 72 grit gauze (212 μm) [55]. It is possible that some aspects of a government-provided standard for a product may be less restrictive than the commercial standard of the customer.

The milling yield of cowpea was found to be 86% (Table 4). Jarrad et al. [18] reported a 90% yield of cowpea flour when using cyclone-assisted impact/attrition milling. The particle size of cowpea flour was found to be 124.57 μm. Abdelrahim and Mudawi [56] reported that in Nigeria, over 40% of the commercial cowpea flour had finer particle size than 75 μm as compared to only 25% of cowpea flour made from traditional paste used in making Akara, a local staple food.

4. Conclusions

The milling flowsheet developed on a pilot-scale flour mill for this study showed that existing rolls in a wheat flour mill could be effectively used to produce flours of

different particle size distributions from grains like sorghum, corn, and cowpea without compromising the nutritional values. The flow and existing equipment in a mill dedicated to wheat flour could produce low-fat and ash flours from alternate grains. These attributes are indicative of the process being effective in removing the germ and bran from the grains. Depending on the type of grain, the tempering and relative length of milling steps could be altered to get the desired flour. The milling process was effective in removing the back eye surrounding the hilum of the cowpea, and this improved the aesthetic value of cowpea flour. The tip cap of the corn kernel was extracted along with germ and pericarp to enhance the visual appeal of the degermed corn products. Starch content increased as the fiber and fat content decreased across the flours obtained for all grains. The knowledge gained in this study could help in adapting wheat flour mills for the size reduction of other similar grains.

Author Contributions: Conceptualization, S.A. and J.G.; methodology, J.G., A.A.A. and S.T.; formal analysis, M.J., S.A., L.Z. and J.G.; investigation, M.J., S.A., A.A.A. and J.G.; resources, S.A.; data curation, L.Z.; writing—original draft preparation, M.J.; writing—review and editing, S.A., J.G. and A.A.A.; visualization, M.J. and J.G.; supervision, S.A.; project administration, S.A.; funding acquisition, S.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the USDA Foreign Agricultural Service (FAS) under the Micronutrient Fortified Food Aid Products Pilot (MFFAPP) program, grant number FFE-621-2012/033-00.

Data Availability Statement: Data that are not proprietary will be made available per case.

Conflicts of Interest: Jeff Gwirtz is employed by JAG Services Inc. The remaining author declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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