Forage Properties of Fresh and Composted Cotton Gin Byproducts as Feed Supplements

Femi Peter Alege 1,*, Sean Paul Donohoe 1, Jaya Shankar Tumuluru 2, Christopher D. Delhom 3, Cody D. Blake 1 and Joe W. Thomas 1

1 USDA ARS Cotton Ginning Research Unit, Stoneville, MS 38776, USA; sean.donohoe@usda.gov (S.P.D.); cody.blake@usda.gov (C.D.B.); joe.thomas@usda.gov (J.W.T.)
2 USDA ARS Southwestern Cotton Ginning Research Laboratory, Mesilla Park, NM 88047, USA; jayashankar.tumuluru@usda.gov
3 USDA ARS Cotton Structure and Quality Research Unit, New Orleans, LA 70124, USA; chris.delhom@usda.gov
* Correspondence: femi.alege@usda.gov; Tel.: +1-662-686-3102

Abstract: Cotton ginning generates millions of tons of byproducts every year. If not properly managed, these materials become waste, which may constitute significant environmental, economic, and logistical issues. The objectives of this study were to characterize fresh and composted cotton gin byproducts (CGBs) for utilization as animal feed supplements and investigate the effects of composting on the forage properties. The study analyzed and compared the nutrients and energy contents of fresh and composted CGB from four commercial cotton gins in Arkansas, Mississippi, Missouri, and Tennessee states, USA. The results suggest that composting CGB may result in more than a 47% increase in fiber and crude protein and at least a 25% decrease in total digestible nutrients and net energy estimations. The differences in macro- and micro-nutrient contents and feed properties suggest that composting CGB may improve the potential for utilization as an animal feed supplement. Establishing the forage properties of CGB is crucial for determining animal feed formulations using CGB as supplements.

Keywords: characterization; compost; gin trash; nutrient composition; waste utilization

1. Introduction

The cotton ginning process generates millions of tons of cotton gin byproducts (CGBs, also commonly called cotton gin trash or gin waste) annually. Approximately 14.7 million bales of cotton, each weighing 218 kg (480 pounds) were ginned in the USA in 2022 [1]. In the same year, four states in the US (Arkansas, Missouri, Mississippi, and Tennessee) ginned approximately 4.3 million bales of cotton [1]. For every ginned bale of cotton, approximately 336 kg (740 pounds) of seeds and up to 91 kg (200 pounds) of “cotton gin trash” are generated [2]. Study [2] reported that states east of the Mississippi River produced up to 700,000 tons of gin trash, which could potentially feed up to 400,000 cows for 100 days with energy supplements such as corn, soybean, sorghum, etc. Similarly, [3] noted that approximately 0.61–1.49 million tons of cotton gin “trash” was generated annually in the Texas high plains between 2001 and 2006. Other studies have reported similar proportions and yields per bale of cotton gin byproducts generated from ginning processes from several top cotton-producing regions [4–6].

In addition to several applications of CGBs [7,8], various research efforts have incorporated these byproducts in animal diets [2,9–11]. However, the properties of the materials and the associated handling costs limit applications [12,13]. Some of the most significant properties limiting the application of CGBs in animal diets are the low bulk density and the high variability in moisture contents and nutritional value. The moisture and low density of byproducts and feedstuff materials directly impact the costs of handling, storage,
and transportation [14]. Prevailing storage or handling conditions and practices at the gins influence the moisture contents of CGBs [9]. Some gins add water to the CGB piles to control the dust and reduce the tendency for fire, while others promptly dispose of the materials or just expose the materials to weather conditions [15]. However, moisture addition increases the tendencies for molding and reduced palatability [2]. In addition to the effects of moisture content, variabilities in the nutritive value and other properties of CGBs have also been associated with the ginning process configurations adopted. For example, “double ginning,” which involves ginning seed cotton multiple times to remove extra lint, has been linked with a further reduction in nutritive value [9].

Previous studies have explored incorporating gin “trash” into cow, lamb, and sheep feeds [9,10,16,17]. Although CGBs are relatively low in nutritional values compared with several other feedstock materials, studies have reported the potential of utilizing CGBs as the sole feedstock or with little supplementation [2,18]. Ref. [9] reported that CGBs are better utilized for mature gestating cows and as a supplement to other feedstock materials. The effects of different formulations of CGBs in the diets have been widely studied. Ref. [10] found that the daily intake, body weight, and feed conversion ratio of sheep improved with increasing proportions of gin trash in the diets. Ref. [19] also reported that gin trash addition improved weight gain in grazing steers, but the performance was lower than a commercial supplement. Therefore, improving the feed values of CGBs continues to attract research attention.

Chemical and biological treatments have been applied to improve the feed value of CGBs. For instance, [16] found that digestibility and weight gains in steers increased with feed rations containing up to 70% of cotton plant byproducts treated with urea and ammonium hydroxide. The aerobic composting of CGBs as a means of storage and treatments prior to subsequent applications is a very common practice among gins. In addition to serving as storage media, composting CGBs is beneficial for many soil nutrient amendment applications because of the resulting nutrient transformations and inactivation of weed seeds and pathogens [20]. However, composting CGBs for animal feeds is often discouraged because it tends to reduce the digestibility [2]. On the other hand, there is relatively limited information on the effect of composting on the nutritive value of CGBs compared with the fresh CGBs and other residues or feedstock incorporated into animal diets. Given the popularity of the composting process in the cotton industry and the broad variability in the properties of CGBs, it is very important to characterize and understand the properties of composted gin byproducts as it relates to utilization in animal feeds.

There is a lack of a complete characterization of the fresh and composted CGBs for macro- and micronutrients for feed applications. Data on comparing composted CGBs at various locations to understand their variability and suitability for feed applications are not well-documented in the literature. Therefore, this study characterizes both fresh and composted CGBs in order to enhance the development of treatment processes and feed formulations for the improved utilization of CGBs. Additionally, this study contributes to addressing the broad variability in the properties of CGBs, which limits the adoption of CGBs as forage. The objectives of this study were to investigate the forage properties of CGBs from multiple locations and compare these properties with values previously reported in the literature relative to the diet formulation.

2. Materials and Methods

2.1. Sampling Locations and Composting

Composted CGB samples were sourced from four commercial cotton gins in four cotton-producing states (i.e., one commercial gin in each of Arkansas, Missouri, Mississippi, and Tennessee). The closest of the gins are approximately 130 km (80 miles) apart, while the furthest two gins are approximately 467 km (290 miles) apart, via road transportation. Therefore, the chances of overlapping cotton production practices are minimized. The fresh cotton gin byproduct (FCGB) samples were sourced from two of the commercial cotton gins (Mississippi and Tennessee). The FCGB samples were generated within 30 days of
ginning, while composted CGB (CCGB) samples were collected from windrow-compost piles that were at least eight months old, i.e., the samples were collected from compost piles generated at the end of the previous ginning season. Table 1 shows a description of the samples used in this study.

### Table 1. Description, Sources, and Composting Age of Cotton Gin Byproducts.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Description</th>
<th>Source/Location</th>
<th>Composting/Storage Age</th>
</tr>
</thead>
<tbody>
<tr>
<td>FCGB-01</td>
<td>Fresh Cotton Gin Byproducts</td>
<td>Gin-01, Tennessee</td>
<td>&lt;30 days</td>
</tr>
<tr>
<td>FCGB-02</td>
<td>Fresh Cotton Gin Byproducts</td>
<td>Gin-02, Mississippi</td>
<td>&lt;30 days</td>
</tr>
<tr>
<td>CCGB-01</td>
<td>Composted Cotton Gin Byproducts</td>
<td>Gin-01, Tennessee</td>
<td>&gt;8 months</td>
</tr>
<tr>
<td>CCGB-02</td>
<td>Composted Cotton Gin Byproducts</td>
<td>Gin-02, Mississippi</td>
<td>&gt;8 months</td>
</tr>
<tr>
<td>CCGB-03</td>
<td>Composted Cotton Gin Byproducts</td>
<td>Gin-03, Arkansas</td>
<td>&gt;8 months</td>
</tr>
<tr>
<td>CCGB-04</td>
<td>Composted Cotton Gin Byproducts</td>
<td>Gin-04, Missouri</td>
<td>&gt;8 months</td>
</tr>
</tbody>
</table>

Rather than building experimental compost piles, all samples were collected “as-is” from four sampling points along the respective windrows/piles, to maintain consistency with the prevailing methods and practices in the industry. All compost piles were at least 1 m high. To ensure that samples older than the target composting/storage periods were not collected and for safety reasons, all the FCGB and CCGB samples were collected from the top 30 cm of the respective windrows or piles. All materials were analyzed separately in order to allow flexibility to inform the future analysis of spatial variabilities within the piles. According to [21], each location recorded an average monthly temperature of 2–31 °C (36–88 °F) in the nine months before sampling. Each location also received a total precipitation of over 1050 mm (43 inches) in the preceding nine months.

### 2.2. Composting Process and Compositional Analyses

The collected samples were stored in 5-gallon plastic buckets for transportation to the USDA-ARS Cotton Ginning Research Unit in Stoneville, Mississippi. At the USDA location, approximately 500 g samples were collected from the 5-gallon buckets and stored in a chest freezer set to approximately −18 °C until shipment to a commercial laboratory for elemental and other analyses. Freezing solid wastes is a common scientific process used to preserve microorganisms and naturally occurring organic and inorganic substances prior to subsequent use or analyses [22–25].

All samples were analyzed at Brookside Laboratories, Inc. (New Bremen, OH, USA). The laboratory is certified by the National Forage Testing Association and participates in the Association of American Feed Control Officials Check Sample Program. The analyses were conducted using wet chemistry methods according to standard procedures of the Association of Official Analytical Chemists (AOAC), the Test Methods for the Examination of Composting and Compost (TMECC), and US Environmental Protection Agency (EPA).

The dry matter was determined by oven-drying the samples for 3 h at 105 °C [26], while the ash content was determined using the TMECC Method 5.07 (adapted from US EPA Method 160.4) [27]. The autoclaved citrate extractable (ACE) protein content method [28,29] was used to determine protein contents, while the minerals were determined through nitric acid digestion, followed by elemental analysis using an inductive coupled plasma spectrometer (iCAP 6500 Duo, Thermo Scientific, Waltham, MA, USA) [26,27,30]. The fat content was determined as the ether extract (AOAC 920.39 method) [31], while the fiber contents—crude, acid detergent (ADF), and neutral detergent (NDF)—were determined by using the refluxing and gravimetric methods (AOAC 973.18 and AOAC 2002.04) [31]. Equations were used to estimate the total digestible nutrients [32], energy contents (digestible, net energy for gain, and lactation, etc.) [32–34], relative feed value, dry matter intake, digestible dry matter [35], and non-saturated carbohydrates [36].
2.3. Statistical Analyses

Statistical data analysis was completed using R software version 4.3.0 [37]. One-way analysis of variance (ANOVA) was conducted to determine if there were significant differences between the mean nutrient properties of the samples collected from the different sources. Using the agricolae package in R [38], post hoc Fisher’s Least Square Differences (LSD) of the means were obtained to determine which means were significantly different in cases where the ANOVA indicated statistically significant differences between the mean properties of the samples at \( p < 0.05 \). Values of other parameters not determined analytically were computed using the respective equations previously reported in the literature. Additional details are listed in [39].

3. Results

3.1. Crude Protein, Ash, and Fat

Figure 1 shows the crude protein, ash, dry matter, and fat contents (in % dry basis, d.b.) of the fresh cotton gin byproducts (FCGBs) and composted cotton gin byproducts (CCGBs) from the different gins. The average crude protein (CP) contents of the CCGB samples from all four gins were approximately 57% higher than those of the FCGB samples. ANOVA showed that there were statistically significant differences (\( p < 0.001 \)) between the mean crude protein contents of the samples from all four gins. The observation held particularly true when comparing both fresh and composted samples obtained from Gin-01 and Gin-02. However, ANOVA showed statistically significant differences in the mean ash contents of all the samples, and the post hoc analysis showed that only the CCGB sample obtained from Gin-03 was statistically higher.

Similar to CP, the ash contents of the FCGB samples were generally lower than those in the CCGB samples (Figure 1). The observation held particularly true when comparing both fresh and composted samples obtained from Gin-01 and Gin-02. However, ANOVA showed statistically significant differences in the mean ash contents of all the samples, and the post hoc analysis showed that only the CCGB sample obtained from Gin-03 was statistically higher.

The mean fat contents of the samples differed significantly (\( p < 0.0001 \)) among the locations. The fat contents of FCGB samples from both locations were generally higher.
than those of the CCGB samples from all four locations (Figure 2). However, while the fat contents of FCGB-02 samples were significantly higher, post hoc analysis indicated that the difference between the fresh and composted samples from Gin-01 was not statistically significant (Figure 2). In addition, the fat composition of the CCGB samples from all four locations did not differ statistically. The implications of the results are discussed later in Section 4.

![Figure 2. Total digestible nutrients (TDNs), acid detergent fiber (ADF) and fat contents of the FCGB and CCGB samples (n = 4; FCGBs = fresh cotton gin byproducts; CCGBs = composted cotton gin byproducts; 01, 02, 03, and 04 are the respective sample locations/gins). Different letters (a–c) indicate statistical significance.](image)

### 3.2. Fiber, Total Digestible Nutrients, and Estimated Energy

The fiber contents of all FCGBs obtained ranged between 30 and 42% (d.b.). This was significantly lower \((p < 0.001)\) than those in all CCGB samples (43–63%, d.b.). The trend is shown in Figure 2 for the acid detergent fiber (ADF). The ADF estimates the cell wall portion of the feedstuff that is made up of lignin and cellulose. The LSD showed that the differences between the FCGB samples from different locations did not differ significantly. However, the mean fiber content of the CCGB samples from Gin-03 were significantly lower than that of the CCGB samples from the other three locations.

The total digestible nutrients (TDNs) of the FCGB samples analyzed in this study were higher than those of the CCGB samples from all four sources (Figure 2). In addition, the mean TDN contents of the FCGB samples did not differ statistically between the source locations. Similarly, the mean TDN values of all CCGB samples were not statistically different, except for the CCGB-03 sample. The TDN value of CCGB-03 was higher than that of the other CCGB samples, but not as high as the FCGB samples from the two locations (gins 01 and 02).

The mean values of the various estimates of energy contents (net energy for gain and lactation and digestible energy) of the FCGB and CCGB samples are shown in Figure 3. The energy composition trends were the same as the TDNs, with the respective energy contents higher in the FCGB samples than in the CCGB samples.
Figure 3. Net and digestible energy contents of the FCGB and CCGB samples. (n = 4; FCGBs = fresh cotton gin byproducts; CCGBs = composted cotton gin byproducts; 01, 02, 03, and 04 are the respective sample locations/gins).

3.3. Macronutrients, Micronutrients, and Trace Elements

3.3.1. Macronutrients

The main macronutrients that are generally required by animals in larger quantities than micronutrients include calcium (Ca), magnesium (Mg), potassium (K), phosphorus (P), sodium (Na), chlorine (Cl), and sulfur (S). While nitrogen (N) in feeds is assessed through the protein contents, Cl analysis was not included in the current study. The calcium compositions of the CCGB samples (Figure 4a) were generally higher than those of the FCGB samples. ANOVA showed that the mean differences in the Ca composition were significant (p < 0.001). The post hoc analyses confirmed that the Ca content of CGB-03 was significantly higher than the Ca contents of all other CCGB and FCGB samples, except FCGB-01. Comparing the samples obtained from the same locations, the mean Ca compositions were statistically different between fresh and composted samples from Gin-01, but not between Gin-02 samples.

The Mg composition (Figure 4b) of the FCGB samples differed significantly from the two locations 01 and 02, but the differences were not significant for the CCGB samples. Except for the significantly higher Mg level in the CCGB samples obtained from Gin-03, all the CCGB samples from the different locations did not differ significantly. Similarly higher levels were observed for the K contents (Figure 4a) of CCGB-03 samples compared with the composted samples from other locations. However, while the K contents were higher in CCGB-01 than in CCGB-02, the K composition of the fresh samples from both locations did not differ significantly. Within the individual locations, FCGB-02 contained more K than CCGB-02, but the difference was not significant between the fresh and composted samples from Gin-01.

The composition of phosphorus (Figure 4b) in the tested samples also differed significantly (p < 0.01). However, post hoc analysis showed that P in CCGB-01 was higher than in FCGB-01, but CCGB-02 and FCGB-02 did not differ significantly. Similarly, the mean P composition of CCGB-03 was not significantly different from that of the other CCGB samples, except CCGB-02.
Figure 4. Macronutrient composition of the FCGB and CCGB samples. (a) Calcium and potassium; (b) Phosphorus, magnesium, sodium, and sulfur. \((n = 4; \text{FCGBs} = \text{fresh cotton gin byproducts}; \text{CCGBs} = \text{composted cotton gin byproducts}; 01, 02, 03, \text{and} 04 \text{are the sample locations/gins}). \text{Different letters (a–d) indicate statistical significance.} \)

The Na and S compositions of the samples are also shown in Figure 4b. The Na composition of all samples differed significantly \((p < 0.001)\). FCGB samples from locations 01 and 02 contained higher amounts of Na than the CCGB samples, but the differences were not statistically significant within the sample types. However, comparing the compost
and fresh samples within individual locations, FCGB-01 and CCGB-01 were not statistically different, but CCGB-02 contained significantly less Na than CCGB-01. For all locations, the mean Na composition of the CCGB samples were not significantly different, except for CCGB-04, with higher Na than all other samples. For S, the CCGB samples contained approximately 40% more S than the FCGB samples, and ANOVA indicated significantly different S compositions (p < 0.036) between all samples. However, the post hoc analysis showed that the S contents of all FCGB and CCGB samples were not statistically different, except in CCGB-03.

3.3.2. Micronutrients

The micronutrients tested in the current study include manganese (Mn), copper (Cu), iron (Fe), and zinc (Zn), and the respective compositions in the CGB samples are illustrated in Figure 5. The Mn composition of the CCGB samples was statistically higher (p < 0.0001) than that in the FCGB samples. Although the Mn contents of the both fresh and composted samples from Gin-02 did not differ significantly, CCGB-01 contained significantly higher Mn than FCGB-01. For Cu, CCGB samples from all the locations (except Gin-01) contained higher Cu than FCGB samples from Gins 01 and 02. ANOVA indicated that the differences in the mean concentrations were also statistically different (p < 0.0001). Results of the post hoc analysis indicated that the Cu composition of FCGB and CCGB samples from both Gins 01 and 02 were not statistically different, but the higher Cu concentrations of CCGB-03 and CCGB-04 were statistically significant.

![Figure 5. Micronutrient compositions of the FCGB and CCGB samples (n = 4; FCGBs = fresh cotton gin byproducts; CCGBs = composted cotton gin byproducts; 01, 02, 03, and 04 are the respective sample locations/gins). Different letters (a–d) indicate statistical significance.](image-url)

The concentrations of Fe in all the samples were significantly different (p < 0.0001), but the FCGB samples from the two gins (01 and 02) were not significantly different (Figure 5). Also, CCGB-02 was significantly higher in Fe content than both FCGB-02 and CCGB-01, but lower than in CCGB-03. For Zn, the compositions in FCGB samples from Gins 01 and 02 did not differ significantly, but the CCGB samples from both locations differed. On the
other hand, the Zn content of CCGB-04 was significantly higher than that of CCGB-03, and both composted samples contained significantly higher Zn concentrations than all the other fresh and composted samples.

4. Discussion
4.1. Dry Matter/Moisture and Ash

Data on comparing composted CGB at various locations to understand its variability and suitability for feed applications are not well-documented in the literature. The changes in physical and chemical properties of biomass materials significantly influence the materials’ storability and consequent suitability for feed applications. The dry matter contents of the byproducts differ significantly with the location ($p < 0.0001$), likely due to the differences in precipitation near the time of collection. For instance, the FCGB and CCGB samples from Gins 01 and 02 were obtained during or immediately after a rainfall event, while the compost samples from Gins 03 and 04 were obtained several days after a rainfall event. In addition, the FCGB and CCGB samples collected from Gin-01 and Gin-02 were collected under similar conditions and approximately at the same time. Therefore, a comparison of the samples from the same locations provides insight into the variability of dry matter, rather than a comparison across locations. Within the locations, the comparison shows that dry matter contents were higher in the FCGB than CCGB samples obtained from both locations (Figure 1). This observation may be due to the CCGB compost piles’ relatively longer exposure to weather conditions and heat during composting (Table 1). The variabilities in the dry matter/moisture contents across different locations affirm the need to incorporate moisture-control equipment into the large-scale processing of CGBs into feeds. To account for these variabilities, the current study includes only dry bases values.

The average ash content of the fresh CGB (FCGB) samples in this study was approximately 10.8%, which was within the range of values that others reported, as shown in Table 2. In addition to the values shown in Table 2, [40] reported ash content values ranging from 10.8 to 21.9% for samples sourced from four gins in three different sampling periods. The ash content of CGBs is generally higher than woody biomass (<3%), but comparable to other agricultural residues, which ranged between 5 and 10% for wheat straw, corn stover, sugarcane bagasse, etc. [40,41]. For processed CGBs, study [42] reported ash content values of 9.5% and 10.2% for extruded and predigested gin “trash,” respectively. Although there was insufficient statistical evidence to show that the differences in the ash contents of FCGB and CCGB samples were significant, it should be noted that the FCGB samples generally contained less ash matter than the CCGB samples from all the locations sampled in this study (Figure 1). Another study [6] showed that the ash contents of CGB are greatly influenced by the harvesting method and the number/type of equipment used in the ginning process. The same study showed that the amount of byproducts generated from the inclines and unloading systems contribute up to 36% of the total CGB generated, and the average ash content of CGB decreased by more than 50% without both equipment/systems. Ref. [43] associated the increase in the ash concentration during composting to an overall reduction in the total solid weight. Except for CCGB-03 samples with average ash contents ranging between 16.5 and 36.2%, the ash contents of all the other CCGB samples ranged between 7.0 and 18.9%. However, the significantly higher ash content of CCGB-03 compared to that of other samples in the current study and in the literature suggests that the variations in composting practices from the locations may significantly impact the ash contents of CCGBs. Based on these findings, both FCGBs and CCGBs have relative strengths, and further study is needed to develop optimal combinations of these materials.
Table 2. Comparison of sample properties with values previously established in the literature (CGBs = cotton gin byproducts).

<table>
<thead>
<tr>
<th>Material</th>
<th>Ash</th>
<th>Crude Protein</th>
<th>ADF a</th>
<th>TDN c</th>
<th>Fat</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fresh CGB</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10.8</td>
<td>13.4</td>
<td>37.9 b</td>
<td>58.0</td>
<td>1.9</td>
<td></td>
<td>The Current Study</td>
</tr>
<tr>
<td>17.8</td>
<td>13.63</td>
<td>69.6</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>[44]</td>
</tr>
<tr>
<td>23.9</td>
<td>7.3</td>
<td>65.9</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>[44]</td>
</tr>
<tr>
<td>12.1</td>
<td>8.7</td>
<td>-</td>
<td>48.5</td>
<td>3.6</td>
<td></td>
<td>[45]</td>
</tr>
<tr>
<td>5.9–20.9</td>
<td>7.4–16.6</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>[12]</td>
</tr>
<tr>
<td>4.2</td>
<td>7.7</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>[43]</td>
</tr>
<tr>
<td>8.9–17.7</td>
<td>6.6–12.5</td>
<td>40.7–48.3</td>
<td>-</td>
<td>3.4–6.1</td>
<td>[47]</td>
<td></td>
</tr>
<tr>
<td>Composted CGB</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CGB Compost (Aerobic)</td>
<td>17.8</td>
<td>20.9</td>
<td>56.0</td>
<td>43.2</td>
<td>0.5</td>
<td>This Study</td>
</tr>
<tr>
<td>CGB Compost (Anaerobic)</td>
<td></td>
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<tr>
<td>16.7–21.1</td>
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<td>[43]</td>
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<tr>
<td>13.87</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>[43]</td>
</tr>
</tbody>
</table>

a Acid detergent fiber (ADF); b reported values are crude fiber; c total digestible nutrients (TDNs); d average values for 35 samples.

4.2. Overall Quality Assessment: Fiber, Estimated Energy, and Nutrient Digestibility

As shown in Figure 2, the fat contents of the FCGB samples from both Gins 01 and 02 were on average 76% higher than those of CCGBs from all four locations. Fats (and fatty acids) are highly digestible by animals and contain more than 2-fold as much energy as carbohydrates [53]. Therefore, feed formulations may meet animals’ energy requirements and improve digestibility using fewer FCGBs than CCGBs. However, the lack of evidence for a statistically significant difference between the CCGB samples from all four locations suggests that it may be easier to predict the fat composition using CCGBs than using FCGBs. This could make feed formulations easier to create for CCGBs.

By contrast, the crude protein and fiber contents of CCGBs were higher than those of FCGBs. Both properties are also important for the ability of an animal to digest the feedstuff [54]. The changes in crude protein contents are associated with the nitrogen transformations, as the results of microbial activities and changes in the weather conditions. Another important feed quality parameter and estimate of the energy content of the feed material is the total digestible nutrients (TDNs), which are estimated from the values of the acid and neutral detergent fibers (ADFs and NDFs), crude protein, and ash components [35]. Forage/feed quality generally improves with higher CP and dry matter digestibility, while it decreases with higher fiber levels [35,53]. Quality standards for livestock diets reported by [35] describe a six-level (0–5) standard in which a “prime” (quality standard 0) forage has above 19% CP, 65% digestible dry matter (DDM), and 3.0% dry matter intake (DMI), but below 31% ADF. While a “poor” (quality standard 5) forage is composed of below 8% CP, 53% DDM, and 1.8% DMI, but above 45% ADF. Similarly, [53] indicated that forages with less than 70% NDF and more than 8% crude protein will generally contain enough digestible protein and energy, vitamins, and minerals to maintain older animals.
Based on the parameters described above [35], Equations (1)–(3) were used to calculate the DDM, DMI, and Relative Feed Values (RFVs) for the FCGB and CCGB samples. Table 3 provides these results.

\[
\text{DDM} \text{ (%) } = 88.9 - 0.778 \times \text{ADF} \tag{1}
\]

\[
\text{DMI} \text{ (%) } = 120 \div \text{NDF} \tag{2}
\]

\[
\text{RFV} = \text{DDM} \times \text{DMI} \div 1.29 \tag{3}
\]

**Table 3. Calculated values of DDM, DMI, and RFV of the CGB samples (mean ± standard error).**

<table>
<thead>
<tr>
<th>Sample</th>
<th>Digestible Dry Matter (%)</th>
<th>Dry Matter Intake (%)</th>
<th>Relative Feed Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>FCGB-01</td>
<td>59.7 ± 0.5</td>
<td>2.2 ± 0.1</td>
<td>100.0 ± 4.9</td>
</tr>
<tr>
<td>FCGB-02</td>
<td>67.9 ± 2.2</td>
<td>2.5 ± 0.3</td>
<td>131.9 ± 16.1</td>
</tr>
<tr>
<td>FCGB-01</td>
<td>66.5 ± 1.6</td>
<td>1.6 ± 0.0</td>
<td>81.6 ± 3.2</td>
</tr>
<tr>
<td>CCCB-02</td>
<td>71.9 ± 0.6</td>
<td>1.5 ± 0.0</td>
<td>84.3 ± 1.4</td>
</tr>
<tr>
<td>CCCB-03</td>
<td>62.5 ± 4.1</td>
<td>1.8 ± 0.0</td>
<td>87.0 ± 5.7</td>
</tr>
<tr>
<td>CCCB-04</td>
<td>37.8 ± 3.8</td>
<td>1.5 ± 0.0</td>
<td>43.9 ± 1.4</td>
</tr>
</tbody>
</table>

For the RFV estimated from Equation (3), a prime quality forage composes above 151, while forage with RFV below 75 is considered poor quality [35]. Based on the values shown in Table 3, a combination of the parameters suggests that the FCGB and CCGB samples would be classified between quality standards 2 and 3, as defined in [35].

### 4.3. Nutrients, Diet Formulation, Net Energy System, and Minerals

Feed formulations generally need to be developed considering animal growth stages and weather conditions [55,56]. It is also important to understand the composition of the feedstock material when making formulations [56,57]. In the case of FCGBs and CCGBs as feedstock materials, variability must be better understood before any feed formulations can be attempted. As shown in Table 2, there has been more emphasis on the characterization and utilization of FCGBs than CCGBs in animal feeds in the literature. However, the continued characterization of both forms of CGBs informs the feedstock selection to establish the suitability of each form for specific diets.

#### 4.3.1. Diet Formulation

The nutrient requirements of animals generally increase with reproduction activities, and feed formulations for breeding animals typically contain higher digestible energy and lower fiber relative to maintenance rations [53,55]. The net energy (NE) system (shown in Figure 3) is an alternative method of energy estimation that allows for the determination of specific rates of gain (NE\(_g\)) and milk quantities produced (NE\(_L\)). Compared to TDNs, the NE system accounts for energy losses from the digestion of different feeds [35]. Therefore, there is usually the need to add other feedstuff materials to supplement the deficient nutrients and improve the overall quality of diets with CGBs.

Micronutrients are required by animals in smaller quantities compared to macronutrients, and feed materials are often able to meet the requirements. However, testing the forage/feed for the micronutrients is important to ensure that the diet can supply the needed quantities. From the predictability and process modeling perspectives, the results show a consistent and overall lack of statistically significant differences in the macro- and micronutrient compositions of the FCGB samples from the two locations (01 and 02). The values obtained for the CCGB samples were less consistent mostly due to the compositions of CCGB-03. This observation suggests that the generalization and modeling of the mineral composition could be more complicated for CCGBs than for FCGBs.
In addition to the raw nutrient properties of the materials, storage conditions can affect animal acceptance of the feeds and their nutritional properties. Climate factors, such as rainfall, along with storage conditions, are also associated with direct and indirect influences on nutrient properties. Ref. [53] reported varying effects of different outdoor storage conditions and periods on the quality of hays. For instance, the study highlighted reductions in dry matter, crude protein, and digestibility levels and an increase in fiber (ADF and NDF) for periods ranging from 5–12 months. Similarly, mature cows refused 22% of outdoor-stored hays, compared to a 1% refusal rate for hay stored indoors. Fertilization during crop production has also been associated with changes in the composition of forage and palatability perceived by the animals feeds [35].

4.3.2. Nutrient Variabilities

The results of this study showed that there are differences in some physical and chemical properties of FCGBs and CCGBs sourced from different locations. These variabilities suggest that differences in the cotton production, ginning, or composting practices may impact the generalization of the CGB properties. The main factors affecting the nutrient variability of the CGB may include the atmospheric and weather conditions, ginning processes and equipment, crop production and harvesting practices, storage conditions, topography, etc. [6]. Some of these effects are suspected to contribute to the differences observed in this study; however, more research using controlled conditions is needed to validate these suspicions. The interconnection of these factors also plays an important role in the nutrient transformations and variability during composting [58,59]. Weather conditions influence the temperature, moisture, microbial activities, and the rate of decomposition and dry matter losses, as well as losses of nutrients, such as N (protein), and P [60,61]. For instance, the differences observed in the K content (Figure 4a) may be due to the topography and prevailing weather conditions of the location, which may favor surface runoff at one location versus the other. In the current study, crude protein (Figure 1) and P (Figure 4b) in CCGBs were higher than those in FCGBs. However, the specific trends during composting are unknown since the initial N and P contents of the compost feedstock are unknown in this study. Dry matter losses may also result in reduced fiber and energy contents in the materials (Figures 2 and 3).

The post hoc analysis found no evidence of significantly different sulfur contents between FCGBs and CCGBs, except in CCGB-03 (Figure 4b). Increases in the S contents of soils or composts may be attributable to absorption—either from the atmosphere or with precipitation [62]. Therefore, the higher S contents of the composts relative to the FCGB samples may be partly due to absorption; however, this cannot be guaranteed since the feedstock for the composting process is not the same between the CCGB and FCGB samples. The mean Ca, Na, and Mg compositions of the FCGB and CCGB samples (Figure 4a,b) were not significantly different, except for at one of the locations. Losses of the elements are often associated with leaching during the composting of agricultural residues [63,64]. Therefore, the topography of the locations may also favor nutrient retention and minimized runoff. The exact causes of these observations necessitate the monitoring of the composting process.

4.4. Other Formulation Considerations

Ultimately, feed/forage quality is best assessed through pertinent animal performances, such as daily gain, milk production, or reproductive rates [35]. One of the long-standing concerns of utilizing CGBs in animal diets is the toxicity associated with the chemical compositions or residues, especially gossypol [12]. However, several studies, including [12], reported that chemicals used in cotton production and heavy metals were either not significantly detected in cotton gin trash or showed a significant decline in concentrations during storage in piles. More specifically, [12] analyzed CGB samples from 21 cotton gins and found that no chemical residue was detected at a significant level, except S, S, S-tributyl phosphorotriithioate (DEF), which was detected with an average value of 4.49 ppm. On the other hand, a previous study [65] found more pesticide residues in cotton
soils than in sorghum and fallow soils, suggesting that there may be more chemical residues in the soil than in the gin trash.

Despite the low levels of chemical residues reported for CGBs, it is recommended that feed programs or products incorporating CGBs, whether fresh or composted, should test for the residues. However, the costs associated with testing the individual chemical residues may be significant and, depending on the locations, analytical laboratories completing the specific residue testing may not be readily accessible. Therefore, formulators should make informed selections of residues of interest. Further research to establish the persistence of currently used chemicals, especially defoliants, which are used immediately before harvesting, may help to inform formulators and producers.

Additionally, if not properly controlled during the composting, storage, and transportation of CGBs, factors, such as temperature, moisture, pH, etc., which influence microbial growth and activities, could pose safety concerns in animal feed. A previous study [66] noted that chemical and physiological changes essential for microbial growth and nutrient assimilation potentially cause the production of mycotoxins and other toxic substances. These toxins may cause diseases, weight loss, low reproduction rates, and other conditions when fed to animals. Therefore, further studies investigating the effect of composting processes and process parameters on the chemical residues, microbial community/activities, and composition of CGBs are necessary. The need for such studies is especially important given the variabilities in composting practices among cotton gins.

5. Conclusions

Data on comparing composted CGBs at various locations to understand their variability and suitability for feed applications are not well-documented in the literature. Therefore, to address this limitation, fresh and composted cotton gin byproducts (CGBs) were characterized for potential utilization as animal feed supplements. Relevant nutrient properties of the materials were analyzed and compared with values previously reported in the literature. The results obtained in the present study agree with previously reported values. Some properties observed included variabilities between different gin locations. These variabilities suggest that differences in the cotton production, ginning, or composting practices may impact the generalization of the CGB properties. Composted CGBs contained higher crude protein, fiber, and ash contents, but lower TDN contents, than fresh CGB samples. The findings affirm the wide variability in the compositions and nutrient properties of fresh and composted gin byproducts previously established in the literature. With limited information on the properties of composted gin byproducts relative to fresh CGBs, this study provides insight into the effect of aerobic composting on CGBs. More studies monitoring the byproducts through the composting process are recommended. Further sampling and analyses will help to establish trends in efforts to overcome the wide variabilities in the sample properties. Establishing the forage properties of CGBs is crucial for determining animal feed formulations using CGBs as supplements.


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