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Cotton Gin By-Products Utilization: Past, Present, and Future

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ABSTRACT

The regional concentration of cotton gin by-products (CGB) has increased significantly over the past three decades because of the consolidation of smaller gins into larger gins. Although several studies have investigated the potential of various waste treatment/valorization technologies to improve the management of CGB, most of the technologies' economic feasibility remains a challenge. Therefore, there is a need to review the existing and emerging technologies vis-à-vis process economics and changes in the cotton ginning industry. This study reviews the published status of these existing technologies (in terms of the challenges and potentials), analyzes the prospects of some emerging waste treatment technologies for CGB, and discusses future economic and environmental sustainability directions. Where appropriate, new information from studies conducted in the U.S. and Australia is provided to support existing published data. The results show that the main limiting factors include production costs (e.g., energy and feedstock/additives costs) and logistics/supply. Additionally, the results support a solid potential for the sustainable use of CGB for various applications. However, the potential can be achieved by optimizing specific treatment processes, combining multiple processes through hybrid or integrated systems, co-treating CGB with other affordable and readily available materials (such as by-products from other agricultural operations), and improving return on investment for products developed.

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Global and Regional Cotton Production. Human utilization of cotton has a long history spanning from antiquity to the present age, and producers have grown it across vast geographic regions. The ancient usage of cotton dates to between 6000 and 5000 BC in Pakistan and 2300 BC in Mexico (Vreeland, 1999). Cotton is still an essential commodity today. Today, cotton is grown in more than 70 tropical and subtropical countries (Cotton Australia, 2024; Wakelyn and Chaudhry, 2009). However, five large geographic areas dominated cotton production in 2022: China, India, U.S., Brazil, and Australia (as measured by 218 kg (480 lb) bale equivalents produced) (USDA FAS, 2022). With such a long history, it is little surprise that cotton and its uses are still the focus of much research and development.

Worldwide, the total cotton production for the 2021/2022 season was 120.2 million 218-kg (480 lb) bale equivalents (Johnson et al., 2022). During this same period, the U.S. planted 4.5 million ha (11.1 million ac) of cotton (Johnson et al., 2022); India had the largest area of planted cotton, with approximately 12 million ha (29.6 million ac) devoted to the crop (Government of India, 2023); and Australia had approximately 0.57 million ha (1.4 million ac) of planted cotton (Cotton Research and Development Corporation, 2022). China and Brazil had a projected harvest of 3.11 and 1.51 million ha (7.7 and 3.7 million ac) of cotton, respectively (International Cotton Advisory Committee, 2021/2022). The total amount of global cotton bales produced varies with time, as does the amount of land planted; however, it is a very large globally produced crop.

Cotton Harvesting Methods. Cotton production and subsequent conversion to finished products requires multiple processing steps and activities. One such step is harvesting. Harvesting affects the efficiency of the ginning process, the quality of the cotton fibers, and the amount and composition of foreign matter removed during ginning (Wanjura et al., 2017). The foreign matter separated from cotton lint and seeds has traditionally been called trash, but it is a potentially valuable co-product with numerous uses. This co-product is referred to as cotton gin by-product (CGB).

Harvest methods have changed over time, and the amounts of foreign matter captured with cotton have varied. Exactly how humans first learned to harvest cotton is unknown, but it is not hard to imagine that hand-picking was used with mechanical harvesting a relatively recent advancement. The first patent for mechanical harvesting was granted in 1850 (U.S. patent number 7631) for a machine invented in Memphis, TN (Holley, 2020; Smith et al., 1932). Later developments in mechanical harvesting generally included one of five types: picker, stripper, thresher, pneumatic, and electrical (static attraction) (Smith et al., 1932). By the 1920s, the International Harvester Company worked on mechanical picking using spindles, as did Hiram Berry (from Greenville, MS) (Holley, 2020; Smith et al., 1932). In the 1930s, the Rust Cotton Picker Company developed a moistened smooth-spindle picker (a concept still used today) that was demonstrated at the experiment station in Stoneville, MS (Holley, 2020). Since then, several innovations and improvements have been made to mechanical harvesting. In 2007, John Deere introduced mechanical harvesting that produced round cotton modules resembling large hay bales wrapped in plastic that shields cotton from the elements (Laws, 2007).

Both hand-picking and mechanical harvesting are still prominent in cotton production, with an estimated 30% of the global cotton production harvested mechanically (Khanpara and Vala, 2023; Tesema and Fetene, 2024). Previous studies (Dai and Dong, 2014; Khanpara and Vala, 2023) have reported that hand-picking is the most prevalent method in China, India, and Pakistan. Khanpara and Vala (2023) also reported that 100% of the cotton produced in the U.S., Israel, and Australia is mechanically harvested, whereas 90% of the total cotton produced in Greece, Mexico, and Spain is picked mechanically. Hand-picking is a slower process with a higher dependence on human labor than mechanical harvesting. By contrast, mechanical harvesting is not only faster but less labor intensive.

In the U.S., two types of machines are used for cotton harvesting: spindle pickers and brush-roll strippers (Wanjura et al., 2017). The adoption of each type of harvester is influenced by environmental factors and regional production practices (i.e., cultivar selection, irrigation practices, fertility management, plant growth regulator use, and harvest aid practices) (Wanjura et al., 2017). Spindle pickers use spindles to selectively remove seed cotton from well-opened bolls. This process collects relatively small amounts of undesirable vegetative plant matter and, consequently, CGB after ginning (Wanjura et al., 2017). By comparison, brush-roll stripper harvesting often produces significantly higher non-lint vegetative matter because the machine indiscriminately pulls in cotton and plant material together (Tesema and Fetene, 2024; Wanjura et al., 2017). Older studies (Baker et al., 1994; Gembler, 1996; Huitink, 2002) reported that hand picking, spindle picking, and stripped cotton generate approximately 36, 34 to 90, and 113 to 450 kg (80, 75-200, and 250-1000 lb) of CGB per bale of ginned cotton, respectively. Regionally, spindle picking is most common in the Southeast, Mid-South, and Far West (California and Arizona). Both mechanical harvesting methods are used in Texas and Oklahoma, however, brush-roll strippers are more common in the Southern High Plains (Kansas, parts of Oklahoma, and West Texas).

Prior research has estimated the value of CGB generated based on annual gin production volumes using methods similar to equation (1) (Huitink, 2002). In this case, TAGV is the Total Annual Gin Volume (i.e., total number of bales of cotton ginned) in bales per year, and BC is the by-products content per bale of cotton.

$$\textit{Annual By-products Generation} = \text{TAGV} \times \text{BC} \quad (1)$$

The value of BC can be estimated at 68 kg bale^{-1} (150 lb bale^{-1}) for picked cotton (Wanjura et al., 2017). For modern stripper harvesters, the value of BC has been reported to be approximately 170 kg bale-1 (375 lb bale^{-1}) (Wanjura et al., 2017). Stripped cotton is estimated to generate at least 67% of CGB in the U.S. (Funk et al., 2005; Holt et al., 2000a).

Overview of Cotton Co-products and their Utilization. Seed cotton delivered to the gin has three components that are separated in the ginning process: fiber, seed, and CGB. Fiber or lint is baled into approximately 227 kg (500 lb) bales (Cotton Incorporated, 2019). For U.S. upland cotton the USDA assumes running bales average approximately 224 kg (494 lb) and the bales are converted to 218 kg (480 lb) for World Agricultural Supply and Demand Estimates (USDA FAS, 2023). For every 45 kg (100 lb) of cotton fiber, approximately 64 kg (140 lb) of seeds are generated (Cotton Incorporated, 2019). In the ginning process, the seeds from the seed cotton form an essential co-product on their own. Cotton seeds are used as a feedstock for animals (Arieli, 1998) and oil production (Sekhar and Bhaskara Rao, 2011). In addition to these co-products, CGB is a lesser utilized biomass co-product whose quantity can be estimated as discussed above. Research efforts have studied CGB for soil remediation, composting, livestock feed, and fuel (Huitink, 2002). In addition, research has looked at using CGB for hydromulch (Holt et al., 2003b) and as the substrate in composites used for building materials (Bajwa et al., 2011; Holt et al., 2009).

From a circular bioeconomy standpoint, there is a critical gap that needs to be addressed in an integrated framework that places wider context on biomass utilization (Muscat et al., 2021). In this sense, the utilization of CGB is a complex process that depends on many factors. Therefore, an in-depth review of the composition, properties, treatments, and options for economical and environmentally sustainable utilization of CGB is critical.

CGB COMPOSITION AND INFLUENCING FACTORS

Physical Properties and Chemical Composition. Figure 1 shows the various processes involved in cotton production and ginning, as well as the main co-products and ginning by-products. Properly storing the seed cotton bales at the gin is critical to maintaining cotton quality (Searcy et al., 2010). In Fig. 1, the highlighted boxes show the various by-products generated during the cotton ginning process. Many researchers have stated that the quantity and makeup of CGB primarily depend on the harvesting method, geographical location of the crop, processing at the gin, and other factors (Holt et al., 2000b; Thomasson, 1990; Thomasson and Willcutt, 1996). CGBs are generated during the precleaning, ginning, and lint cleaning operations during the seed cotton ginning. The cylinder cleaners and stick machines used in the precleaning typically generate sticks, burs, and leaf with some lint, whereas ginning and lint cleaning unit operations generate primarily motes as by-products. The quantity and quality of CGB greatly depend on the harvesting method followed by the type of cleaning and ginning systems used. If the stripper harvesting method is used during harvesting, it can generate more leaf, whereas picker harvesting can result in cleaner seed cotton with fewer leaf fractions. The composition of CGB is greatly influenced by the number and types of cleaning equipment used during ginning. For example, extractor cleaners such as stick machines remove materials (e.g., burs and sticks) by actions of centrifugal forces created by rotating saws. On the other hand, cylinder cleaners remove small foreign materials (e.g., leaf and soil particles) when rotating cylinders with spikes convey seed cotton across grid rods (Hardin and Byler, 2013). According to Anthony (2000), standard sequences of gin machinery should be used for specific cotton quality and harvesting methods followed to maintain the quality/monetary returns for cotton producers.

Table 1 provides some published literature on CGB's bulk density, ash, and volatile matter collected at different outlet locations in a commercial gin. It is clear from the table that these properties vary across collection points in a gin. The relatively low densities of the CGB make it take up a large volume for a given mass; if the density were higher, the material would be more accessible to transport economically.

Work has been conducted to densify CGB using various methods to make it take up less volume or be easier to transport. Table 2 lists some physical and energy properties of materials generated from the gin (raw), and processed CGB (subjected to various post-processing techniques such as pelleting and torrefaction). The density ranges as low as 112 kg m^{-3} (7 lb ft^{-3}) up to 640 kg m^{-3} (40 lb ft^{-3}) after being pelleted. As shown in Holt et al. (2000a), the ash content and other properties of CGB are highly variable.

Cotton seeds are collected after ginning when fibers are separated (Zabaniotou and Andreou, 2010). Though cotton seeds are used as the raw material in the oil industry and for growing new cotton plants, CGB remains a waste material that the ginners must dispose of (Hamawand et al., 2016). Agblevor et al. (2003) concluded that CGB is a more complex waste, as it is a heterogeneous mixture of cotton burs, motes, sticks, leaf parts, and fine particles. In addition, the broad composition of CGB complicates the cleaning process and is sometimes associated with losses in fiber because of the entanglement of CGB with fibers and other fractions (Haque et al., 2021).

The increase in mechanical harvesting worldwide coincides with an increase in CGB, and it is estimated that the amount of CGB produced annually is approximately 3.6 million tons, with the U.S. producing close to 2.5 million tons each year (Holt et al., 2000b; Placido et al., 2012). A four-year survey

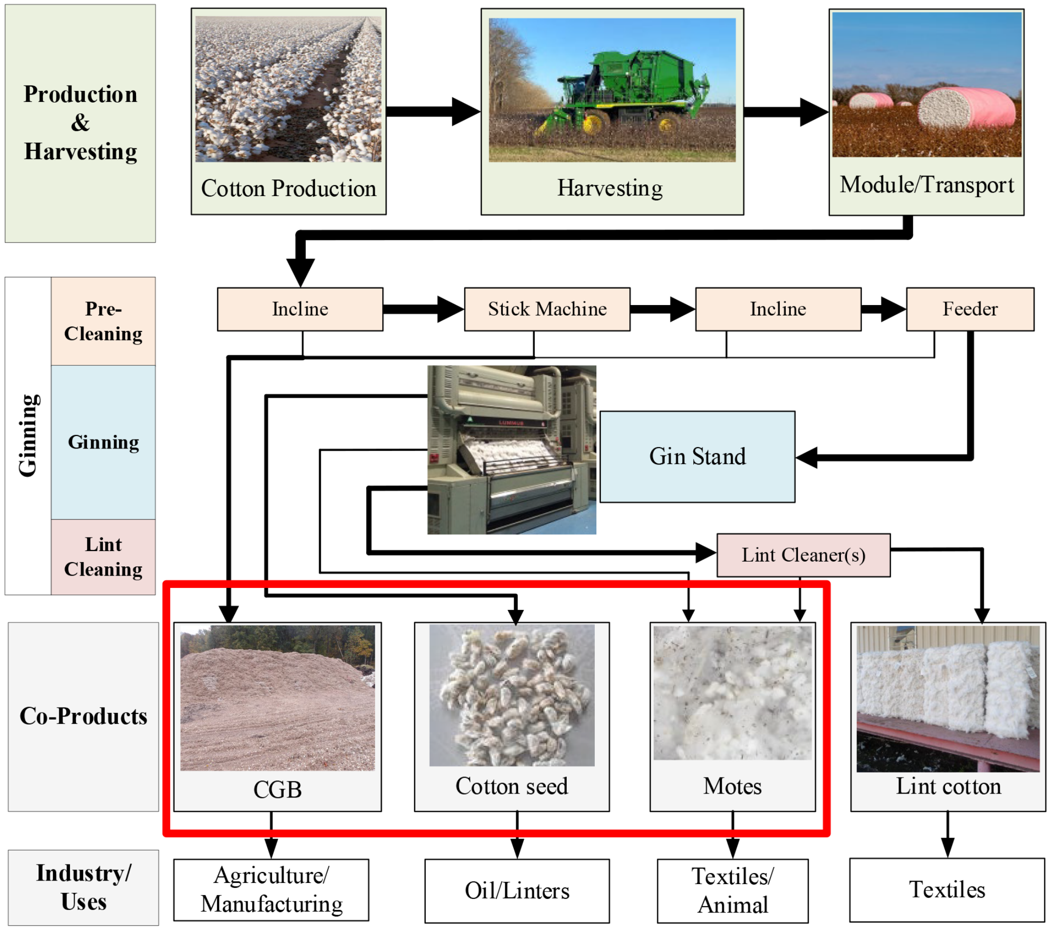

Figure 1. Overview of cotton production, ginning, co-products, and industrial uses

Table 1. Physical properties and chemical composition of gin by-products collected at different locations in a commercial gin (Adapted from Holt et al., 2000a)

Parameter	Unloading System	Feeder/Gin Stand	Inclines	Extractors	Lint Cleaners
Particle Density (g cm^{-3})	1.58	1.18	1.34	0.92	1.41
Bulk Density (kg m^{-3})^z	212.6	123.0	69.5	91.9	81.7
Moisture Content (%)	7.67	9.82	8.3	10.6	6.87
Ash (%)	36.0	8.73	21.4	7.8	6.17
Volatile Matter (%)	51.4	63.5	58.7	63.6	61.3
Carbon (%)	34.5	45.8	40.8	46.6	45.5

^{z}Average of bulk densities determined by loose fill and hand-packed methods.

conducted with the Australian Cotton Ginners Association (ACGA) from 2016 to 2019 showed that Australian gins produce approximately 200 million kg (220, 462 tons) or 5.5% of the average CGB produced worldwide annually. As shown in Table 3, studies conducted at multiple gins in the U.S. and Australia have reported the various compositions of machine-harvested seed cotton.

The ginning process affects the composition of the CGB. The gin system separates the incoming seed cotton into four products: lint, seed, motes, and CGB. Most CGB is handled by pneumatic conveying systems employing centrifugal fans and closed ducts. The trash collection system must remove CGB from this large air volume efficiently and without interrupting the normal ginning process. To date,

Table 2. Density, ash content, and calorific values of the gin waste from various processes

CGB	Bulk Density	Ash	Calorific Value	Reference
	(kg m^{-3})	(% d.b.)	(MJ kg^{-1})	
Raw	390	10.5	16.6	Sadaka (2013)
Raw	390	10.5	-	Widjaya (2018)
Raw	112	-	-	Velmourougane et al. (2021)
Burs/sticks	-	9.8	-	Bajwa et al. (2011)
Burs/sticks (Extractors)	92	7.8	16.6	Holt et al. (2000a)[z]
Leaves/fines (Inclines)	70	21.4	16.2	Holt et al. (2000a)[z]
Motes (Lint cleaners)	82	6.2	17.4	Holt et al. (2000a)[z]
Torrefied	426	15.2	17.2	Sadaka (2013)
Pelletized[y]	676	5.22	18.3	Holt et al. (2006)
Pelletized[x]	678	8.17	17.9	Holt et al. (2006)

[z]Approximate mean values for CGB recovered at each equipment outlet. Calorific value was reported as gross heating value, and bulk densities were determined from loosely filling a container

[y]Pellet samples from Texas, blended with 10% corn starch

[x]Pellet samples from Mississippi, blended with 10% corn starch

Table 3. Fractional composition of machine-harvested seed cotton in the U.S. and Australia

Year	Lint	Seed	CGB	Mote	Lint + Seed	Location	Reference
	----------	----------	----------	%	----------		
2004	-	-	5.0–32.3	1.0–20.9	66.4–93.8	USA[z]	Whitelock et al. (2007)
2004	-	-	0.8–4.2	0.2–1.2	95.0–98.9	USA[y]	Whitelock et al. (2007)
2006		-	6.09–6.59	1.93–2.19	-	USA	Armijo et al. (2006)
2016	39.3–43.8	45.5–51.0	5.4–12.4	0.0–4.3	-	Australia	van der Sluijs et al. (2018)
2017	39.9	47.1	12.1	0.7	-	Australia	van der Sluijs (unpub. data)
2018	42.3	47.6	10.2	0.5	-	Australia	van der Sluijs (unpub. data)
2019	40.8	47.9	11.0	0.5	-	Australia	van der Sluijs (unpub. data)
Avg	41.4	47.5	10.6	0.7	-	Australia	van der Sluijs (unpub. data)

[z]Fractions obtained from pre-cleaning process for Pima cotton

[y]Fractions obtained from post-cleaning process for Pima cotton

cyclones are the most widely used method to remove CGB from the conveying air. CGB is extracted by various equipment during the seed cotton cleaning stage prior to the gin stand and by the lint cleaners after the gin stand. The seed cotton cleaning stage removes the heavier and coarser materials, which include leaves, burs, stems/sticks, and some sand from the seed cotton. Lint is separated from the seed at the gin stand, where some burs, small particles, and motes (short fibers, some immature seeds, and fine leaf) are also removed. The lint is then cleaned during lint cleaning, where the remaining small leaf and organic particles, dust, motes, and short fibers are removed.

Furthermore, the extracted CGB is combined prior to transportation to the trash house/bur hoppers for disposal. A study conducted in 1999 in the U.S. found that approximately 73% of CGB was removed during the seed cotton cleaning stage, mostly by extractor cleaners (stick machines) followed by cylinder cleaners, with approximately 11% extracted during module feeding, approximately 6% at the feeder and gin stand, and 10% during lint cleaning (Holt et al., 2000a). However, another study found that operating at higher production rates than recommended by machinery manufacturers can lead to an overall reduction in the amount of CGB removed (Hardin and Byler, 2013). Operating at higher production rates than recommended is common as the increase in cotton production has resulted in changes to gin layouts, specifically in producing more bales per day and season. As a result, gin stands are either upgraded, replaced with higher capacity gin stands, or increased in number per cotton gin. However, installing additional seed cotton cleaning equipment is often economically or physically not feasible, and the recommended capacity is often exceeded (Hardin and Byler, 2013).

Although precleaning removes the bulk of the CGB from the cotton, the lint cleaners are the last chance to remove CGB before the cotton is pressed into a bale. Analysis of 2016 and 2017 data provided by Australian gins showed that CGB generated at the lint cleaners ranged from 2 to 11 kg/bale in 2016 and 1 to 13 kg/bale in 2017 (van der Sluijs, 2018; van der Sluijs et al., 2018). The amount of CGB from the lint cleaners can be substantial. To address this, some gins reclaim lint cleaner waste to recover lint that would otherwise be lost as CGB from the lint cleaners. Most of the gins in Australia practice reclaiming the lint cleaner fiber waste into mote as reclaiming and feeding back into the line is detrimental to the fiber quality and is discouraged (Rogers, 1997). During the reclaiming process, some gins produce very clean motes, referred to as moss in Australia, whereas other gins reprocess their motes through conventional seed cotton cleaning equipment or the entire gin, bypassing the gin stand. Similar mote cleaning systems, typically designed to return the reclaimed fiber to mote bales, are used in the U.S. (Buser et al., 2014).

Biomass/Biological Composition. It is commonly accepted that CGB contains varying degrees of sand, dust, and leaf material such as stems/sticks, hulls, and immature lint (Agblevor et al., 2003; Holt et al., 2000b), with trials conducted in 2016 and 2017, in conjunction with ACGA, showing similar results (van der Sluijs, 2018; van der Sluijs et al., 2018). A study conducted in 2003 on fractionated CGB collected from five gins in the U.S. found that sticks/stems (4-7%) and grass (0.2-0.4%) were fairly even but that there was a considerable variation between the other components in terms of lint (5-12%), hulls/burs (16-48%), seeds (6-24%), motes (16-24%), and leaves (14-30%). The study concluded that the seed cotton was likely harvested by a similar method and that the gins used different processing practices (Agblevor et al., 2003). These numbers were similar to those quoted in 1996, which showed that CGB was composed of 21% leaf, 35% sticks/stems and hulls, and 42% lint (Thomasson and Willcutt, 1996).

Table 4 summarizes the results of studies on the composition of CGB produced by gins in the U.S. and Australia. For Australian gins, the analyses found that the composition of CGB varied widely, with some gins producing CGB without any hulls or lint, and contrary to the study in the U.S., no seeds were found in the CGB. In addition to the values reported in Table 4 for the Australia gins, other materials (dust and leaf residues) constituted 19 to 65% and 22 to 77% of CGB in 2016 and 2017 surveys, respectively (van der Sluijs, 2018; van der Sluijs et al., 2018). The amount of lint contained in CGB significantly depends on whether the gin reclaims the short fibers into mote bales. Gins that do not generate mote bales will have more fiber in their CGB. However, breakdowns and blockages, for example, will bypass the reclaiming process, resulting in all non-baled lint and motes combined with the other CGB.

CGB is an underutilized resource for the ginning industries worldwide that deserves considerable research attention. Although the amounts of CGB generated at each gin vary significantly, the major chemical composition (cellulose, hemicellulose, and lignin) remains within the range of ordinary agro-based wastes. Table 5, partly adapted from Haque et al. (2021), shows the chemical composition of CGB that was previously reported by various authors. CGB is composed of approximately 24 to 40% cellulose, 7 to 18% hemicellulose, and 18 to 26% lignin, which are within the typical range of other lignocellulosic crop residues, such as wheat straw, rice straw, oat straw, and other biomass feedstocks (Agblevor et al., 2006; Carvalheiro et al., 2009; McIntosh et al., 2014; Passoth and Sandgren, 2019; Plácido et al., 2013; Sahuand and Pramanik, 2017).

By contrast, lignin is an important difference between CGB and the other agro-waste (Table 5). In lignocellulose materials, cellulose is commonly the principal proportion, followed by hemicellulose and lignin. However, in CGB, the amount of lignin is reportedly higher than that of hemicellulose. Because lignin is responsible for holding cellulose and hemicellulose together and restricting the chemical degradation of the overall structure, the cellulose-hemicellulose-lignin bonding in CGB is likely more substantial than most agro-waste. Lignin in CGB is reportedly acid insoluble (72% sulfuric acid), possibly due to the presence of guaiacyl lignin (g-type) units, which are difficult to dissolve (Agblevor et al., 2006; Ibrahim et al., 2010; Nishiwaki-Akine et al., 2017). In addition, CGB contains non-lignin acid-insoluble parts from condensed protein and

Table 4. Fractional composition of CGB from multiple geographical locations

Year	Hulls	Lint	Sticks/Stems	Seed	Location	Reference
	----------	----------	%	----------		
2000	15.9–48.1	5.3–12.5	3.6–7.1	5.6–24	USA	Agblevor et al. (2003)
2001	18.5–32.9	8–15	5.2–6.7	0.0–2.9	USA	Agblevor et al. (2006)
2006	1.15–1.35	-	0.54–0.59	-	USA	Armijo et al. (2006)
2007	0.6–3.4	-	0.2–0.9	-	USA	Whitelock et al. (2007)[z]
2007	0.1–1.5	-	0.0–0.7	-	USA	Whitelock et al. (2007)[y]
2016	0.0–34.9	0–78.7	1.4–17.5	19.0–65.2	Australia	van der Sluijs et al. (2018)
2017	0.0–47.2	19.9–66.2	0.0–7.5	21.9–76.6	Australia	van der Sluijs et al. (2018)

[z]Fractions obtained from pre-cleaning process for Pima cotton

[y]Fractions obtained from post-cleaning process for Pima cotton

Table 5. Chemical composition of cotton gin by-products (CGB) compared with other commonly co-treated lignocellulosic materials

	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Reference
CGB	24–37	14–18	18–23	McIntosh et al. (2014)
	~25	~10	~26	Plácido et al. (2013)
	25–33	7–16	20–25	Agblevor et al. (2006)
Cotton Linters	86.9 (Holo-) 66.6 (α-)	20.3	8.9	Bajwa et al. (2011)
Cotton Burs & Sticks	50.5 (Holo-) 29.7 (α-)	20.8	20.7	Bajwa et al. (2011)
Cotton Stalks	72.9 (Holo-) 58.5 (α-)	14.4	21.5	Jiménez et al. (2007)
Corncob	69.2	22.8	8.0	Millati et al. (2019) Lu and Chen (2014)
	40–44	31–33	16–18	Wang et al. (2011)
Oil Palm Fruit Bunch	39.1	23.0	34.4	Ishola et al. (2014) Millati et al. (2019)
	62.9 82.4 (Holo-)	28.0	36.6	Law et al. (2007)
Wheat Straw	28–39	23–24	16–25	Carvalheiro et al. (2009)
	37.8	26.5	17.5	Millati et al. (2019)
	41.2	27.7	18.5	Chen et al. (2016)[z] Cao et al. (2017)
	76.2 (Holo-) 39.7 (α-)	36.5	17.3	Jiménez et al. (2007)
Rice Straw	29–35	12–29	17–19	Passoth and Sandgren (2019)
	36.0	24.0	15.6	Millati et al. (2019)
	36.1	24.7	16.4	Cao et al. (2017) Zhang et al. (2017)
	70.6 (Holo-)	-	25.2	Jiménez et al. (2007)

Continued

Table 5. Continued

	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Reference
Rice Husk	43.3	28.6	22.0	Millati et al. (2019)
	34.7	17.4	25.5	Cao et al. (2017) Heng et al. (2017)
	28.5	25.5	25.7	Nakason et al. (2018)
Sugarcane Bagasse	46.4	23.9	28.1	Candido et al. (2017) Millati et al. (2019)
	50	25	25	Ahmed and Gupta (2012)
	56.0	4.6	36.4	Cao et al. (2017) Robl et al. (2016)[z]
Oat Straw	31–35	20–26	10–15	Passoth and Sandgren (2019)
Sorghum Straw	32–35	24–27	15–21	Passoth and Sandgren (2019)
Switchgrass	~31	~24	~18	Rao et al. (2010)

[z]Tested samples were dewaxed/hydrothermally pretreated

lipids from cotton seeds and small leaf fractions (Agblevor et al., 2006), which differentiates it from other agricultural residues.

Chemical Composition. Plant biomass composition varies among species but generally is comprised of cellulose, hemicellulose, lignin, and small proportions of protein, ash, pectin, and extractives (Bajpai, 2019; Cao et al., 2017). In addition to these, CGB also contains cotton fibers, which are composed of approximately 0.9% pectin and 0.6% wax (Hauser, 2015). Given the fiber composition and considering approximately 16 to 24% motes (major cotton proportion) in CGB, Agblevor et al. (2006), reported that pectin and wax could be between 0.14 to 0.22% and 0.1 to 0.14%, respectively. The elemental composition of CGB, including carbon (C), oxygen (O), hydrogen (H), and nitrogen (N), as previously reported by Zabaniotou and Andreou (2010) and White et al. (1996), are shown in Table 6. Both studies reported similar values, with approximately 39% C, 36% O, 5% H, and 1.4 to 2% N, on dry weight bases. Additional values of inorganic and trace elements composition of CGB have been reported in other studies (Haque et al., 2021; Zabaniotou and Andreou, 2010).

Previously unpublished data on the chemical composition of CGB samples obtained in Texas in 2023 are also shown in Table 6. The samples were obtained during the 2023/2024 ginning season, from a gin that processed stripper harvested cotton in West Texas. The values obtained were within the ranges previously reported for O and N. However, the samples contained relatively higher amounts of C (45.3%) and lower ash (9.8%). From a potential toxicity perspective, several metals/metalloids and trace elements (including arsenic, lead, cadmium, chromium, nickel, and mercury) were below the respective limits of quantification in the tested samples. Although measured from particulate emissions from ginning equipment, Hughs et al. (1997) found that none of the 19 tested elements (including the above metals and metalloids) were detected at levels significantly over the native soil contents. Therefore, the low metals/metalloids composition was associated with plants, native soils, and the wear of gin equipment. The values obtained in the current study support the conclusions of Hughs et al. (1997) that the CGB composition of those regulated elements (e.g., arsenic) could be well below the threshold levels of Environmental Protection Agency or the Occupational Safety and Health Administration regulations.

The N content of CGB is also higher (1.09%) than that of many other agricultural residues (corn stover: 0.42 and switchgrass: 0.36) (Tumuluru, 2015). However, the relatively lower energy and higher ash content of CGB compared with other agricultural by-products could limit its suitability for thermochemical applications such as pyrolysis, gasification, and cofiring. Ideally, the variability of CGBs' composition and properties across different stages of the ginning process (Holt et al., 2000a) could imply a potential to adapt CGB to specific processes.

Table 6. Physicochemical and elemental composition of cotton gin by-products (CGB). (values are dry basis unless otherwise indicated)

Property/element	Composition			
	Previous studies		Current study	
	(White et al., 1996)	(Zabaniotou and Andreou, 2010)	Values	Analytical Method
Bulk density (as-is, kg m^{-3})	-	-	128	DIN EN ISO 17828:2016-05
Moisture (%, as-is)	-	-	11.1	DIN EN ISO 18134-2:2017-05
Gross calorific value (kJ kg^{-1})	-	-	17400	DIN EN ISO 18125:2017-08
Net calorific value (kJ kg^{-1})	-	-	16200	DIN EN ISO 18125: 2017-08
Carbon (%)	39.59	38.8	45.3	DIN EN ISO 16948:2015-09
Oxygen (%)	36.38	-	37.3	DIN EN ISO 16993:2016-11
Hydrogen (%)	5.26	4.7	5.2	DIN EN ISO 16948:2015-09
Nitrogen (%)	2.09	1.44	1.09	DIN EN ISO 16948:2015-09
Ash (%)	16.68	23.5	9.8	DIN EN ISO 18122:2016-03
Volatile compounds (%)	-	-	69.9	DIN EN ISO 18123:2016-03
Fixed carbon (%)	-	-	20.3	DIN 51734: 2008-12
Ash content (%)	-	-	9.8	DIN EN ISO 18122:2016-03
Sulphur (%)	-	-	0.300	DIN EN ISO 16994:2016-12
Chlorine (%)	-	-	0.906	DIN EN ISO 16994:2016-12
Arsenic (mg kg^{-1})	-	-	<0.8	DIN EN ISO 17294-2 (E29): 2017-01
Lead (mg kg^{-1})	-	-	<2	DIN EN ISO 17294-2 (E29): 2017-01
Cadmium (mg kg^{-1})	-	-	<0.2	DIN EN ISO 17294-2 (E29): 2017-01
Chromium (mg kg^{-1})	-	-	<1.0	DIN EN ISO 17294-2 (E29): 2017-01
Copper (mg kg^{-1})	-	-	2.0	DIN EN ISO 17294-2 (E29): 2017-01
Nickel (mg kg^{-1})	-	-	<1.0	DIN EN ISO 17294-2 (E29): 2017-01
Mercury (mg kg^{-1})	-	-	<0.05	DIN EN ISO 12846 (E12): 2012-08
Zinc (mg kg^{-1})	-	-	3.0	DIN EN ISO 17294-2 (E29): 2017-01

CGB UTILIZATION

Erosion Control/Soil Amendment/Vegetative Establishment. One potentially valuable use for CGB is as an agent to reduce soil erosion. Controlling soil erosion is beneficial because of the number of negative effects of unchecked erosion. These adverse effects include downstream transport of sediment and nutrients/chemicals, aquatic habitat degradation, and formation of gullies (Flanagan et al., 2002; Holt et al., 2005b). The intensity of erosion is influenced by several factors, including soil conditions and disturbance activities, vegetation cover, topography/slope of the site, and length of the period between soil disturbance and reestablishment of vegetation (Fryrear, 1985). In addition, control and mitigation of soil erosion is important because the global erosion rate is higher than the rate of soil formation (Zuazo and Pleguezuelo, 2008). Efforts towards soil erosion control generally target enhancing soil/nutrient retention by minimizing disturbance while improving vegetation cover.

One way to use CGB for erosion control and soil amendment is by applying it as mulch. To control soil water erosion, several materials or combinations of materials have been used as mulch, including gravel and crushed stone, in addition to various plant residues (Prosdocimi et al., 2016). Using a proprietary production process called COBY (COtton BYproducts) (Holt and Laird, 2002), Holt et al. (2003b) investigated the use of CGB as hydromulch and evaluated the effects on plant growth and effectiveness in suppressing weeds. Compared with commercially available erosion control material, the results showed that treatments with higher CGB-based feedstock contained fewer weeds than other treatments (including the commercial material), with no adverse effects. Holt et al. (2005b) also evaluated the effectiveness of CGB-based hydromulches and cottonseed hulls, compared with wood and paper mulches. Although soil loss is widely considered the most critical indicator of mulch performance, the study also evaluated the performances through time to runoff, sediment loading of runoff, percentage soil component of the total runoff, and grass seedling counts. The use of CGB as cover materials for reducing wind erosion has been explored for several decades (Anthony et al. 1992; Bilbro and Fryrear, 1994).

In addition to erosion control, CGB is also used as substrate in growing nursery and ornamental crops, and CGB disposal in fields increases the organic matter and improves soil structure and nutrient composition (Norsworthy et al., 2009; Tejada and Gonzalez, 2006a, 2006b). CGB application as soil amendment enhances nutrient cycling and helps recover degraded soils. Table 7 summarizes key findings from previous studies that considered CGB as a soil amendment or mulch.

Animal Feed. Livestock rations constitute an immediate market for CGB (Ozkan et al., 2015). The amount of CGB added to animal feed ration is limited due to its coarse texture and relatively lower quality in terms of bulk density, protein content, and digestibility (Hamawand et al., 2016; Rogers et al., 2002). Another challenge in using CGB in animal feeds is associated with its high ash and lignin contents compared to other feed materials such as grass hay (Alege et al., 2023; Myer, 2007). However,

Table 7. Previous studies and key findings on CGB utilization as soil amendment and mulch

Study Category	Study Focus	Key Findings	Materials Used	Reference
Mulching	Developed mulch coefficient to assess the influence of surface mulch on erosion, evaporation, soil water storage/ retention, and crop yields.	As CGB rate increases, quantity of erodible aggregates decreases and percentage soil organic matter increases. An annual application of 9 $t\text{-}ha^{-1}$ of CGB protects Anarillo Sandy Clay Loam in the winter before spring mulch application. The percentage of soil cover required to hold wind erosion on loamy fine sand for CGB is 35. Differences in mulch depend on texture and density.	Mulching with varying amounts of CGB, wheat, and sorghum stubble.	Fryrear and Koshi (1971)
Soil fertility amendment and mulching	Investigated the effect of different soil amendments on southern blight (disease caused by *Scelrotium rolfsii*), tomato processing yield, and soil microbial community.	Disease incidences in CGB-amended plots were respectively 23% vs 61% for synthetic fertilizer-amended plots; and 3% for CGB-surface-mulched, tilled plots vs. 67% for tilled bare plots with synthetic fertilizers. Yields were higher for synthetic fertilizers in Year 1 but not different in year 2. Fungi (Propagule) were higher in CGB and other organic amendments than in synthetic, and enteric bacteria were higher in raw swine manure than other amendments in both years.	CGB, swine manure, a rye-vetch green manure, or synthetic fertilizers,	Bulluck and Ristaino (2002)
Mulching; Wind erosion control	Reviewed wind erosion control regarding the application, methods, and required amounts of various mulch types such as crop residues (including CGB), chemical soil stabilizers, and manure.	CGB was applied to untilled, listed, or chiseled soils at rates of 0, 2.5, 7, 11, 16, and 21 $t\text{-}ha^{-1}$. Compared with untilled and unmulched plots, chiseled plots with CGB application at 7 and 11 $t\text{-}ha^{-1}$ reduced wind erosion by 63% and 87%, respectively. Tillage after surface application and at lower amounts did not improve the effectiveness of CGB as wind erosion control. Wind erosion control is any mulch treatment that resists the erosive force of a 38.0 m s^{-1} (85 mph) wind velocity measured at 1.52 m (5 ft)	Crop residues (including CGB), chemical soil stabilizers, and manure	Armbrust (1977)

Continued

Table 7. Continued

Study Category	Study Focus	Key Findings	Materials Used	Reference
Soil fertility amendment and mulching; soil nematode community; tomatoes.	Evaluated the interaction of disturbance (tillage on bare soil vs. tillage followed by surface mulch), and synthetic vs. organic (including CGB) soil fertility amendments on free living and plant-parasitic nematodes communities in field soils.	Tillage did not affect free-living or plant-parasitic nematode community dynamics, but soil amendments greatly impacted nematode community structure and diversity. Populations of bacterivorous nematodes (mainly in the Rhabditidae and Cephalobidae, and fungivorous nematodes) were greater after planting in soils amended with swine manure, composted CGB, or rye-vetch than in soils amended with synthetic fertilizer at both locations. Populations of *Meloidogyne incognita* in soil were unaffected by soil amendments; Root-gall indices were lower in plots containing CGB than in plots with synthetic fertilizer during the second season.	Wheat straw, synthetic fertilizer, composted CGB, swine manure, and rye-vetch green manure	Bulluck et al. (2002)
Mulching; wind erosion control.	Evaluated soil losses with different percentages of soil covered with different materials.	Soil covered with 20, 40, and 60% ground cover will lose 43, 10, and 6% of the soil loss from flat bare soil, respectively. Hence, the entire soil surface does not have to be covered with mulch to reduce wind erosion.	Crop residues and nonerodable materials, including CGB, large clods, and gravel. And 3.1-25.4 mm sticks.	Fryrear (1985)
Mulching; tillage; disease control/ suppression; bell pepper.	A multi-year evaluation of effects of tillage and surface mulching on the dispersal of Oomycete pathogen Phytophthora capsici and infection of bell pepper.	Amendment with CGB was associated with increased or higher levels of soil porosity, water content, pH/extractable acidity, sum of cations, Cation Exchange Capacity (CEC), K, Ca, Mg, humic matter, microbial respiration, microbial biomass carbon, microbial biomass nitrogen, extractable and net mineralizable nitrogen, and extractable carbon. Amendment with CGB was associated with decreased or lower levels of soil bulk density and Cu. Increased levels of soil porosity, moisture, humic matter, and extractable N levels may affect zoospore movement and enhance Phytophthora blight (disease) development.	Composted CGB, composted poultry manure, rye-vetch green manure, and synthetic fertilizer.	Liu et al. (2008)
(Hydro-)mulch; Erosion control.	Evaluated the performance of cottonseed hulls and proprietary cotton/ CGB-based mulches in erosion control and reestablishment of vegetation.	Cotton-based mulches had significantly lower (numerical) soil/ sediment losses than paper and wood mulches. CGB-based mulches had significantly less soil in the total runoff than paper and wood mulches. Reduction of soil erosion and promotion of grass seed germination were equal or better with cotton-based mulches than the conventional wood and paper hydromulches.	Three proprietary CGB-based mulches (COBY - Red, Green, and Yellow), cottonseed hulls, paper, and wood.	Holt et al. (2005c)

Continued

Table 7. Continued

Study Category	Study Focus	Key Findings	Materials Used	Reference
(Co-)composting	Compared to integrated swine manure (co-) composting systems based on mechanical turning Swine manure was co-composted with (1) cereal straw and (2) CGB.	Swine-manure co-composted with CGB exhibited fast temperature rise and long thermophilic phase (which enhances compost sanitization), high recovery of nutrients (77% TN, >85% P and K), and organic matter (45%).		Sáez et al. (2017)

these properties vary widely in CGB depending on the growing location and production/harvesting practices, as previously discussed (Kennedy and Rankins Jr, 2008). Previous studies (Hamed et al., 2014; Holt et al., 2000a; Ozkan et al., 2015; Rogers et al., 2002; Stewart and Rossi, 2010) have investigated the nutritional composition of CGB as well as the effects of feeding CGB to different animals including beef cows and lambs. Warner et al. (2020) studied the effects of including CGB as a major source of protein, fat, and fiber in finishing diets of beef cattle. The study found that CGB (and whole cottonseed) can be effectively used as a source of those nutrients in finishing feedlot diets without compromising performance or carcass characteristics. Table 8 shows the nutritional characteristics of CGB compared with other forage feedstocks/supplements.

Compared with other applications, data on the current use of CGB in animal feeds are limited, but older studies suggest an increasing trend. For instance, a survey of five states in the U.S. midsouth in 1989, prior to the elimination of incineration as a CGB treatment method, reported that approximately 5 to 13% of the total CGB generated was used as animal feed (Anthony et al., 1992). Another study conducted in the Texas High Plains in 1999 (Castleberry and Elam, 1999) found that 48% of CGB was fed to livestock, 33% applied to fields, and 16% composted. In addition, it appears reasonable to suggest that the utilization of CGB in animal feeds has increased over the years, given how the nutritional value compares with other commonly used agricultural by-products (Table 8).

Grains such as corn, grain sorghum, and protein sources such as soybean meal and cotton seed meal are often used in a cattle ration. However, these feedstock materials are low in crude fiber content. This limitation necessitates using feedstocks rich in fiber as supplements in the cattle feed rations. Galyean and Rivera (2003) stated that increasing roughage levels in feedlot diets decreases the percentage of highly fermentable concentrates, and potentially decreases incidences of nutritional disorders. Therefore, feedlot rations for animals at different growth stages often require minimum levels of fiber to minimize digestive disturbances and maintain normal ruminal functions (Galyean and Defoor, 2003; Kung, n.d.). For example, weaned calves have no minimum fiber requirement if other nutrient requirements are met, but it is recommended that diets for lactating cows should contain a minimum of 19 to 21% acid detergent fiber (ADF) (Kung, n.d.). According to the National Research Council (2001), the recommended minimum neutral detergent fiber (NDF) concentrations of forages for dairy cattle is 15 to 19% dry matter; and diets that contain less than 15% NDF should not be fed to dairy cows. Also, lower-producing cows that require less energy could have diets with concentrations greater than the minimum. Because CGB can also serve, to a lower extent, as a source of protein and fat (Warner et al., 2020), there appears to be significant potential for increased utilization of CGB in animal feeds.

Typically, crude fiber resources that are used in cattle rations are cotton seed, wheat straw, sorghum stover, and others. However, as shown in Table 8, CGB is added for the same purpose. To justify using CGB over other commonly used alternative sources of fiber economically, CGB must provide comparable or better benefits than fiber. Firstly, the added value of CGB depends on the cost and availability of fiber. CGB can prove valuable as a supplement in situations or areas where roughages or crop residues are not readily available or costly. As shown in Table 8, several studies have shown that the crude protein content of CGB competes with several other materials, including fescue, prairie, and grass hay.

Additionally, the protein content and added value of CGB can also depend on the cotton harvesting method. Although focused on biomass residues in

Table 8. Nutritional characteristics of CGB and selected feed supplements

Feedstuff	DM	NDF	TDN	Nem	NEg	CP	Ca	P	K	Reference
	----------- % -----------			--MCal kg^{-1}--		-----------------% -----------------				
CGB	90	59.9	-	0.35	0.11	9.3	1.19	0.15	2.35	National Research Council (2000)
	90	-	44	0.77	0.07	7.0	0.8	0.2	1.2	Andrade et al. (2020) Myer (2007)
	90	-	44	0.86	0.07	7.4	0.65	0.12	-	Bath et al. (1980)
	77	-	57	-	2.35	14.3	1.63	0.37	2.09	Alege et al. (2023)
	59	-	58	-	2.56	12.4	2.27	0.36	2.24	Alege et al. (2023)
Cottonseed Hulls	91	90.0	45.0	0.79	0.25	4.1	0.15	0.09	0.87	National Research Council (2000)
	90	-	38	0.86	0.00	4.3	0.16	0.10	0.84	Bath et al. (1980)
	-	-	42	0.68	0.15	4.2	0.15	0.09	-	
Cottonseed Meal	92	28.9	75.0	1.79	1.16	46.1	0.20	1.16	1.65	National Research Council (2000)
	92	-	75.0	1.72	1.10	44.8	0.17	1.31	1.20	Bath et al. (1980)
Soybean Meal	90	7.8	87.0	2.15	1.47	54.0	0.29	0.71	2.36	National Research Council (2000) Rogers et al. (2002)
	89	-	81.0	1.90	1.26	54.0	0.36	0.75	2.21	Bath et al. (1980)
Wheat Straw	89	78.9	41.0	0.64	0.11	3.5	0.17	0.05	1.41	National Research Council (2000)
	90	-	41.0	0.77	0.04	3.6	0.19	0.09	1.11	Bath et al. (1980)
Oat Straw	92	74.4	45.0	0.79	0.25	4.4	0.23	0.06	2.53	National Research Council (2000)
	90	-	45.0	0.90	0.20	4.5	0.27	0.10	2.23	Bath et al. (1980)
Fescue Hay	88	65.0	56.0	1.18	0.61	9.1	0.37	0.29	1.84	National Research Council (2000)
Prairie Hay	91	72.7	48.0	0.90	0.35	5.3	0.35	0.14	1.00	National Research Council (2000)
Grass Hay	90	-	50.0	0.88	0.33	8.0	0.50	0.20	1.50	Myer (2007)
Alfalfa	91	39.3	60.0	1.31	0.74	25.0	1.41	0.22	2.51	National Research Council (2000)
Flaked Corn	86	9.0	93.0	2.33	1.62	9.8	0.03	0.31	0.33	National Research Council (2000)

NDF = Neutral detergent fiber, NEm = Net energy required for maintenance adjusted for acclimatization, NEg = Net energy required for gain, CP = crude protein, Ca = calcium, P = phosphorus and K = potassium.

fields, Wanjura et al. (2014) reported the crude protein (and other feed properties) for stick, bur, and other vegetative matter fractions from stripper- and picker-harvested cotton. The study showed that the protein in picked cotton is usually higher than in stripped cotton. The values reported in the study were also within the range of values reported by Holt et al. (2000a) for CGB recovered from stripper-harvested cotton at different ginning equipment outlets. Although these crude protein values are reasonably competitive with other agricultural by-products and residues commonly used as roughage, economically viable pretreatments of CGB could provide superior value.

Various pretreatment methods to improve the feed qualities of CGB also have been investigated. Andrade et al. (2020) investigated the effects of chemical and biological pretreatment of CGB on the feed composition, digestibility (both in vitro and in vivo), gas production, feed intake, and growth performance of feedlot Santa Ines lambs. The study reported a strong but economically unproven potential of combining urea and exogenous fibrolytic enzyme treatments of CGB for improved digestibility, intake, and growth performance. An older study (Conner, 1985) on the effects of treating CGB with 4% NH_4OH, 8% NH_4OH, and 4% NaOH showed that the treatments with NH4OH resulted in statistically significant increases in crude protein (CP), ADF, and cellulose; but reduced the in vitro dry matter digestibility (IVDMD). By contrast, the NaOH treatment resulted in a statistically significant increase in the IVDMD and cellulose availability of CGB but reductions in the CP and ADF. The reductions in CP and ADF as a result of NaOH treatment were not statistically significant, like the reported increase in the permanganate lignin and cellulose composition that resulted from the same treatment.

Similarly, Bernard et al. (2001) investigated the effects of chemical and mechanical treatments (hypochlorite oxidant, extrusion, and others) on nutrient intake and CGB digestibility in Holstein heifers' diets. The study reported that the apparent digestibility of dry matter, organic matter, and NDF were similar for all treatments, as both hypochlorite oxidant and extrusion altered the molar proportions of volatile fatty acid (VFA) but did not improve dry matter or fiber digestion. The study also found that extrusion achieved the VFA alterations and improved the bulk density and handling characteristics of CGB but did not improve the intake or apparent digestibility. Compared with cottonseed hulls, the study also reported that the fiber in CGB is more digestible.

Another concern previously associated with using CGB for cattle feed is chemical residue from applying pesticides (Bath et al., 1980). However, previous studies have reported that residues of chemicals used in cotton production are not detected at concentrations that pose risks to animals (Buser, 2001; Holt et al., 2000a; Stewart et al., 1998). In regard to feeding CGB to animals, Australia and many states in the U.S. (except California) allows feeding CGB based on research showing chemical residues being below levels of concern.

Composites. Composite materials are materials produced by combining multiple materials with different properties. From sustainability and environmental perspectives, research on the utilization of agricultural residues and by-products in producing new/alternative materials to petroleum-based products has gained significant attention in several industries (Holt et al., 2012). Efforts on CGB utilization in composites have explored the performance of the products when produced solely from CGB and in combination with CGB and other agents to improve specific properties. Therefore, the relative composition of CGB in product formulations varies depending on the target product's properties.

By-products derived from agricultural materials such as cotton are often used as fillers to enhance structural properties in composites and other products suitable for packaging, construction panels, insulation, and acoustic/sound absorption (Jones et al., 2019; Pelletier et al., 2013). Because of the price of CGBs and their suitability for combining with other materials in several processes, there is potential for cost-competitiveness with polymer materials and environmentally sustainable use (Holt et al., 2012; Jones et al., 2019). Alma et al. (2005) used cotton carpels combined with additive materials (urea-formaldehyde and melamine urea-formaldehyde) to produce particleboards. The study found that the cotton carpel-based products were comparable to the minimum standard requirements for general-grade particleboards in bending, internal bonding, lateral screw-holding strengths, and hardness. Ziegler et al. (2016) investigated the potential of multiple fiber-fungal strains (including CGB) in a patented fungus mycelium-based bio-composite.

Other studies have investigated the potential of growing fungi on digestible agricultural materials (Pelletier et al., 2013, 2017, 2019). Incubation of fungal mycelium with plant wastes results in the growth of interconnecting fibrous threads that form structural oligosaccharides and, consequently, biodegradable porous products (Attias et al., 2020; Pelletier et al., 2013). However, relatively higher complex carbon sources (e.g., cellulose and lignin) compared to fungal nutrients (such as fructose, glucose, lactose) in agricultural by-products can be limiting for desired mechanical properties in mycelial composites (Jones et al., 2019). To explore the acoustic properties of composites made from mycelium, cotton by-products, and other agricultural residues, Pelletier et al. (2013) showed strong potential for cotton fiber. Considered the low performer, 100% cotton bur fiber yielded over 70% acoustic absorption at the peak frequency of 1000 Hz.

Another study (Holt et al., 2009) assessed the viability of CGB and guayule bagasse as individual and blended raw materials in producing composite boards. Investigating various blending ratios of both materials, the study confirmed the potential of incorporating both materials in particle boards. However, higher CGB components in the blend tend to reduce the boards' mechanical properties and overall quality. The negative effects of CGB were associated with the broad composition and particle sizes of CGB; additional preprocessing to improve the size distribution of both materials was deemed critical to enhancing the viability of materials.

Nanocrystals are cellulose with diameters ranging from 2 to 20 nm and lengths from 100 to 2100 nm (Morais et al., 2013). Because of their unique mechanical properties (such as stiffness-enhancing capacities and low gas permeability), nanocrystals are used as components of electronic devices, aerogels, and foams as fillers in composites production, and as reinforcements for adhesives (Morais et al., 2013). Cotton fiber is an established source of cellular nanostructures. However, the influence of the genetic composition of the various cultivars and the environmental conditions during cotton production on the relevant chemical properties have also attracted research attention. Such studies have focused on extracting and characterizing cellulose from different components of CGB and coproducts to enhance the reliable use of the extracts as raw materials.

Jordan et al. (2019) investigated the suitability of CGB (including cotton gin motes) for preparing cellulose nanocrystals. Similarly, Morais et al. (2013) investigated the extraction of cellulose nano-whiskers from raw cotton linters. The study showed successful isolation of cellulose from CGB and reported various properties of cotton linter nanocrystals, such as high crystallinity (91%) and hydrophilicity. Additionally, Jordan et al. (2019) showed that cellulose can be isolated with or without chemical pretreatments, and post-process chemical treatments to purify the extracted cellulose nanocrystals did not significantly affect the high crystallinity and aspect ratios.

The effects of CGB composition on other properties of raw materials of particle boards have also been investigated. Holt et al. (2012) studied the termite resistance of composition boards made from cotton by-products and guayule bagasse. The study showed that termite resistance, in terms of total weight loss and one-week termite mortality rate of boards containing up to 50% CGB, was comparable to that of commercial-oriented strand boards (OSB). Additionally, the boards produced from all six blending ratios of CGB and guayule bagasse tested in the study had better visual grading ratings than commercial OSB and pine lumber.

TREATMENTS

Biological and Biochemical Treatments. Several changes in physical and elemental/chemical composition and other properties of biomass materials are associated with the presence, quantity, diversity, and activities of the microorganisms/microbial community. Biological treatments (also referred to as biotreatment processes) are considered highly effective for biodegradable materials. For organic wastes (e.g., CGB), these processes involve decomposition through the activities of various aerobic and/or anaerobic microorganisms (bacteria and fungi) and are therefore operated aerobically and anaerobically (Oshins et al., 2022; Saravanan et al., 2022). Technically, the most prominent methods are (aerobic) composting and (anaerobic) digestion. However, an advanced composting with select species of earthworms, called vermicomposting, is widely considered effective for treating organic wastes prior to disposal or application (Hamer, 2003; Li et al., 2023; Mahitha et al., 2016). In addition to the presence and circulation of air in the process, a major difference between aerobic and anaerobic biotreatment is that aerobic composting remains a solid-state process at high-rate operation. Digestion requires processing as slurry and is often optimized for biogas generation (Hamer, 2003). Compared with vermicomposting, traditional aerobic composting comprises various stages of mesophilic and thermophilic processes, whereas vermicomposting is a faster, mesophilic (using microorganisms that are active at 10 to 32 °C (50-90 °F) process (Mahitha et al., 2016).

Several previous studies (Díaz et al., 2002; Ghosh et al., 2011; Hamawand et al., 2016; Jackson, 2005; Tejada and Gonzalez, 2006a) investigated the application of biologically treated CGB as a soil amendment to improve soil fertility. Various nutrient compositions and resulting effects on the crops have been reported, confirming the material's beneficial application for soil amendment. Tejada and Gonzalez (2006a) evaluated the effects of crushed cotton gin compost with or without inorganic fertilizer on both soil properties and crop (rice) yield. The study reported higher nutrient uptake, crop yield, and grain quality by adding inorganic fertilizer to CGB compost. The result was linked with the effects of each material on N-transformations. The application of CGB compost without inorganic fertilizer resulted in N immobilization, whereas the addition of inorganic fertilizer led to net mineralization of N. A similar study (Tejada and Gonzalez, 2007) evaluated the effects of CGB compost and other organic wastes on wheat yield and the soil's physical, chemical, and biological properties. The study reported that CGB compost application improved crop yield and soil properties, including structural stability, bulk density, exchangeable sodium percentage, soil respiration, and microbial biomass.

Despite the numerous prospects of application of CGB composts in soil amendment, the process has several challenges. Such challenges include understanding different crops' curing times and compost application rates. The wide variability in the composition of CGB complicates the uniformity of the process parameters across the profile of the pile/windrow. For instance, the broad differences in particle sizes and density of the various constituents of CGB can influence the aeration and decomposition rate. A possible consequence of a nonuniform composting process is the nonuniform properties of the composts at different points on the pile, which is necessary for both marketing and subsequent valorization processes. To address these challenges, previous works have studied options such as co-composting CGB with other materials or modifying composting technologies for adapting CGB with other agricultural by-products. On general composting processes, Onwosi et al. (2017) investigated the methodologies, challenges, and prospects of composting technologies in waste stabilization. Bernal et al. (2017) reviewed organic matter composition and transformations during composting. Sáez et al. (2017) tested the effectiveness of CGB as a bulking agent in pig manure composting.

Furthermore, Paredes et al. (1996) investigated co-composting CGB with poultry manure and sewage sludge, with CGB composition of 65 and 68%, respectively. Waqas et al. (2023) reviewed and compared aerobic composting processes for various agricultural wastes, including CGB. The same study also compared forced vs. static windrow systems in terms of the degree of humification, evaporation, moisture content requirement, ideal organic matter, and particle sizes. Rynk et al. (2022) compared/ranked various properties (moisture content, nitrogen content, bulk density, structure, degradability, odor risk, contamination concern) of CGB with other feedstock materials, including municipal waste, various animal manures, agricultural crop residues, food wastes, fish and seafood, and meat residues. Roberts and Pittaway (2000) investigated CGB composting to remove pathogens and residues, whereas Díaz et al. (2002) composted vinasse and CGB in two composting systems: a static aerated pile and a windrow. Oshins et al. (2022) compared the co-composting of different mix ratios of CGB and other by-products (including bagasse and rice hulls) as feedstocks. Waqas et al. (2023) discussed two-stage composting as an emerging technology that combines two different methods into a single composting system. The goal of the two-stage composting was to enhance the quality and consistency of the final product, improve the speed and reliability, and mitigate the environmental impact of the process.

The above-referenced studies further established the strong prospects of CGB composting, especially when compared with other agricultural residues and by-products. The various parameters investigated in the studies also provide useful information for improving the composting process for sustainable utilization of CGB and CGB composts. Future efforts could incorporate the findings to improve the uniformity of the CGB composting process across the entire profile. Optimization of the different technologies and methods for CGB would enhance the economics of the CGB valorization processes and improve marketability. More studies into adopting emerging technologies such as multi-stage composting (Waqas et al., 2023) for CGB would help establish technical, economic, and environmental feasibility. Enhancing the use of CGB compost tea, the water-based extracts of composts, is another potentially strong prospect for pursuing sustainable utilization of CGB. According to Velmourougane et al. (2021), compost teas are gaining significant attention in North America, Asia, and Europe; and are largely used as alternatives to chemical fungicides in commercial horticulture. Compost teas also are associated with improved soil quality, with reported enhanced bio-efficiency through integration with inorganic fertilizers (Velmourougane et al., 2021).

Thermochemical Treatments. Thermochemical processes combine high temperatures and chemical reactions in converting various materials, including biomass by-products of agricultural processes, to products with added values (Durak, 2023). The most direct process of converting biomass to usable energy is combustion, which converts heat to mechanical energy and power generation (De Jong and van Ommen, 2014). However, the most common thermochemical processes in waste treatment include pyrolysis, gasification, torrefaction, and hydrothermal processes: hydrothermal liquefaction (HTL), hydrothermal carbonization (HTC), and hydrothermal gasification (HTG) (Durak, 2023; Lachos-Perez et al., 2022; Mathanker et al., 2021). Thermochemical treatments are an essential component of sustainable solid waste management systems. They are characterized by higher temperature and conversion rates than other treatment processes (Arena, 2012). Consequently, thermochemical treatments are considered relatively environment-friendly, especially when operated for co-generation of heat and power (Arena, 2012). These processes are also associated with a significant reduction in mass and volume of materials, less land space requirement, immobilization of inorganic contaminants, destruction of halogenated hydrocarbons and other organic contaminants, and reduced greenhouse gas emissions (Arena, 2012).

Several thermochemical conversion techniques have been explored for CGB treatment. This section presents an overview of the main techniques before discussing the outcomes of their applications for CGB treatment.

Overview of Thermochemical Processes. Pyrolysis is the thermochemical decomposition of dry organic matter (< 10% moisture content) at relatively moderate temperatures (350-550 °C or 662-1022 °F) and atmospheric pressures in the absence of oxygen (Hognon et al., 2015). The main factors influencing bio-oil production and fractions of other components from biomass pyrolysis processes include the operating conditions or process parameters (temperature, heating rate, residence time, and the presence or amounts of oxygen) and feedstock properties (De Jong and van Ommen, 2014; Hognon et al., 2015; Piersa et al., 2022). Based on the operating conditions, pyrolysis can be classified into three main types: slow, intermediate, and fast. Forms of fast pyrolysis include flash and microwave, which have specific process requirements that relatively limit their applications (Piersa et al., 2022). Slow pyrolysis is carried out at a relatively lower temperature (~300 °C or 572 °F) and heating rate (<1 K s^{-1}). Intermediate pyrolysis is characterized by moderate temperature (~500 °C or 932 °F) and heating rate (1-10 K^{s-1}), whereas fast pyrolysis is conducted at moderate temperature (~500 °C or 932 °F) but at a relatively higher heating rate (>10 K s^{-1}). All three pyrolysis processes yield bio-oil, biochar, and biogas, but in different proportions. Hognon et al. (2015) reported the respective percentage oil-char-gas yield from the slow, intermediate, and fast processes as approximately 35-35-30, 50-20-30, and 70-12-13. Therefore, suitable processes can be adopted for target end products.

Torrefaction has been described as a mild form of pyrolysis involving biomass's slow heating at temperatures between 200 to 300 °C (392-572 °F) in an inert environment (Kumar et al., 2016; Tumuluru et al., 2011). The process is widely associated with retention of up to 80% of initial mass and 85 to 90% of initial energy content. As in pyrolysis, the thermochemical decomposition of hemicellulose and lignin results in torrefaction, resulting in the removal of hydroxyl functional groups and, consequently, increased stability against moisture sorption, microbial degradation, and chemical oxidation. Torrefaction as a biomass conversion process has been shown to have significant technical and market potential. However, the process is often incorporated as a pretreatment process due to high capital cost and, therefore, the need to integrate into an existing bioenergy value chain (Kumar et al., 2016).

HTL uses high temperature (250-400 °C or 482-752 °F), high pressure (10-25 MPa or 1,450-3,626 psi), and water (usually in wet or high moisture feedstock) to activate thermal decomposition and other chemical reactions that convert the feedstock to liquid bio-oil and other products (Cao et al., 2017; Durak, 2023; Nakason et al., 2018; Ponnusamy et al., 2020). For example, through hydrolysis and fragmentation/dehydration processes, the decomposition of cellulose and hemicellulose typically occurs at 240 to 390 °C (or 464-734 °F) and 160 to 360 °C (or 320-680 °F), respectively (Anukam, 2013; Ponnusamy et al., 2020). Similarly, lignin begins to dissolve through hydrolysis at ≥200 °C (≥392 °F) temperatures, and through both hydrolysis and dealkylation reactions, the dissolved lignin is rapidly converted to various phenolic compounds (Biller and Ross, 2016; Ponnusamy et al., 2020). The phenolic compounds and insoluble lignin form solid residues by polymerization and solid-solid conversion, respectively (Ponnusamy et al., 2020). Bio-oil (or biocrude) produced from HTL is an energy-dense liquid fuel containing various organic compounds. These properties make biofuel suitable as potential replacements for fossil fuels in existing combustion systems and as high-value chemical feedstocks for further refinery or upgrade applications in agriculture, plastics, and pharmaceuticals. (Biller and Ross, 2016; Durak, 2023). Apart from bio-oil, biochar recovery from biomass the organic components greatly influence HTL. Previous studies have highlighted a strong correlation between biochar recovery in HTL and the lignin and carbohydrate contents of the feedstock (Cao et al., 2017; Ponnusamy et al., 2020).

HTC and HTG differ from HTL mainly in terms of the operating conditions and the fractions of main products. Whereas HTL is operated at intermediate temperature ranges, HTC is operated at relatively lower temperatures (180-250 °C) and mainly yields char (or hydro-char) with high heating values and ash contents comparable with low-rank coal (Biller and Ross, 2016; Luthfi et al., 2024). At higher temperatures (>375 °C or >707 °F), gasification reactions begin to dominate (hence, the name hydrothermal gasification), and the main products shift from bio-oil to syngas (Biller and Ross, 2016). Compared to gasification-derived syngas, which comprises mainly hydrogen and carbon monoxide, syngas from HTG is typically high in hydrogen or methane content, with some CO2 (Biller and Ross, 2016).

The above distinctions in product composition are mainly due to the contrast between the processes. The gasification process typically involves the application of heat (in the range of 700-1500 °C or 1,292-2,732 °F) in the presence of a gasifying agent to break down biomass to produce syngas (De Jong and van Ommen, 2014; Richardson et al., 2015; U.S. EPA, 2007). Ponnusamy et al. (2020) noted that biochar yield in HTL can be as high as 70%, compared to approximately 35% in pyrolysis. In addition to the feedstock composition, the differences in biochar yield were associated with the use of catalysts, residence time, and temperature. Therefore, specific process parameters (temperature, heating rates) can be modified for target product yields or properties for different biomass materials. In addition, apparent advantages of hydrothermal processes over other conversion technologies that require pre-drying include adapting the method to a broader range of materials and avoiding the energy penalty of latent heat of vaporization, which implies a significantly lower energy requirement (Biller and Ross, 2016; Pecchi and Baratieri, 2019). Biller and Ross (2016) also noted that water as a reaction medium is not only cheap, readily available, and ecologically safe, but the weak hydrogen bonds result in property changes that allow it to act as a catalyst and allow reaction pathways that would not occur at ambient conditions.

Thermochemical Treatment of CGB. Successful development and adoption of technologies to convert CGB to green energy have environmental and economic benefits for the cotton industry in reducing greenhouse gas emissions and creating investment opportunities in rural areas (Zabaniotou and Andreou, 2010). Therefore, this section provides an overview of the thermochemical conversion technologies that have been researched for sustainable CGB utilization and the various levels of success or potential. As feedstock for bioenergy production, a previous study (Curtis et al., 2003) reported that CGB is one of the least expensive agricultural by-products in terms of purchase and transport costs. The study suggested that the overall feasibility of CGB conversion processes could depend on other production costs (such as equipment and land/infrastructure) rather than feedstock costs. Based on the changing scenarios in terms of production costs, further research is needed to understand the current cost distribution for CGB utilization.

To address the low density while exploring the bioenergy potential of CGB, Widjaya (2018) pelletized various proportions of CGB with 5 to 20% biochar. The study reported a 4 MJ kg^{-1} (1,719 Btu/lb) increase in heating values when 20% of biochar was blended with CGB. Aquino et al. (2010) investigated the effects of varying operating conditions (500-800 °C or 932-1472 °F temperature) on the pyrolysis of CGB. The study found that the respective maximum yield of biochar (38 wt. %), bio-oil (30 wt. %), and biogas (35 wt. %) were obtained at 500, 600, and 800 °C (932, 1112, and 1472 °F). Sadaka (2013) combined torrefaction and gasification processes in an auger system to investigate the effect of torrefaction in the pretreatment of CGB. The study reported that torrefaction increased the heating value, bulk density, and the stoichiometric air required for the complete combustion of CGB, as well as reductions in the moisture content and volatile solids. Similar results were obtained for the biochar produced using torrefied CGB compared with those obtained from raw CGB.

Similarly, Zabaniotou et al. (2000) studied the effects of temperature and heating rates on product yield during pyrolysis of CGB in a batch reactor using helium air as the catalyst. At temperatures ranging between 350 to 850 °C (662-1562 °F), and heating rates of 80 to 100 °C s^{-1} (176-212 °F s^{-1}), the study showed equal percentages of biogas and biochar were recovered at 550 °C (1022 °F). Above this temperature, biogas recovery was increasingly higher than biochar. Bio-oil and tar recovery were almost negligible, and these were attributed to the slow pyrolysis process. In addition to the effects of operation conditions on biochar production, another study (Hernandez et al., 2007) investigated the production of activated carbon from pyrolysis and steam activation of CGB. The study found that pyrolysis time did not significantly affect biochar yield but, like other studies, biochar yield decreased with increasing temperature: from 38 to 40% at 600 °C (1112 °F) to 28 to 34% at 800 °C (1472 °F). In addition, optimum activation (in terms of iodine value) was obtained at a pyrolysis temperature of 700 °C (1292 °F) for 45 minutes.

Ethanol production from CGB also has been widely investigated (Agblevor et al., 2003, 2006;

McIntosh et al., 2014; Vancov et al., 2019). Agblevor et al. (2003) reported that ethanol yield from the steam explosion of CGB is influenced by the origin, composition, and heterogeneity of the feedstock and the severity of the steam explosion process. The same study reported an ethanol yield of up to 113 to 190 liters (30-50 gal) per ton of CGB, and ethanol yield was directly correlated with the cotton lint and hull contents. Investigating various pretreatment processes for ethanol production from CGB, McIntosh et al. (2014) optimized the temperature, time, and concentration of H2SO4, and Vancov et al. (2019) investigated a two-stage pretreatment process. The first stage involved adding 12% H2SO4 and heating it at 180 °C (356 °F) for 15 minutes, whereas the second stage included additional heating of the fiber generated from the first stage at a higher temperature. Both studies showed that the valorization of CGB can be improved with suitable pretreatment. In addition to the methods experimentally explored for CGB pretreatment, Sahu and Pramanik (2015) discussed other chemical and physicochemical methods applied to lignocellulosic biomass that can be explored for CGB. The costs or time requirements could limit some of the methods. Additional research on CGB treatment and utilization should investigate the potential of other pretreatment methods or some of the newer hydrothermal conversion methods described earlier.

Mechanical and Physical Treatments. Properties of CGB, such as the low bulk density, significantly limit its processing, utilization, transportation, and storage. Therefore, previous efforts in mechanical and physical treatments of CGB have focused mainly on improving the density and mitigating the associated issues. Other research efforts have incorporated mechanical processes as pretreatments to improve specific product qualities and enhance the efficiencies of other processes. The most common mechanical pretreatment processes for lignocellulosic materials are grinding and densification (Tumuluru et al., 2011). The study explained that these processes are common because they improve transportation efficiency and biomass feedstock's handling and conveyance efficiencies throughout the supply system and biorefinery infeed. In addition, these mechanical processes also result in consistent particle size distribution for improved feedstock uniformity and products' compositional quality to meet the specifications of conversion technologies and supply systems.

Various densification systems, including pellet mills, briquette presses, screw extruders, cubers, and agglomerators, have been explored for improving the density of agricultural biomass/residues (Tumuluru et al., 2011). Of these systems, the first three are the most tested for various woody and herbaceous biomass densification. Mechanical densification systems are known to increase the density of materials by up to 500%, and, like the thermochemical processes, the qualities of densified products are mostly influenced by process variables and feedstock composition.

Pelleting, in combination with various pretreatment processes, appears to be the most widely investigated densification method for CGB. The COBY process patented by Holt and Laird (2002) has been extensively evaluated for developing various products for bioenergy, livestock feed, and mulch (Holt et al., 2003b, 2005a, 2005b; Holt et al.,). In addition, Holt et al. (2006) investigated the feasibility of producing industry-grade CGB-based fuel pellets. The study used the COBY system to pelletize CGB samples obtained from two locations in the U.S. (Lubbock, TX, and Stoneville, MS). Along with the differences in source locations, the formulations also varied by adding different blended proportions of corn starch, crude cottonseed oil, and guayule bagasse. The study concluded that CGB-based pellets that meet the Pellet Fuel Institute (PFI) standards (e.g., bulk density ≥640 kg m^{-3} or 40 lb ft^{-3}) could be produced with appropriate additives and manufacturing methods. Compared with premium-grade wood pellets in residential applications, the study also reported that the main limiting factors associated with producing and using CGB-based pellets for heating fuel include high ash content, high emission rates, consistency of product properties, and adaptability with existing pellet stoves.

Other studies on the pelletization of CGB have explored adding other materials or pretreatment processes. As previously mentioned, a study (Widjaya, 2018) used a small-scale pellet mill to produce pellets of cotton gin waste with 5 to 20% biochar. The results indicated that pelleting increased bulk density from 112 kg m^{-3} to 600 kg m^{-3} (7 to 37.5 lb ft^{-3}). The study also showed that blending biochar increased heating values from 14 MJ kg^{-1} (6,019 Btu lb^{-1}) with 100% CGB to 18 MJ kg^{-1} (7,739 Btu lb^{-1}) with 20% biochar. These and other studies have established the potential of producing good-quality pellets for various applications. However, the main limitation of pelletization (and generally, densification) of CGB has been identified as the overall economics of the processes. Therefore, it appears that a breakthrough process for CGB treatment and utilization will significantly depend on its economic and environmental sustainability. This implies that continued investigation of co-treating CGB with readily available and affordable waste materials is necessary.

SUSTAINABILITY AND ECONOMICS

CGB, like other lignocellulosic biomass, is highly variable in composition and contains various compounds with different functional groups. These broad variabilities imply the prospect of incorporating CGB in a broad range of processes and a strong potential to develop a wide range of products. Previous research efforts also have highlighted the potential of several biomass conversion systems and techniques and their potential for commercialization (U.S. EPA, 2007). However, the application of these techniques to CGB is relatively in the early/non-commercial stages compared to other technologies successfully adopted at commercial scales for other materials.

Measures to sustainably address the system challenges associated with developing biomass conversion processes can be broadly categorized into three levels: process chemistry, process design, and enterprise analysis/optimization (Daoutidis et al., 2013). The process chemistry aims to establish the range of chemical transformations available for biomass upgrade and the associated kinetics. In this regard, continued investigation of the potential of co-treating CGB with various materials, especially by-products of other agricultural processes, which are readily available within economically viable distances, is vital. There is an enormous amount of information on the various agricultural residues with physical and chemical properties that can complement the limiting characteristics of CGB in the different processes.

Process design focuses on identifying suitable reactor configurations and operating conditions for producing the target products (Daoutidis et al., 2013). Although unsuccessful at commercial scales, many technologies previously explored for CGB treatment/utilization have shown strong potential. Therefore, in addition to exploring other materials, future studies on modifying existing processes to establish the optimum operating conditions and proportions of materials are also important. For example, Holt et al. (2003a) reported that replacing extruders with blending augers in a fuel pellet operation would increase operational throughput, reduce power consumption by eliminating approximately 745 kW, and reduce the capital costs by approximately $0.5 million.

Hybrid or integrated systems for biomass processing could also be explored for CGB. These systems typically combine multiple processes to counteract the system's weaknesses with another's strengths (González et al., 2016). Thermochemical conversion processes can be combined with biological treatments or different thermochemical conversion processes can be combined at different stages (Cao et al., 2017). Pecchi and Baratieri (2019) reported the incorporation of gasification, pyrolysis, and HTC as pre-and/or post-treatments for anaerobic digestion. Other developments have incorporated different processes as separate but controlled stages in a single multistage system (Heidenreich et al., 2016). The studies highlighted strong prospects for each combination of treatments, especially in terms of increased product yield per unit mass of substrates and improved quality of products. On the other hand, Pecchi and Baratieri (2019) also reported the need for more research to address the specific phases' energy requirements and establish the energy balance and overall feasibility at the industrial scale.

Finally, the enterprise analysis/optimization category of sustainability assessment explores the technical, geographical, and infrastructural components at multi-plant levels (Daoutidis et al., 2013). In addition to the limitations associated with the inherent properties of CGB, logistics are an important factor in large-scale CGB utilization. Holt et al. (2004) evaluated the feasibility of CGB treatment technology from three main perspectives: marketing, transportation, and manufacturing. Process and equipment designs should be optimized for adaptability with existing ginning equipment and (infra) structures to reduce capital costs. For example, Holt et al. (2004) noted that purchasing used versus new equipment could reduce the total capital cost by up to 30%. Farmer et al. (2014) reported that the delivery scale dilemma—the conflict between the right size and the right transportation process—is a central economic problem for biomass-to-energy conversion processes. To optimize transportation costs, proximities of both feedstock materials (CGB) and market distribution hubs to the processing plant are also critical to sustainable CGB processing. In addition, circular systems with conversion processes fueled by CGB can potentially offset electricity costs if generated onsite (Multer et al., 2010). For various processes, CGB could also be pelletized and stored for off-season use or transported offsite to other users cost-effectively (Capareda et al., 2006). Future efforts also should consider cooperative systems among multiple gins within a geographic area to share and reduce costs, where suitable.

Overall, the future of research on biomass utilization, and indeed CGB, seems significantly hinged on the circular bioeconomy concept. Generally, the concept implies a focus on integrating systems that seek to encourage regenerative practices, minimize depletion of resources, prevent the loss of natural resources, and stimulate the reuse and recycling of by-products in ways that add the highest possible value to the system (Muscat et al., 2021). As discussed by Tripathi et al. (2019), perhaps a potentially viable option in the future is to explore technological developments for CGB utilization that create opportunities for carbon dioxide capture, storage, and utilization.

CONCLUSIONS AND FUTURE DIRECTIONS

The utilization of CGB as a feedstock for bioenergy, soil amendment, animal feeds, and other processes has gained research attention for several decades. Several technologies developed or successfully applied to other agricultural residues/by-products have been explored for CGB. However, adaptation of most of the technologies discussed regarding CGB are still in the pre-commercialization stage. An exception to this was the cotton-based hydromulch that was commercialized with an industry partner that manufactured the material for over a decade. Studies have established the potentials and limitations of those technologies, and more studies are investigating ways to optimize the processes, improve the economy, and mitigate limiting environmental impacts.

It should be noted that CGB is not worse than other materials. It has the same challenges as other biomass materials and agricultural by-products that depend on whether the materials are readily available, cost-effective, and produced in quantities that meet the needs of the local/regional facilities. This has been true of most biomass materials, other than wood, being researched for various value-added processing.

Technical (and economic) aspects of the primary biomass conversion and CGB treatment techniques have been presented in this paper. However, for any of the technologies to break through to commercialization, it appears there is the need to modify existing processes to incorporate a combination of techniques at both production and end-use/marketing stages. At the production stage, treatment processes must adapt to the broad variability of composition and properties of CGB and incorporate other materials to complement the limiting characteristics of CGB. Such materials must be readily available and sufficiently economical to ensure the profitability of the process. It is equally vital for the processes to address the density and the costs of handling and transporting CGB. At the end-use/marketing level, the product must be either reusable within the cotton production pipeline or in other industries within reasonable distances.

There are specific needs in each of the areas discussed in this paper that could enhance the utilization of CGB. However, those factors are beyond the scope of this paper. Future research on CGB utilization would depend on several factors such as the specific situations of individual gins in terms of economics and quantities of CGB generated. Future studies need to consider the logistics, economics, environmental, as well as the start-of-the-art science and technology available.

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