

Some Physical Characteristics and Heavy Metal Analyses of Cotton Gin Waste for Potential Use as an Alternative Fuel

Sungsoo Kim^{*,†}, Sun Ku Park^{***} and Kenneth E. Daugherty^{**}

Department of Chemistry, University of North Texas, Denton, TX 76203, USA

^{***}National Institute of Environmental Research, Incheon 404-170, Korea

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Abstract—The use of cotton gin waste as a fuel is an attractive solution to the problems of disposing of a surplus agricultural waste as well as supplementing energy resources. Because a qualified alternative fuel must meet both environmental emission standards and industrial fuel standards, the physical characteristics of cotton gin waste and its toxic element concentrations are important for its initial objective evaluation as a fuel. Constituent components, moisture contents, and ash contents of four separate parts of cotton gin waste were determined and evaluated, closely following the American Society for Testing and Materials (ASTM) test methods. The three most toxic heavy metals, arsenic (As), chromium (Cr), and lead (Pb), chosen for quantitative analyses were also determined by using an inductively coupled plasma atomic emission spectrometry and a microwave oven sample digestion method. This study revealed that the lint component is the leading candidate for fuel, which closely meets both environmental emission and industrial fuel standards.

Key words: Cotton Gin Waste, Fuel, Heavy Metals, Environmental Emission Standards, Industrial Fuel Standards

INTRODUCTION

From 1991 through 2001, an average of 1 million tons or 4.4 million bales per year of cotton were produced in Texas [NASS, 2002]. All of the cotton produced in Texas today is harvested by machine. There are two types of machine harvesters: spindle pickers and strippers. Pickers are used primarily in areas where the growing season is long, the cotton matures over an extended period of time, and more than one picking is required. They are most commonly used in the irrigated areas of South and South-central Texas. Since pickers are designed to be a more selective method of machine harvesting than strippers, the amount of waste that is collected in the harvesting process is considerably less. Cotton strippers go over the field only once, after the plant is desiccated either by frost or by the application of chemicals. In the process of harvesting, strippers collect a much larger quantity of leaves, burs, stalks, other plant materials, and soil particles than do pickers. Strippers harvest about 70 percent of all cotton in Texas [Glad et al., 1995].

All material collected by the harvesting machines is transported to gins, which separate lint, seed and foreign matter. The amount of foreign material of gin waste that is collected varies considerably according to season, geographic location and the harvesting process. Previous research indicates that it averages close to 50 kg per bale of spindle-machine-picked cotton and 300 kg per bale for stripper-harvested cotton [Lalor and Smith, 1977; Alberson and Hurst, 1964; Pendleton and Moore, 1967]. Table 1 shows some of the val-

Table 1. Estimated amount of cotton gin waste per bale (218 kg lint) of cotton

Investigators	Harvesting method	
	Mechanically stripped	Mechanically picked
Lalor and Smith	294 kg	60 kg
Pendleton and Moore	238 kg	37 kg
Alberson and Hurst	270-455 kg	54-68 kg

ues reported by investigators for the amount of waste material produced from the seed cotton which is required to produce a 218 kg bale of lint cotton. It reflects that approximately 1 million tons of CGW, out of a total 1.7 million tons produced in the whole United States, are produced annually in Texas alone.

Despite the strict enforcement of environmental regulations, there has been very little progress in the development of alternative methods, e.g., composting, fuel, and cattle feed, to traditional methods such as incineration or landfill for the effective utilization and safe treatment of CGW. Today the waste is generally being distributed as raw original gin waste in the fields, due to EPA (Environmental Protection Agency) or state regulations limiting landfill and open burning of the waste. Even though various possible methods of conversion of the waste to energy sources have been widely studied since the mid-1960s [Alberson and Hurst, 1964; Reddell et al., 1975; Griffin, 1976; LePori et al., 1978; Gordon et al., 2001], they have not been successful. This has been mostly due to two limiting factors.

First, modern production of cotton is accomplished by the substantial use of chemicals like pesticides and harvest aid chemicals, etc. The categories of special interest among those chemicals are the arsenical crop protection chemicals such as herbicides, defoliants and desiccants listed in Table 2, chiefly because of their heavy

[†]To whom correspondence should be addressed.

E-mail: skim@postech.ac.kr

*Current address: Department of Chemical Engineering, Pohang University of Science and Technology, Pohang, Kyungbuk 790-784, Korea

**Current address: President and CEO, The KEDS, Inc., P.O. Box 2502, Oak Harbor, WA 98277

Table 2. Arsenical crop protection chemicals in cotton gin waste and their emission standards

Crop protection chemicals	Substances*	EPA HAPs [†]	OSHA PEL [‡]
Herbicides	MSMA	Yes	500 µg/m ³
	DSMA	Yes	500 µg/m ³
Defoliant	Cacodylic acid (Arsenical)	No	
Desiccant	Arsenic acid**	Yes	10 µg/m ³

*: MSMA (monosodium methanearsonate); DSMA (disodium methanearsonate); Cacodylic acid (hydroxyldimethylarsine oxide).

** : Currently not used.

[†]: Environmental Protection Agency Hazardous Air Pollutants.

[‡]: Occupational Safety and Health Administration Permissible Exposure Limit.

usage during the cotton growth and harvest. It has long been recognized that this chemical usage leads to relatively high levels of residues in CGW [Miller et al., 1975; Seiber et al., 1979; Winterlin et al., 1986]. Surveys in Texas and California [Miller et al., 1975; Winterlin et al., 1986] have shown that cotton gin waste almost always contains residues ranging between 10 and 450 ppm (µg/ml) of these chemicals. Among these chemical residues, the content of arsenic residue in particular, was exceptionally high in CGW. Notwithstanding the fact that the use of arsenic acid as a desiccant was banned from the 1994/95 season of cotton harvest [Williams, 2002], it is highly suspected that the gin waste still contains a significant amount of arsenic [Pamell et al., 1980; Columbus et al., 1984; Perkins and Brushwood, 1993]. Thus it should be carefully considered that the residual chemicals, especially arsenic residue, in cotton gin waste, might create a problem during its combustion as a clean fuel.

Second, CGW consists of burs, bits of lint, sticks, and fine dust. The fine dust, commonly referred to as "fines", makes up to 33% by weight and 20% by volume of cotton gin waste [Seiber et al., 1979]. Presence of high content of fine dust in the waste constitutes one of the problems in its utilization as a source of energy as it will leave a considerable amount of ash during the combustion process. For the successful utilization of cotton gin waste as an energy source, fine dust must be removed before its use as a fuel and an effective fine dust removal method needs to be developed.

Nonetheless, cotton gin waste is a potential energy source, chiefly because of its reasonably good heat content, of about 16,300 kJ per kg of material [Griffin, 1976], and its large availability. Low emission of sulfur and low ash content from the combustion of pure cellulosic parts of CGW [Shafizadeh, 1968a] suggest the possibility of the waste as a clean fuel. A promising new market, that can utilize agricultural wastes as pellet fuel, is quickly growing in the United States [Newsletter from PFI, 1995]. Accordingly, the commercialization of pelletized agricultural waste is being watched with considerable interest. Consequently, solving the above-mentioned problems will decide whether or not cotton gin waste can become an attractive and competitive energy source.

One of key factors for a successful reuse of cotton gin waste is that emissions from combusted cotton gin waste must meet environmental emission standards, e.g., OSHA (Occupational Safety and Health Administration) PELs (Permissible Exposure Limits). Several fundamental physical characteristics of cotton gin waste,

which are other important factors for the successful utilization of cotton gin waste as an energy source, must also meet minimum industrial standards as a fuel. Hence, as a part of these needs, this research has carried out an investigation of some important physical characteristics and heavy metal analyses of cotton gin waste.

EXPERIMENTAL METHODS

1. Constituent Parts

Cotton gin waste was collected at the end of harvest season at Modern Gin (five different gins) in Buckholts, Texas. It was physically separated into four different parts—burs, sticks, lint, and fine dust—using ten different sizes of ASTM (American Society for Testing and Materials) standard testing sieves continuously stackable. The size of those sieves varies from 5 mm to 38 µm. Approximately 8 g to 49 g of composite waste were randomly picked by hand eleven times. After initial mass determination of each sample, the long-term task of separating the quantity of waste into four separate constituents was begun. Each of the 11 specimens was placed on the top of the sieves stacked continuously and shaken for 30 minutes using a testing sieve shaker (Ro-Tap®, Model B, Combustion Engineering Co., Inc., Houston, Texas). After being roughly separated, dissection microscope and magnifier were used to separate very small foreign matter from the separated lint, burs, and sticks. The material that fell through the 4 mm sieve was referred to as fine dust. Any small pieces of lint, burs, and sticks that fell through the 4 mm testing sieve were removed from fine dust each to the corresponding components. Separation continued until it was not feasible to search any longer for the various components. Each portion - burs, sticks, lint, and fine dust - was placed on the balance and the mass determined. From the mass of each constituent part, the total mass and the percentage of the total due to each was determined. The difference between the beginning mass and the sum of constituent masses was calculated as percent loss. It ranges from 0% to 3.2%. This loss can be attributed to both the particles and the moisture being lost during handling.

Bur and stick separation was very nearly 100 percent accomplished. Some of the lint contained very small particles of leaf, stick, and other foreign matter. Even though the dissection microscope and the magnifier were used during the separation procedure, any equipment that could remove such fine particles of foreign matter more effectively was not readily available to the investigator. Therefore, the hand separation was accomplished as best as humanly possible. Sand, soil, small sticks (less than 4 mm in length normally), and leaf particles were the major items found in the fine dust.

2. Moisture Content

Moisture content of the received samples was determined by the oven drying method. The mass of aluminum sample cans, 7.6 cm diameter × 2.5 cm deep with lids, was determined to the nearest 1 mg using a side loading balance. Approximately 0.2 g to 1.0 g each of a total 50 samples (40 specimens taken from separated cotton gin waste and 10 specimens from original cotton gin waste sample) were used for the determination of moisture content. All of the samples were tested as directed in the ASTM Test Method D 2495, Moisture in Cotton by Oven-Drying. Using the balance, the combined mass of can and sample was determined.

A forced air-drying oven (Modern Laboratory Equipment, Model

4-357-120) was then used to dry the samples for 12 hours at $105 \pm 4^\circ\text{C}$. After drying, desiccators were used to allow the cans and samples to cool without picking up any moisture. Mass determinations, to the nearest 1 mg, were then made for the cans and dried waste using the same balance. Specimens and cans were returned to the oven for an additional hour of drying. The specimens were then allowed to cool in the desiccators and mass determinations made.

A difference in mass for two successive dryings of 0.1% or greater of the most recent specimen mass called for an additional hour of drying, cooling, and mass determinations. Whenever the change in specimen mass between successive determinations was less than 0.1%, the last mass was recorded as the final mass. Moisture content (MC) was then calculated by using the equation below.

$$\text{MC} = [(M - D)/M] \times 100 \quad (1)$$

$$M = G - E$$

$$D = B - E$$

where:

M = mass of specimen as received, g,

G = gross mass of specimen and container, g,

D = oven-dry mass of specimen, g,

B = mass of oven-dry specimen and container, g, and

E = mass of empty container, g.

The final moisture content reported for each sample is the average of the ten moisture contents calculated for the ten specimens from four separate constituent parts of cotton gin waste. Average moisture content of original cotton gin waste was obtained from the average weight percent times the average moisture content of each of the corresponding constituent parts. For a verifying purpose, ten specimens of original cotton gin waste were examined for moisture content determination.

3. Ash Content

Ash content determination was made on as received test specimens. Empty porcelain crucibles were heated to 600°C , allowed to cool in a desiccator, and the mass determined to the nearest 0.1 mg. Approximately 0.2 g of each of the 30 specimens from three constituent parts of cotton gin waste—burs, lint, and sticks—was placed in the crucible and the total mass was determined. The recorded specimen mass was the total mass minus the mass of the crucible.

The as-received specimen and crucible were placed in a Lindberg, Model 51333, muffle furnace and the temperature increased slowly up to a final temperature of 600°C . This process took approximately five hours. Crucible and contents were then removed from the muffle furnace, cooled in a desiccator, and the mass was determined. Heating at 600°C was repeated for 30-minute periods, the crucible and contents cooled, and the mass was not determined until the mass was constant to within 0.1 mg. After the final mass determination, the ash material was placed in a 2 ml vial for later use.

Ash percent, for the as received specimen (APAR) was calculated by using the equation,

$$\text{APAR} = (W_1/W_2) \times 100 \quad (2)$$

where:

W_1 = weight of ash, and

W_2 = weight of as received sample.

To find the ash percent, on an oven-dried basis (APOD), the follow-

ing calculation was made,

$$\text{APOD} = \text{APAR} \times \left(\frac{100}{100 - \text{MC}} \right) \quad (3)$$

This procedure follows very closely the ASTM Standard D-1102, Ash in Wood.

4. Reagents

All nitric acids used in this work were analytical reagent grade chemicals from Fisher Scientific Chemical Co., Houston, Texas. The water used to prepare all the solutions and analyze the sample was deionized water obtained by purifying the house deionized water with a MilliQ system from Millipore Corp. This system produced a water of $18 \text{ M}\Omega/\text{cm}$ specific resistivity. An ICP-AES analysis of all of the water and acid used showed the presence of none of the nine elements analyzed in this study. Thus, if any elements were present in it, they would be in sub-ppb amounts. The standard stock solution ($1,000 \mu\text{g}/\text{ml}$) of As was purchased from Alfa Aesar Chemical Co., Wardhill, MA, and each stock solution ($100 \mu\text{g}/\text{ml}$) of Cr and Pb was prepared by dissolving a weighed portion of the high purity metal or salt (CrO_3 and $\text{Pb}(\text{NO}_3)_2$) in a dilute acid.

5. Sample Digestion Procedure

About 100 mg of sample were placed in a poly-tetrafluoroethylene (PTFE) container and treated with 2.5 ml of nitric acid. And then the container was inserted into an acid digestion bomb (Parr Instrument Co. Molin, IL). After the bomb was tightly capped, it was placed in a microwave oven (Kenmore Inc., Model 566 Chicago, IL). The system was operated at full power (700 W) for 30 seconds. After heating, the rack was removed from the oven and cooled by cold water for 30 minutes. When cool, the PTFE container was uncapped and 10 ml of deionized water was quickly added. The container was recapped and stood for 1 minute at room temperature.

At this stage, a very small amount of undigested residues still remained. The sample solution with the residue was filtered and washed with deionized water, and the filtrate was diluted to 50 ml in a volumetric flask.

6. Analytical Procedure

An ICP-AES (Perkin-Elmer Analytical Instrument ICP/5500, Norwalk, CT) was used for analyzing samples. The instrumental operating parameters together with the analytical lines chosen are given in Table 3. It was calibrated by using a calibration blank solution containing the same amount of nitric acid, and single element standard solutions containing 10 ppm each of As, Cr, and Pb. Before beginning the sample run, the highest mixed calibration standard was reanalyzed as if it were a sample. The concentration values obtained did not deviate from the actual values by more than 5%. The analyzing system was flushed with the calibration blank solution for at least 1 minute before the analysis of each sample. After each 10 samples, the instrument check standard and the calibration blank were analyzed for a verifying purpose. Finally, the toxic heavy metal concentrations of the sample solutions were obtained.

7. Detection Limits

In order to determine the detection limits of nine different elements, SBR-RSDB approach (signal-to-background ratio and relative standard deviation of background) was chosen since it is more widely accepted for various ICP systems. The mathematical expres-

Table 3. ICP-AES operating parameters and sample introduction conditions

ICP operating parameters		
ICP-AES	Perkin-Elmer ICP/5500	
RF power	1.25 kW	
Plasma gas	13 L/min argon	
Nebulizer gas	0.5 L/min argon	
Auxiliary gas	0.8 L/min argon	
Nebulizer pressure	12 psi	
Viewing height	15 mm above load coil	
Integration time	3 sec	
Sample introduction conditions		
Torch type	Quartz torch demountable (Fassel type)	
Nebulizer type	Cross flow type	
Spray chamber	Scott double pass type	
Peristaltic pump rate	0.5 mL/min	
Analytical lines		
Element	Wavelength (nm)	Background correction
As	193.76	−0.07+0.06
Cr	205.55	−0.08+0.05
Pb	220.35	−0.05+0.05

sion of this approach is as follows:

$$C_L = k \times 0.01 \times \text{RSDB} \times \frac{C_0}{\text{SBR}} \quad (4)$$

where:

C_L is a detection limit; RSDB is the relative standard deviation of the background (expressed as a percentage); SBR is the signal-to-background ratio; C_0 is the concentration which is yielding a net analyte signal; k is a constant of 2 or 3.

An integer of 2 was used for k constant, and 10 replicates of the background noise of each element were measured for the detection limit.

RESULTS AND DISCUSSION

Average weight ratio of burs, sticks, lint, and fine dust in 11 samples was determined and included in Table 4. This table shows that almost half of cotton gin waste consists of fine dust. This value is

higher than the previously reported value of 33% [Winterlin et al., 1986]. However, since the previous study used a smaller mesh size of screen (1.3 mm) to separate fine dust, it is hard to say that our sample contains more dust. In addition, the high standard deviation (± 11.1) of fine dust due to its most heterogeneous nature further supports this inference. If the availability of the waste is based on the results, roughly a maximum of 0.6 million tons of the waste could still be a potential fuel. Particularly, the weight percentage of the lint portion, which is of our main interest, is an average of 21.1%. It reflects that Texas alone will produce about 0.21 million tons of lint and nearly 3.4×10^9 megajoules from it each year [Shafizadeh, 1968b].

Table 4 also shows the moisture content of four constituent parts and of the raw material of cotton gin waste. All averaged values of moisture content have considerably good standard deviation at 95% confidence level. Among them, the lint portion has the lowest moisture content of averaged 7.26% and the stick portion has the highest moisture content of 10.42%. As shown in Table 8, lint was identified as within the Pellet Fuels Institute (PFI) standards of 8% moisture content requirement for premium grade fuel. Average moisture content of the original cotton gin waste was calculated and examined, and they were found to show a good agreement within an allowable error (not shown).

Ash content of each of three constituent parts is listed in Table 4. All of the APAR data in the table were determined on an as-received basis. On the other hand, every APOD was calculated from the APAR data and the moisture content of each corresponding sample. The lint portion showed a good standard deviation and the lowest ash content either in as-received or oven-dry basis, mainly due to both good homogeneity and pure cellulosic composition of lint. Both APAR and APOD of lint were satisfied at 95% confidence level and were very close to the PFI standards of 3% ash content required for standard grade fuel. However, this is still not good enough to meet the standards for premium grade fuel ($<1.0\%$), mainly because of the fine dust that could not be easily removed from lint as visually checked directly from the sample.

Prior to a full-scale quantitative elemental analysis, it was necessary to narrow down possible choices of the elements to be analyzed. Thus, a semi-quantitative analysis of nine environmentally toxic elements in the waste was first conducted by using ICP-AES. The results are included in Table 5. They reveal that the three elements, arsenic, chromium and lead, exist in the sample at an environmentally noticeable level. Their concentrations are 5, 28 and 30 ppm, respectively. Therefore, these three elements were chosen

Table 4. Quantitative analyses* of some physical characteristics of cotton gin waste

Type of analysis Constituent parts	Constituent ratio (wt%)	Moisture content (%)	Ash content APAR (%)	Ash content APOD (%)
Burs	25.0±5.2	10.1±0.26	7.51±1.87	6.76±1.68
Sticks	6.7±3.0	10.42±0.42	8.55±2.02	7.68±1.84
Lint	21.1±8.2	7.26±0.30	3.57±0.72	3.31±0.67
Fine dust	47.2±11.1	8.62±0.41	-	-
CGW	-	8.25±0.32	-	-

*: Average of 10 different samples of each constituent part.

Table 5. Semi-quantitative element analysis of cotton gin waste

Element	Concentration
As	5 ppm
Cd	not detected
Hg	not detected
Pb	30 ppm
Sb	not detected
Se	not detected
Tl	not detected
Ba	not detected
Cr	28 ppm

Table 6. Quantitative analysis* of heavy metal concentration in cotton gin waste

Type of elements	Arsenic (As)	Chromium (Cr)	Lead (Pb)
Constituent parts			
Burs	8.8	14.8	nd
Sticks	4.5	10.0	nd
Lint	6.2	13.1	nd
Fine dust	7.4	43.2	nd
Total	26.9	81.1	nd

*: Average of seven different samples of each constituent part; The result of each sample (not shown) was an average of three replicates. Unit - $\mu\text{g/g}$ (ppm)
nd: not detected

for the quantitative analysis.

The results of the quantitative analyses of these toxic heavy metals are shown in Table 6. A total of 43 samples were analyzed and the units of all data obtained were reduced from $\mu\text{g/ml}$ to $\mu\text{g/g}$ for practical convenience. The detection limits of the three elements for the ICP-AES were 0.082 ppm for As, 0.023 ppm for Cr and 0.25 ppm for Pb. Based on the detection limits, all of the metal concentrations were finally determined.

According to the analysis, arsenic (As) and chromium (Cr) concentrations in all of the four constituent parts were fairly close to their semi-quantitative values. On the contrary, somewhat surprisingly, lead (Pb) was not detected at all from any constituent part as well as raw sample. For chromium, its concentration in the four different constituent parts ranges from 10.0 to 43.2 ppm ($\mu\text{g/g}$). Noticeably, fine dust contains almost four times higher concentration than

any other parts. Similarly, Hughs et al. [1997a] recently analyzed and reported chromium contents from cotton gin external emission collected at gins in several western states. The authors showed that it ranges 11 to 50 ppm. They attributed the possible sources of chromium to either soil or machinery. Chromium background level in the United States soil is 20-85 ppm [Public info. from SNL, 2003a]. Total concentration of chromium in our sample is 81.1 ppm, and it is obviously in the background range. Since gin machinery and crop protection chemicals are not a main source of chromium but soil is [Hughs et al., 1997a], these facts strongly support that the possible source of the chromium is highly likely to be soil from the cotton field, not from either gin machinery or chemicals.

Arsenical compounds have been used on cotton fields in the United States for a long time because of their effectiveness and low cost. The use of inorganic arsenical compounds as desiccants was completely prohibited from 1993/94 harvest season because of their extreme carcinogenicity. Instead, these compounds were entirely replaced by organic arsenicals. The organic compounds include the herbicides MSMA and DSMA, used for postemergence control of perennial grass weeds, and the defoliant cacodylic acid ($(\text{CH}_3)_2\text{As}(\text{O})\text{OH}$), used as a harvest aid. Before the use of inorganic arsenicals was banned, Miller et al. [1975] reported that arsenic contents in CGW collected in Texas gins were 50 to 450 ppm. On the other hand, Hughs et al. [1997a] recently reported arsenic contents from cotton gin external emission collected in Texas (Organic arsenicals are still used on cotton fields). It was about 20 ppm. From this value, it is reasonable to infer that arsenic concentration in CGW would be higher than 20 ppm due to its heavy elemental characteristic. In fact, our study showed that arsenic concentration in CGW is a bit higher than airborne arsenic contents. As shown in Table 6, arsenic contents in the four constituent parts are fairly evenly distributed (Maximum 2 fold difference). Arsenic is a natural soil component found at the range of 3.6 to 8.8 ppm in the United States [Public info. from SNL, 2003b]. Arsenic contents in our sample are at least three times higher than its background soil level. It clearly supports that arsenic at least partially comes from residual amounts left in soil from past applications of agricultural chemicals. Hughs et al. [1997a, b] also suggested that the source of the arsenic is chemical and/or soil. However, it is not very clear which one is a major source. Further investigation is necessary to figure out this matter.

In terms of environmental emission standards, a high concentration of arsenic and chromium in a point source could be a potential hazard to our environment when the source is used as a fuel. Therefore, whether the CGW emits arsenic and chromium to the environment during its combustion is one of most critical factors for a

Table 7. Concentrations and residual fractions of arsenic and chromium in bottom ash samples of three different constituent parts of cotton gin waste

Type of elements	Arsenic (As)		Chromium (Cr)	
	Concentration*	Residual fraction	Concentration*	Residual fraction
Constituent parts	$\mu\text{g/g}$ (ppm)	(%)	$\mu\text{g/g}$ (ppm)	(%)
Burs	8.2	93	12.7	86
Sticks	3.2	71	8.9	89
Lint	4.9	79	10.6	81

*: Average of five different samples of each constituent part; The result of each sample (not shown) was an average of three replicates.

Table 8. Summary of pellet fuel standards from Pellet Fuels Institute (PFI)

Fuel characteristics	Premium grade	Standard grade
Bulk density	$\geq 0.64 \text{ g/cm}^3$	$\geq 0.64 \text{ g/cm}^3$
Dimensions	Diameter 0.64 to 0.79 cm	Diameter 0.64 to 0.79 cm
Heat values	$\geq 1.91 \times 10^4 \text{ kJ/kg}$	$\geq 1.8 \times 10^4 \text{ kJ/kg}$
Moisture content	8%	8%
Ash content	<1%	<3%
Fines	$\leq 0.5 \text{ wt\%}$	$\leq 0.5 \text{ wt\%}$

successful reuse of CGW as a fuel. In order to investigate the emission of these elements, we also conducted full-scale quantitative analyses of the bottom ash samples from three different constituents of the waste except fine dust after their combustion at 600 °C during 5 hours. Table 7 shows a residual fraction of each element in the three different parts. Residual fraction is defined as the ratio of the concentration of an element in the bottom ash relative to that in the original waste. If we assume that the rest of the element except that in bottom ash was completely vaporized to the atmosphere, it is not hard to deduce a released amount of the element from the residual fraction. The estimated amounts for arsenic and chromium are 3.2 and 5.7 ppm, respectively (these values are total amounts calculated from all of the three constituents). Any type of fuel burning appliance in the United States has a typical burning rate of 5 kg per hour. It means that about 0.13 and 0.23 g of arsenic and chromium are released to the environment when 40 kg of the waste fuel is burned during 8 hours. For these values, human exposure at 100 m distance from the emission source would be about $0.13 \mu\text{g/m}^3$ for arsenic and $0.23 \mu\text{g/m}^3$ for chromium well below the OSHA PELs of $500 \mu\text{g/m}^3$ (8 hours time weighted average exposure (TWA)) for organic Arsenic, Chromium (II) and (III) compounds- and $10 \mu\text{g/m}^3$ (8-h TWA) for inorganic Arsenic.

CONCLUDING REMARKS

Our study showed that, unlike two other recyclable components of cotton gin waste, i.e., burs and sticks, lint closely meets most of the industrial fuel standards of Pellet Fuels Institute. However, 3.31% of its ash content is even slightly higher than the standards for standard grade fuel. Such high ash contents are generally caused by a large incorporation of fine dust into lint. Therefore, in order to significantly reduce the amount of fine dust, especially soil particles, a more effective dust removal method during harvest and ginning process must be developed.

High arsenic and chromium concentrations in lint as well as burs and sticks obviously point out that their toxic emission could be a potential danger to our environment when they are reused as a fuel. However, fortunately, our emission study showed that this would not be the case. In other words, none of the three constituent parts exceeded the environmental emission standards from OSHA. Our study strongly proposes that these toxic heavy metals originate from soil and crop protection chemicals, especially in the case of arsenic.

Our study has confirmed that the lint portion of CGW is a highly prospective candidate for an alternative fuel in some environmental and industrial aspects. However, there will still be more steps ahead to realize it. For example, an exact heat value of lint, analysis

of organic emission, pelletization-study of lint, more fundamental and effective way to remove colloidal soil particles, etc. After all, the results from the tasks listed above will deeply influence the future of cotton gin waste as a fuel.

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