Australia Samples

Laboratory Testing Report

Phase 1

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Abbreviation

ABBREVIATION	DEFINITIONS
Al	Aluminium
As	Arsenic
Ba	Barium
BRE	Bluefield Renewable Energy Pte Ltd
C	Carbon
Cd	Cadmium
Co	Cobalt
CP	Cotton Pellets
Cr	Chromium
Cu	Copper
CW	Cotton Waste
DTG	Differential Thermogravimetric Graph
EBC	European Biochar Certificate
EPA	Australia Environmental Protection Agency
Fe	Iron
H	Hydrogen
H/C_{org}	Molar Ratio of Hydrogen over Organic Carbon
Hg	Mercury
Mn	Manganese
Mo	Molybdenum
N	Nitrogen
NEA	National Environment Agency Singapore
Ni	Nickel
O	Oxygen
O/C_{org}	Molar Ratio of Oxygen over Organic Carbon
Pb	Lead
S	Sulphur
Sb	Antimony
Se	Selenium
Sn	Tin
TCLP	Toxicity Characteristic Leaching Procedure
TGA	Thermogravimetric Analysis
Ti	Titanium
V	Vanadium
Zn	Zinc

Table of Contents

1 Executive Summary

In 2022, raw cotton waste sample was sent to BRE to be evaluated for its suitability as a feedstock for BRE's pyrolysis systems. A study was then carried out in a third-party laboratory and the feedstock properties and the biochar properties (after undergoing a pyrolysis in a laboratory-scale pyrolysis reactor) were tested and documented. It was observed that the cotton samples and the resulting biochar exceeds EBC limits in mercury content.

In 2023, new batches of pelletised samples of cotton waste (6 tons) and almond hulls (4 tons) were sent to BRE for similar analysis. It was found that cotton pellets biochar had an Oxygen / Organic Carbon (O/C_{org}) molar ratio of more than 0.4 based on a process temperature of 500°C– 700°C. This also fails the EBC requirements. It is likely that the process temperature needs to be increased further in order to reduce the O/C_{org} molar ratio to meet the EBC requirements.

For environmental tests, the cotton pellet biochar and almond hulls pellet biochar could not meet Singapore NEA leaching properties due to a high manganese leaching content. However, based on Australia's EPA's standards this leaching amount of manganese is allowed and as such, both biochar samples are eligible to be applied into the ground for agricultural use in Australia.

2 Objective

The objective of Phase 1 is to evaluate the suitability of using cotton and almond hulls pellets as feedstocks for BRE's pyrolysis processing and the commercial viability of the by-products, principally the biochar output.

Figure 2-1 Waste Samples sent for testing

All three feedstock samples (cotton waste, cotton pellets and almond hulls pellets) were sent to an independent third-party laboratory for various tests and properties analysis, as well as to pyrolyzed the samples using a laboratory scale reactor.

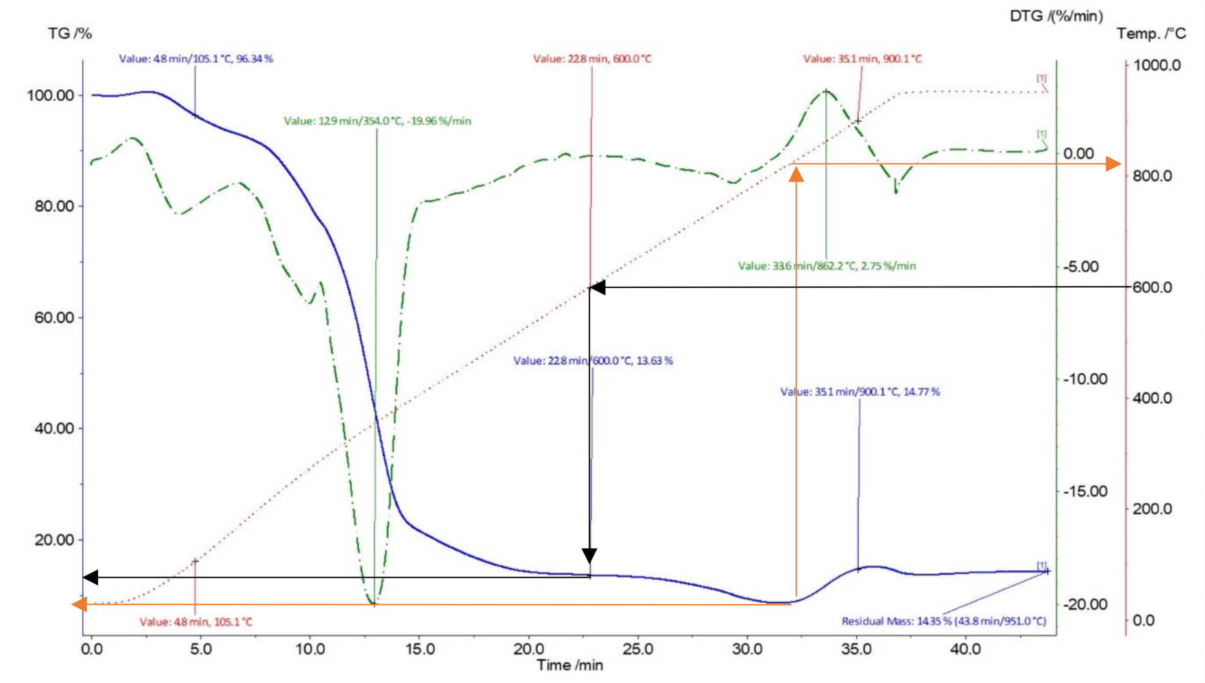
This report documents and explains the laboratory testing results on the properties of both feedstock and biochar.

3 Results and Discussion

3.1 Cotton Waste

3.1.1 TGA Analysis

3.1.1.1 Cotton Waste



Thermogravimetric Analysis (TG Analysis)

Differential Thermogravimetric Curve (DTG)

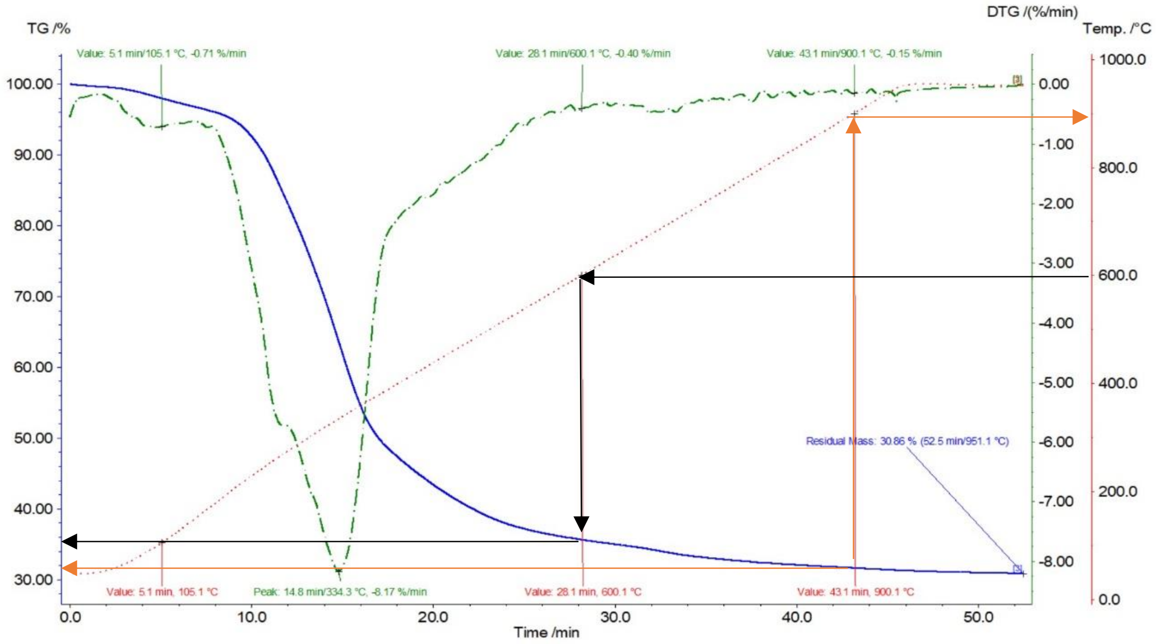
Temperature

Figure 3-1 TGA Analysis on Cotton Waste Received in 2022

Figure 3-1 above shows the analysis results of cotton waste received in year 2022. The Blue line indicate the thermogravimetric analysis (TG Analysis) which shows the rate of decomposition through mass loss percentage over the temperature range of 20°C to 1000°C. The Differential Thermogravimetric Curve (DTG) represented by the green line presents the rate of thermal decomposition of cotton waste. Lastly, temperature (red dotted line) acts as a reference line for the TGA data interpretation.

It shows that the highest mass loss of cotton waste occurs at temperature of 820°C, indicated by the orange arrowed line. This shows that the operation temperature of 820°C is expected to generate the highest quality of biochar, where all other organic components have been decomposed and converted into syngas / pyrolysis oil. Comparing this with an operation temperature of 600°C (represented by the black line), the mass low percentage between 600°C and 820°C is not significant, and it implies that the operation temperature should be at least at 600°C.

3.1.1.2 Cotton Pellet



Thermogravimetric Analysis (TG Analysis)

Differential Thermogravimetric Curve (DTG)

Temperature

Figure 3-2 TGA Analysis on Cotton Pellets Received in 2023

Figure 3-2 above shows the analysis results of cotton waste pellets received in year 2023. The Blue line indicate the thermogravimetric analysis (TG Analysis) which represents the rate of decomposition through mass loss percentage over a temperature range of 20°C to 1000°C. Differential Thermogravimetric Curve (DTG) represented by the green line depicts the rate of thermal decomposition of cotton waste pellets. Lastly, the temperature (red dotted line) acts as a supporting line for TGA data interpretation.

It shows that the highest mass loss of cotton waste occurs at a temperature of 900°C, indicated by the orange arrowed line. This shows that a process temperature of 900°C is expected to generate the highest quality of biochar, where all other organic components have been decomposed and converted into syngas / pyrolysis oil stream. Comparing this with an operation temperature of 600°C, the mass low percentage between 600°C and 900°C is not significant (around 4% difference), and it implies that the operation temperature should be at least 600°C.

3.1.2 Properties Analysis

3.1.2.1 Feedstock

3.1.2.1.1 Physical Properties

Table 3-1 below shows the physical properties of both the cotton waste received in year 2022 (CW) and cotton pellet received in year 2023 (CP). The moisture content of both samples is similar with just 2% of moisture content difference between the two samples.

Smaller particle size in cotton pellet could be the reason contributing to higher bulk density compared to raw cotton waste [1]. This also results in higher volumetric energy density (higher heating value). Heating value also referred to as calorific value, it is the heat value (amount of thermal energy) released during its combustion [2].

Higher ash content contributes to higher electrical conductivity of samples [3]. This could be proven indirectly using the ratio between CP and CW on ash content and electrical conductivity. With 29% increase in ash content in CP compared to CW, the electrical conductivity of the feedstock increased by 36% in CP as compared to CW.

Table 3-1 Physical Properties of Cotton Waste

Sample		Cotton Waste (CW)	Cotton pellet (CP)
Moisture Content (%)		11.36	9.27
Ash Content (%)	Mean	7.34	10.37
	Standard Deviation	0.98	
Bulk Density (kg/m^3)		153.00	482.50
Higher Heating Value (kJ/g)		16.52	18.11
Electrical Conductivity (µS/cm)	Mean	844.67	1318.00
	Standard Deviation	91.13	
pH	Mean	7.54	6.59
	Standard Deviation	0.01	

3.1.2.1.2 Total Elemental Content

Table 3-2 below shows the heavy metal content in both types of cotton feedstock samples. These heavy metals can be integrated into biomass through regular growth, long-term application of chemical-based pesticides and fertilizers on arable land, industrial processes including smelting and processing metal, waste emissions, development of mineral resources, and irrigation with sewage [4]. Potentially toxic heavy metals such as arsenic (As), cadmium (Cd), chromium (Cr), lead (Pb), nickel (Ni) copper (Cu) and manganese (Mn) (highlighted in pink below) are required to comply within acceptable limits due to their potential contribution to human health problems [5]. As such, it is not advisable to bury these wastes in landfills as it can potentially contaminate the soil and the ground. The metal contents such as aluminium (Al) and iron (Fe) are relatively high in concentrations compared to other elements. However, these elements exhibit no toxic effects and thus, it can be ignored [6] [7].

Table 3-2 Total Elemental Content of Cotton Wastes (Potential toxic heavy metals highlighted in pink)

Total Element Content (mg/kg) Element	**Cotton Waste (CW) (mg/kg)**	**Cotton pellet (CP) (mg/kg)**
Al	494±121.8	362.986±9.426
As	<0.5	0.066±0.01
Ba	15.4±6.8	13.196±0.704
Cd	0.5±0.3	0.009±0.001
Co	<0.5	0.169±0.029
Cr	3.1±1.4	4.129±4.497
Cu	6.4±1.9	2.788±0.232
Fe	243.8±60.7	336.235±73.781
Mn	27±5.1	19.726±2.315
Mo	2±0.9	0.582±0.302
Ni	1.3±1	1.845±2.163
Pb	2.1±1.5	0.169±0.029
Sb	<0.5	0.011±0.001
Se	1±0.3	0.049±0.014
Sn	2.7±1.4	1.441±0.049
Ti	42.6±14.3	18.287±0.799
V	0.8±0.1	0.476±0.036
Zn	13.5±10.8	9.67±2.269
Hg	2.3±0.4	0.014±0.002

3.1.2.1.3 Environmental Leaching Test

Leaching test on the cotton wastes has been conducted on both samples. The leaching results of all elements in CW are within Singapore NEA's leaching limits while for CP, leaching of Manganese has exceeded leaching limit set by National Environmental Agency Singapore (NEA) (highlighted in yellow). Manganese is an essential micronutrient in cotton and thus high level of manganese might be due to the fertiliser used in cotton plants [8].

Comparing both samples' leaching results to Australia Leaching Limits for solid waste disposal, both cotton waste samples are within acceptable limits based on Australia Environmental Protection Agency (EPA) standards. This is because the leaching limits for manganese elements is 10 times higher for EPA standards versus the NEA standards.

Besides, leaching of elements in CP are generally much higher compared to CW due to lower pellet water stability. It is recommended to increase pellet strength by increasing binder content to reduce the elemental leaching properties in CP [9].

Table 3-3 TCLP Results of Cotton Wastes

TCLP Element	Aus EPA Leaching Limits (mg/kg)	NEA Leaching Limits (mg/kg)	Cotton Waste (CW) (mg/kg)	Cotton pellet (CP) (mg/kg)
Al	-	-	0.0333±0.0057	107.685±1
As	20	5	<0.001	0.172±0
Ba	300	100	0.2288±0.0699	42.752±10.1
Cd	3	1	<0.001	0.018±0
Co	170	-	<0.001	0.195±0.1
Cr	1	5	0.0016±0.0002	0.367±0.1
Cu	60	100	0.0041±0.0031	1.119±0.3
Fe	-	100	0.0758±0.0193	82.57±15.9
Mn	500	50	0.649±0.2321	111.778±26.5
Mo	-	-	0.0008±0.0002	0.163±0
Ni	60	5	0.0076±0.0018	1.968±0.5
Pb	300	5	<0.001	0.046±0
Sb	-	-	<0.001	0.035±0
Se	-	1	<0.001	0.011±0
Sn	-	-	<0.001	0.02±0
Ti	-	-	0.5931±0.2015	64.876±16.2
V	-	-	<0.001	0.15±0
Zn	200	100	0.0348±0.0097	10.854±2.3
Hg	1	0.2	0.0018±0.0004	0.003±0

3.1.2.2 Cotton Biochar

3.1.2.2.1 Physical Properties

Table 3-4 below shows the properties of cotton pellet biochar produced via the laboratory-scale reactor at a temperature of 500°C – 700°C and cotton pellet biochar produced by BRE's system under a similar 500°C – 700°C operating temperature range.

In general, the physical properties of cotton pellet biochar produced by both the laboratory-scale system and BRE's system are similar, except for the bulk density of biochar. The difference in bulk density may be due to the different reactor types used in the biochar production. In the case of the laboratory-scale system it is based on a fluidised bed reactor whereas BRE is using batch reactor with an agitator. Biochar produced in a batch reactor could be crushed by the agitator and thus more ash / biochar in smaller sizes were produced, contributing to higher bulk density.

It was observed that cotton pellet biochar produced at 500°C - 700°C failed to meet EBC criteria whereby the molar Oxygen / Organic Carbon ratio should be lower than 0.4 (highlighted in yellow in table below). Biochar produced at 900°C can meet molar O/C_{org} ratio of 0.4 set by EBC as more non-carbon compounds would be decomposed into the gaseous state, leading to higher carbon content in the biochar. Moving forward it is likely that BRE will need to explore running more samples in our system in Phase 2 at higher temperatures.

High electrical conductivity in cotton pellet biochar produced by both systems could be due to high ash content resulting from the production under high temperature conditions [3]

Table 3-4 Properties of Cotton Pellet Biochar

Sample	**Cotton Pellet Biochar**	
	LABORATORY-scale system	**BRE's pyrolysis system**
	500 - 700°C	**500 - 700°C**
Ash Content (%)	28.57	30.36
Bulk Density (kg/m^3)	230.00	395.33
Higher Heating Value (kJ/g)	22.96	23.46
Ultimate Analysis (Mass %)		
N	2.44	2.72
C	52.51	60.30
H	1.62	1.48
S	0.22	0.17
O	43.21	35.33
Ultimate Analysis (Molar %)		
N	1.97	2.18
C	49.34	56.43
H	18.14	16.51
S	0.08	0.06
O	30.48	24.82
O/C_{org}	**0.62**	**0.44**
H/C_{org}	**0.37**	**0.29**
Electrical Conductivity (µS/cm)	3706	3263
pH	13.014	12.798

Comparing both batches of cotton waste (pelletised and non-pelletised), total carbon content in the cotton biochar produced at 500°C - 700°C is similar. This complies with the EBC requirements whereby the total carbon content needs to be higher than 50%.

Table 3-5 Carbon content in cotton biochar

Sample	**Cotton Waste Biochar**	**Cotton Pellets Biochar**	
	LABORATORY	**LABORATORY**	**BRE**
Total Organic Carbon (TOC) (%)	62.41	63.61	63.89
Total Carbon (TC) (%)	62.56	63.78	63.91
Total Inorganic Carbon (TIC) (%)	0.15	0.17	0.02

3.1.2.2.2 Total Elemental Content

Note:

In the previous batch (received in 2022) of cotton biochar, the tested mercury content was high and exceeded the EBC limits.

In the latest batch (received in 2023) of cotton pellet biochar, all elemental contents fall within EBC biochar limits.

Table 3-6 Total Elemental Content of Cotton Biochar

Total Element Content	EBC Standards					Cotton Waste Biochar (2022) (mg/kg)	Cotton Pellets Biochar (2023) (mg/kg)	
	Feed	AgroOrganic	Agro	Urban	Consumer Materials	LABORATORY-scale system	LABORATORY-scale system	BRE's pyrolysis system
Al	-	-	-	-	-		547.605±27.304	406.682±188.567
As	2	13	13	13	13	0.5±0.3	0.074±0.012	0.065±0.021
Ba	-	-	-	-	-	87±21.9	19.934±1.078	21.385±9.637
Cd	0.8	0.7	1.5	1.5	1.5	0.3±0.2	0.008±0.006	0.01±0.002
Co	-	-	-	-	-	1.8±0.4	0.195±0.014	0.197±0.088
Cr	70	10	90	90	90	6±1.9	1.529±0.043	1.447±0.655
Cu	70	70	100	100	100	24.7±10.3	3.127±0.284	4.217±2.019
Fe	-	-	-	-	-	1300.9±291.1	405.847±25.358	405.256±173.299
Mn	-	-	-	-	-	124.2±14	27.427±1.517	27.025±12.008
Mo	-	-	-	-	-	2.2±0.6	0.342±0.016	0.811±0.282
Ni	25	25	50	50	50	5.8±2.1	0.793±0.073	0.91±0.432
Pb	10	45	120	120	120	6±3.5	0.191±0.017	0.4±0.133
Sb	-	-	-	-	-	0.5±0.2	0.011±0.007	0.009±0.001
Se	-	-	-	-	-	<0.5	0.041±0.006	0.045±0.015
Sn	-	-	-	-	-	16.9±11.3	0.964±0.07	1.18±0.568
Ti	-	-	-	-	-	502.4±257.1	27.23±1.996	24.035±10.204
V	-	-	-	-	-	2.3±0.6	0.638±0.067	0.557±0.244
Zn	200	200	400	400	400	59.1±14	10.258±1.029	13.693±3.845
Hg	0.1	0.4	1	1	1	1.2±0.4	0±0.001	-0.002±0.002

3.1.2.2.3 Environmental Leaching Test

The leaching test results of all elements on cotton waste biochar fall within the leaching limits set by NEA except for the manganese content in the cotton pellet biochar which exceeds Singapore's NEA leaching limits.

Comparing all both types of cotton biochar samples' leaching results to Australia EPA leaching limits for solid waste disposal, both cotton biochar samples passed the Australia's EPA standards as the leaching limits for manganese is 10 times higher than the Singapore NEA limits.

Generally, the leaching of cotton pellet biochar elements are much higher compared to cotton waste biochar due to the lower water stability in pellets. It is recommended to increase the pellet strength/compactness by increasing the binder content so as to reduce the elemental leaching properties in CP [9].

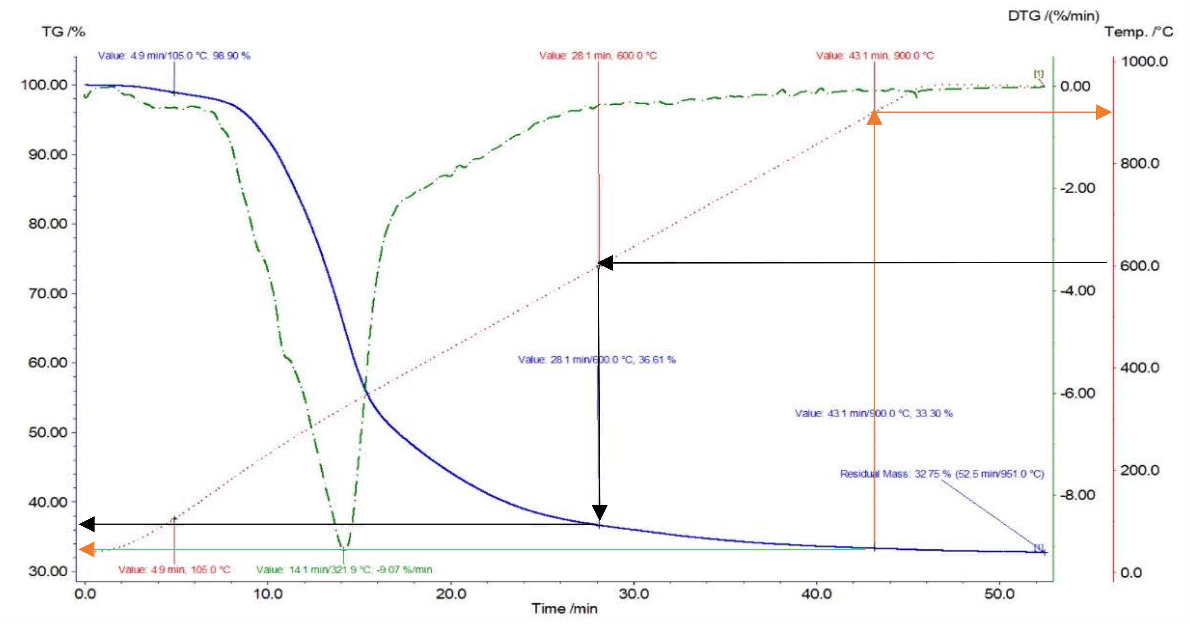
Table 3-7 Leaching Test of Cotton Biochar

Total Element Content	Leaching Limits		Cotton Waste Biochar (2022) (mg/kg)	Cotton Pellets Biochar (2023) (mg/kg)	
	Singapore NEA	Australia EPA	LABORATORY-scale system	LABORATORY-scale system	BRE's pyrolysis system
Al	-	-	0.0453±0.0666	3.397±0.1	3.51±0
As	5	20	0.002±0.0009	0.219±0.1	0.233±0.1
Ba	100	300	0.3789±0.0567	75.917±18.7	79.892±20.8
Cd	1	3	<0.001	0.007±0	0.01±0
Co	-	170	<0.001	0.102±0	0.053±0
Cr	5	1	<0.001	0.012±0	0.033±0
Cu	100	60	<0.001	-0.306±0	-0.303±0
Fe	100	-	<0.001	-0.16±0.1	0.354±0.3
Mn	50	500	0.1266±0.0426	137.647±38.6	133.942±39.9
Mo	-	-	0.0233±0.0027	0.139±0	0.165±0
Ni	5	60	<0.001	0.013±0	ND
Pb	5	300	<0.001	0.013±0	0.011±0
Sb	-	-	<0.001	0.055±0	0.071±0
Se	1	-	<0.001	0.051±0	0.026±0
Sn	-	-	<0.001	0.08±0	0.088±0
Ti	-	-	1.5078±0.1405	222.403±54	213.38±57.5
V	-	-	<0.001	0.004±0	0.006±0
Zn	100	200	<0.001	2.596±0.7	3.37±0.9
Hg	0.2	1	0.0043±0.0012	0.014±0	0.022±0

3.2 Almond Hulls Pellet Waste

3.2.1 TGA Analysis

3.2.1.1 Almond Hulls



Thermogravimetric Analysis (TG Analysis)

Differential Thermogravimetric Curve (DTG)

Temperature

Figure 3-3 TGA Analysis on Almond Hulls Pellet Received in 2023

Figure 3-3 above shows the analysis results of almond hulls pellets received in year 2023. The Blue line indicate the thermogravimetric analysis (TG Analysis) which represents the rate of decomposition through mass loss percentage over a temperature range of 20 °C to 1000 °C. Differential Thermogravimetric Curve (DTG) shown as the green line represents the rate of thermal decomposition of almond hulls pellets. Lastly, the temperature (red dotted line) acts as a reference line for the TGA data interpretation.

It shows that the highest mass loss of cotton waste happens at temperature of 900°C, indicated by the orange arrowed line. This shows that operation temperature of 900°C is expected to generate the highest quality of biochar, where all other organic components have been decomposed and converted into syngas / pyrolysis oil stream. Comparing this with an operation temperature of 600°C, the mass low percentage between 600°C and 900°C is not significant (around 4% difference), this implies that the process temperature should be at least 600°C.

3.2.2 Properties Analysis

3.2.2.1 Feedstock

3.2.2.1.1 Physical Properties

Table 3-8 below shows the physical properties of the almond hulls pellet as received.

Table 3-8 Physical Properties of Almond Hulls Pellet

Sample		**Almond Hulls Pellet**
Moisture Content (%)		11.8
Ash Content (%)	Mean	7.8
Bulk Density (kg/m^3)		514.67
Higher Heating Value (kJ/g)		18.77
Electrical Conductivity (µS/cm)	Mean	2411.00
pH	Mean	5.4

3.2.2.1.2 Total Elemental Content

In general, almond hulls pellet has a relatively high content in Aluminium (Al) and Iron (Fe) as compared to other elements. The following heavy metals, which have the potential to be hazardous to humans [4]: arsenic (As), cadmium (cd), chromium (Cr), lead (Pb), nickel (Ni), copper (Cu) and manganese (Mn). These metals must be kept within acceptable ranges. It is not advisable to bury these heavy metals in landfills due to the possibility of soil and ground contamination. In comparison to other elements, the high concentrations of iron (Fe) and aluminium (Al) based on Table 3-9 show no harmful consequences and can be disregarded [5][6].

Table 3-9 Total Elemental Content of Almond Hulls Pellet (Potential toxic heavy metals highlighted in pink)

Total Element Content Element	**Almond Hulls Pellet (mg/kg)**
Al	210.757±18.581
As	0.05±0.009
Ba	2.912±0.311
Cd	0.008±0.004
Co	0.087±0.012
Cr	0.946±0.184
Cu	3.255±0.133
Fe	195.184±32.968
Mn	11.219±1.036
Mo	0.367±0.235
Ni	0.473±0.067
Pb	0.111±0.024
Sb	0.011±0.005
Se	0.024±0.017
Sn	1.256±0.062
Ti	9.494±0.885
V	0.327±0.034
Zn	9.644±2.479
Hg	0.044±0.026

3.2.2.1.3 Environmental Leaching Test

Leaching test on the almond hulls wastes has been conducted. The leaching results of all elements in almond hulls pellets are within leaching limits except for Chromium (Cr) which exceeded the Australia's EPA leaching limits. This implies that disposal of almond hulls pellet by burying into the ground or via landfill will likely violate EPA's standards.

Table 3-10 Toxicity Characteristic Leaching Procedure (TCLP) Results of Almond Hulls Pellet

TCLP Element	Australia's EPA leaching limits **(mg/kg)**	**NEA's leaching limits (mg/kg)**	**Almond Hulls Pellet (mg/kg)**
Al	-	-	117.531±2
As	20	5	0.222±0
Ba	300	100	15.882±3.9
Cd	3	1	0.029±0
Co	170	-	0.479±0.1
Cr	1	5	1.929±0.5
Cu	60	100	7.997±2.1
Fe	-	100	96.491±27.6
Mn	500	50	125.862±32
Mo	-	-	0.396±0.1
Ni	60	5	2.76±0.7
Pb		5	0.152±0
Sb	300	-	0.032±0
Se	-	1	0.072±0
Sn	-	-	0.01±0
Ti	-	-	17.076±4.3
V	-	-	0.218±0.1
Zn	-	100	61.05±12.1
Hg	-	0.2	-0.004±0

3.2.2.2 Almond Biochar

3.2.2.2.1 Physical Properties

It can be seen that almond hulls pellet biochar produced met the EBC criteria where molar Oxygen/ Organic Carbon ratio limit is less than 0.4. Furthermore, it can be seen that the pH of almond hulls pellet biochar is 13.72, indicating that the almond hulls pellet biochar is alkaline and corrosive, resulting in a hazardous base when the pH value is greater than 12.5 [11].

Table 3-11 Properties of Almond Hulls Pellet Biochar

Parameters	Almond Hulls Pellet Biochar
Ash Content (%)	22.46
Bulk Density (kg/m^3)	159.5
Higher Heating Value (kJ/g)	24.72
Ultimate Analysis (Mass %)	
N	1.15
C	65.2
H	1.89
S	0
O	31.76
Ultimate Analysis (Molar %)	
N	0.88
C	57.93
H	20.01
S	0
O	21.18
O/C_{org}	0.37
H/C_{org}	0.35
Electrical Conductivity (µS/cm)	10430
pH	13.72

Table 3-12 below shows the carbon content in Almond Hulls Pellet Biochar.

Table 3-12 Carbon content of Almond Hulls Pellet Biochar

Sample	Almond Hulls Pellet Biochar
	LABORATORY
Total Organic Carbon (TOC) (%)	68.82
Total Carbon (TC) (%)	69.21
Total Inorganic Carbon (TIC) (%)	0.38

3.2.2.2.2 Total Elemental content

Referring to Table 3-13, Almond Hulls Pellet Biochar has attained the highest grade of EBC standard ('Feed' grade), which means that biochar produced can be used in industrial application.

Table 3-13 Total Element Content of Almond Hulls Pellet Biochar

Element	EBC standards					Almond Hulls Pellet Biochar (500 – 700) °C (mg/kg)
	Feed	Agro Organic	Agro	Urban	Consumer Materials	
Al	-	-	-	-	-	479.936±188.879
As	2	13	13	13	13	0.058±0.02
Ba	-	-	-	-	-	6.076±1.885
Cd	0.8	0.7	1.5	1.5	1.5	0.002±0
Co	-	-	-	-	-	0.193±0.081
Cr	70	10	90	90	90	1.288±0.541
Cu	70	70	100	100	100	4.889±1.608
Fe	-	-	-	-	-	362.492±147.325
Mn	-	-	-	-	-	21.535±8.267
Mo	-	-	-	-	-	0.159±0.049
Ni	25	25	50	50	50	0.829±0.289
Pb	10	45	120	120	120	0.16±0.065
Sb	-	-	-	-	-	0.008±0.002
Se	-	-	-	-	-	0.026±0.02
Sn	-	-	-	-	-	1.232±0.376
Ti	-	-	-	-	-	17.573±6.384
V	-	-	-	-	-	0.637±0.236
Zn	200	200	400	400	400	13.388±4.087
Hg	0.1	0.4	1	1	1	0.006±0.002

3.2.2.2.3 Environmental Leaching Test

Leaching test on the almond hulls pellet biochar has been conducted and the results are shown in Table 3-14. Based on the Toxicity Characteristic Leaching Procedure (TCLP) results for the Almond Hulls Pellets biochar, it can be seen that most elements fall below leaching limits except for **Manganese (Mn)** which exceeds the Singapore NEA's leaching limits.

Table 3-14 Leaching Test of Almond Hulls Pellet Biochar

Element	Australia EPA leaching limits (mg/kg)	Singapore NEA leaching limits (mg/kg)	Almond Hulls Pellet Biochar (mg/kg)
Al	-	-	9.387±0.1
As	20	5	0.207±0.1
Ba	300	100	71.962±18.6
Cd	3	1	0.006±0
Co	170	-	0.127±0
Cr	1	5	0.039±0
Cu	60	100	-0.291±0
Fe	-	100	0.634±0.4
Mn	500	50	114.58±30.5
Mo	-	-	0.1±0
Ni	60	5	0.121±0
Pb		5	0.013±0
Sb	300	-	0.053±0
Se	-	1	0.032±0
Sn	-	-	0.007±0
Ti	-	-	170.095±45.9
V	-	-	0.006±0
Zn	-	100	5.156±1.4
Hg	-	0.2	0.016±0

4 Conclusions

4.1 Cotton Waste samples received in 2022 compared to Cotton Pellets samples received in 2023

TGA analysis of both cotton waste samples exhibits similar trend lines, whereby rapid decomposition starts at 200°C and ends at around 400°C. However, at operation temperatures between 500°C to 700°C, the cotton waste's mass loss is higher at 86% as compared to the mass loss of cotton pellets which is 64% due to higher compactness of pellets.

Cotton waste biochar has higher mercury content and it failed to meet EBC requirement on all classes of application whereas for cotton pellet biochar, all heavy metal contents comply with EBC in all classes of requirements.

In order to comply with national environmental emission regulations, both samples were sent for leaching tests and compared with both Singapore NEA and Australia EPA solid waste leaching requirements. The results showed that cotton pellet biochar failed to meet Singapore NEA leaching limits due to a high concentration of manganese leaching. However, it can meet all the leaching limits requirements set by Australia EPA due to a higher allowable manganese leaching limits.

4.2 Samples as received in 2023: Cotton Pellets as compared against Almond Hulls Pellets

4.2.1 Raw samples

Comparing both TGA analysis results, both types of pellet samples decompose rapidly starting at 200°C and ends at around 400°C. A 500°C – 700°C process temperature for both types of pellet samples will allow ~ 64% of mass loss, resulting in ~36% of residual mass in the solid by-product, which is biochar. This is due to similar compactness of the pellets, as shown by their similar bulk density and energy density.

Table 4-1 Physical Properties of Pelletised Samples

Sample		**Cotton pellet (CP)**	**Almond Hulls Pellet**
Moisture Content (%)		9.27	11.8
Ash Content (%)	Mean	10.37	7.8
Bulk Density (kg/m^3)		482.50	514.67
Higher Heating Value (kJ/g)		18.11	18.77
Electrical Conductivity (µS/cm)	Mean	1318.00	2411.00
pH	Mean	6.59	5.4

4.2.2 Biochar

Comparing both cotton pellet biochar and almond hulls pellet biochar, cotton pellet biochar fails to meet EBC requirement for the Oxygen / Organic Carbon molar ratio which needs to be less than 0.4. As shown in Table 3-5, this is due to the lower total carbon content in the cotton pellet samples, resulting in low total organic carbon. Based on Equation 1 and 2 [12], with the decreased total organic carbon, the Oxygen/Organic Carbon molar ratio will be increased.

$$Total\ Organic\ Carbon\ \%\ (TOC) = Total\ Carbon\ Content\ \%\ (TC) - Total\ Inorganic\ Carbon\ \%\ (TIC) \qquad (Eq1)$$

$$\frac{Oxygen}{C_{org}} = \frac{Oxygen}{\frac{TOC}{(TC \times C)}} \qquad (Eq2)$$

Both pelletised biochar samples are strong alkali base, given their high pH level of more than 13. Biochar with pH value of more than 12.5 pH makes it a corrosive and hazardous base substance, which will result in human or environmental health problems [11].

Table 4-2 Properties of Pelletised Biochar

Parameters	Cotton Pellet Biochar	Almond Hulls Pellet Biochar
Ash Content (%)	28.57	22.46
Bulk Density (kg/m^3)	230.00	159.5
Higher Heating Value (kJ/g)	22.96	24.72
Ultimate Analysis (Mass %)		
N	2.44	1.15
C	52.51	65.2
H	1.62	1.89
S	0.22	0
O	43.21	31.76
O/C$_{org}$	**0.62**	0.37
H/C$_{org}$	**0.37**	0.35
Electrical Conductivity (µS/cm)	3706	10430
pH	13.014	13.72

Both pelletised biochar samples share similar heavy metal content and attained the highest grade of EBC standard (‘Feed’ grade), which means that biochar produced can be used in industrial application.

Table 4-3 Total Element Content in Pelletised Biochar

Element	EBC standards					Cotton Pellet Biochar (500 – 700)°C (mg/kg)	Almond Hulls Pellet Biochar (500 – 700)°C (mg/kg)
	Feed	Agro Organic	Agro	Urban	Consumer Materials		
Al	-	-	-	-	-	547.605±27.304	479.936±188.879
As	2	13	13	13	13	0.074±0.012	0.058±0.02
Ba	-	-	-	-	-	19.934±1.078	6.076±1.885
Cd	0.8	0.7	1.5	1.5	1.5	0.008±0.006	0.002±0
Co	-	-	-	-	-	0.195±0.014	0.193±0.081
Cr	70	10	90	90	90	1.529±0.043	1.288±0.541
Cu	70	70	100	100	100	3.127±0.284	4.889±1.608
Fe	-	-	-	-	-	405.847±25.358	362.492±147.325
Mn	-	-	-	-	-	27.427±1.517	21.535±8.267
Mo	-	-	-	-	-	0.342±0.016	0.159±0.049
Ni	25	25	50	50	50	0.793±0.073	0.829±0.289
Pb	10	45	120	120	120	0.191±0.017	0.16±0.065
Sb	-	-	-	-	-	0.011±0.007	0.008±0.002
Se	-	-	-	-	-	0.041±0.006	0.026±0.02
Sn	-	-	-	-	-	0.964±0.07	1.232±0.376
Ti	-	-	-	-	-	27.23±1.996	17.573±6.384
V	-	-	-	-	-	0.638±0.067	0.637±0.236
Zn	200	200	400	400	400	10.258±1.029	13.388±4.087
Hg	0.1	0.4	1	1	1	0±0.001	0.006±0.002

Comparing the leaching properties of both pelletised biochar samples, the manganese content (Mn) in both samples is high and exceed Singapore NEA solid waste leaching limits. However, both samples are acceptable according to Australia' EPA standards and is safe to be applied to the ground for agricultural use.

Table 4-4 TCLP Leaching Results for Pelletised Biochar

Leaching Elements	Leaching Limits (mg/kg)		Cotton Pellets Biochar (mg/kg)	Almond Hulls Pellets Biochar (mg/kg)
	Singapore NEA	Australia EPA	500 - 700°C	500 - 700°C
Al	-	-	3.397±0.1	9.387±0.1
As	5	20	0.219±0.1	0.207±0.1
Ba	100	300	75.917±18.7	71.962±18.6
Cd	1	3	0.007±0	0.006±0
Co	-	170	0.102±0	0.127±0
Cr	5	1	0.012±0	0.039±0
Cu	100	60	-0.306±0	-0.291±0
Fe	100	-	-0.16±0.1	0.634±0.4
Mn	50	500	137.647±38.6	114.58±30.5
Mo	-	-	0.139±0	0.1±0
Ni	5	60	0.013±0	0.121±0
Pb	5	300	0.013±0	0.013±0
Sb	-	-	0.055±0	0.053±0
Se	1	-	0.051±0	0.032±0
Sn	-	-	0.08±0	0.007±0
Ti	-	-	222.403±54	170.095±45.9
V	-	-	0.004±0	0.006±0
Zn	100	200	2.596±0.7	5.156±1.4
Hg	0.2	1	0.014±0	0.016±0

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