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Effects of ash removal by agitated aqueous washing and sedimentation on the physico-chemical characteristics and fast pyrolysis of trommel fines

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Abstract

A pre-treated trommel fines feedstock (DPT) with 35.1 wt% ash content and particle size range of 0.5 -2 mm was processed through two (100% distilled water and 1% surfactant in distilled water) aqueous agitated washing and sedimentation procedures for ash reduction prior to fast pyrolysis in a bubbling fluidized bed reactor. The washing process led to more than 36% reduction in the ash/inorganic contents of the DPT feedstock and yielded about 78 wt% of organic-rich feedstocks denoted as WPT1 and WPT2. Characterization and fast pyrolysis of all three feedstocks were carried out to evaluate the effect of the washing process on their physico-chemical characteristics and yields of fast pyrolysis products. Results show that the ash reduction led to increase in the volatile matter contents of the washed feedstocks by 20%, while reducing nitrogen contents. In addition, fast pyrolysis of the feedstocks show improved yield of liquid and gas products, with a dramatic reduction of reaction water, indicating that the ash removal reduced the catalytic effect of the ash on water formation during the fast pyrolysis process. The major organic compounds in the liquids included phenols and furans from biogenic fraction of the feedstock as well as aromatic hydrocarbons such as those obtained from pyrolysis of plastics. More importantly, the overall energy yields from the fast pyrolysis process increased by over 35% after washing the feedstock, with washing with only distilled water alone giving the highest energy yield of 93%. Hence, coupling the water-washing ash reduction process with fast pyrolysis appears to be a suitable technology for valorising feedstocks with high ash contents such as trommel fines for energy and chemicals.

KEYWORDS: pre-treated trommel fines; agitated washing; ash removal; fast pyrolysis; energy recovery

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1.0. Introduction

Trommel fines, obtained from the mechanical recycling of municipal solid wastes (MSW), is a special kind of waste; it is a complex admixture of organic and inorganic materials. The organic content of this waste is considered too high, so that landfilling is no longer an acceptable disposal method, without incurring recently increased landfill gate fees. A recent development is the assessment of the organic content by a ‘loss-on-ignition’ (LOI) test, through which gate fee classifications are determined (HMRC, 2014; Watts, 2016). This increase in landfill disposal costs means that alternative methods are required. Based on the direct link between the organic content and LOI, it becomes sensible to reduce or eliminate the organic fraction of trommel fines through energy recovery. Apart from incineration, pyrolysis appears to be a possible energy recovery technology to be applied to trommel fines. Pyrolysis offers more versatility in products (gas, liquid and solid) compared to heat energy from incineration. However, the large presence of inorganic materials (including ash) in trommel fines sample (stones, aggregates, glass and soil), represent a significant technical problem during fast pyrolysis.

Depending on their physical characteristics (e.g. particle size, density and hardness), these inorganic materials can cause blockages to parts of process equipment such as grinding mill and reactor feeding system. Operationally, the inorganics in feedstock for fast pyrolysis can remain in the fluidized bed reactor, leading to increase in volume and weight of bed material, which can have significant influence on the pyrolysis process. In addition, the chemical properties such as thermal decomposition and catalytic activity of the inorganic materials can influence the yield and selectivity of fast pyrolysis reaction products. For example, the presence of certain types of ash have been reported to promote the formation of solids and gas at the expense of pyrolysis liquid yield (Xue, Braden and Bai, 2017; Banks, 2014; Oasmaa et al., 2010; Teng et al., 1998). In some cases, through attrition, the inorganics can become fine particles capable of being entrained in the fluidising gas, giving rise to the contamination of the liquid and char products (Bernardo et al., 2010). These problems highlight the need to reduce the inorganic contents of high-ash feedstocks such as trommel fines prior to fast pyrolysis. In addition, the reduction of inorganic material through physical pre-treatment will lead to an apparent increase in the volatile content of the feedstock. As such, the proportions of volatile fractions delivered for pyrolysis at any set feeding rate will increase, leading to better fast pyrolysis process and indeed better yields as well as qualities of pyrolysis products. In particular, the presence of alkali metal has been reported to favour gas formation (Pradhan, 2015; Renkonen, 2016) over oil, which is the desired product of fast pyrolysis.

One of the methods recommended for the separation of inorganics from high-ash waste materials is to wash them with aqueous solutions. For example, some researchers have reported substantial removal of majority of soluble alkali metals following their dissolution in water, which became more effective with agitation (Jenkins et al., 1996; Baxter et al., 1998; Fahmi et al., 2007; Renkonen, 2016). However, ash due to soil contamination tend to have low solubility in water (Fahmi et al., 2007) but could be removed by sedimentation. In addition, the application of surfactants can further aid the sedimentation process leading to improved ash content removal (Banks, Nowakowski, Bridgwater, 2014). While significant amount of research has been reported on aqueous washing of biomass for ash removal, the extension of this practice to waste streams with much higher ash contents is novel. Indeed, reports of ash removal from high-ash wastes have centred mostly on flyash and bottom ash from the post-incineration of municipal solid waste (Sani et al., 2010; Chen et al., 2016; Quek et al., 2016), mostly to remove soluble chloride and sulphate salts prior to application (e.g. in construction).

The aim of this present work was to investigate the possibility of applying fast pyrolysis technology to recover energy from a high-ash feedstock as a solution to preventing the diversion of trommel fines from landfills. Thus, saving costs on trommel fines disposal due to the recently increased landfill gate fees for this type of solid waste. In this work, reduction of the ash/inorganic contents of a prepared (0.5 – 2 mm particle size range) trommel fines feedstock was carried by an agitated washing and sedimentation procedure prior to applying the feedstock for fast pyrolysis using a bubbling fluidized bed (BFB) reactor. The particle size range was selected to meet the requirements of the feeding system of BFB reactor (Eke, Onwudili and Bridgwater, 2017). The agitated washing involved the use of aqueous media to partition the organic and inorganic materials in the trommel fines sample into separate fractions based on density differences. Using this procedure, the expectation was that the organic components would remain afloat in the water, while the heavier inorganics settled at the bottom; thus, allowing separation and removal of the inorganics. The influence of washing process on the yields of fast pyrolysis products was investigated at an optimum temperature 500 ºC, as determined from preliminary work.

2.0 Materials and methods

2.1 Trommel fines feedstock

Trommel fines feedstock (<10 mm particle size) was supplied by Biffa Limited, a UK commercial waste management company, based in Leicester. Due to the high heterogeneity of the feedstock, manual separation was initially used to remove large particles of stones, concrete and textiles before subjecting it to mechanical processing (including size reduction by grinding and sieving) to obtain a particle size range of 0.5 – 2 mm. This size range, labelled as dry physically pre-treated (DPT), represented over 70 wt% of the original feedstock as well as more than 80% of its energy content. The detailed procedure for obtaining DPT feedstock has been reported earlier (Eke, Onwudili and Bridgwater, 2017).

2.2. Agitation - sedimentation procedure

Figure 1 shows the schematic of the process designed to reduce the inorganic/ash contents of the DPT feedstock prior to fast pyrolysis. Two different aqueous washing agents were used in this present study; namely 100% distilled water and distilled water containing 1 vol% of a surfactant (Decon Neutracon). The surfactant is a commercial formulation of anionic and non-anionic surfactants in a polyhydric alcohol base, with a neutral (pH 7) It is biodegradable, non-toxic, non-flammable and highly water soluble (totally rinsable), which means it is safe to use and does not leave any residues when washed off with water. Distilled water was used to prevent any contamination of the feedstock. In the procedure, batches of 300 g (dry basis) of the DPT feedstock were separately washed with 3 litres each of distilled water or distilled water containing the surfactant, respectively. The washing was carried out by adding the DPT feedstock into a large laboratory plastic bucket containing each liquid. The mixture was stirred for 30 min at room temperature with a metal bar and left to settle for 1 hour, allowing for sedimentation of the denser components, notably the inorganics (stones, glass, sand etc.). To accumulate sufficient pre-treated feedstock material for a fast pyrolysis experiments, duplicate washings were carried for both methods and the recovered feedstock materials combined.

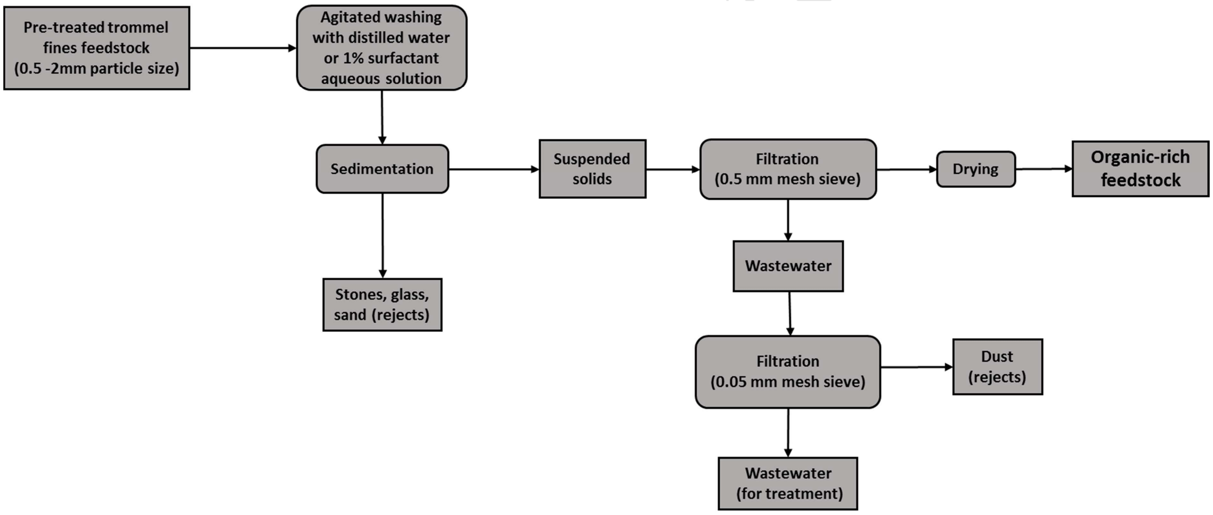

Figure 1: Block flow diagram for agitated washing and sedimentation of prepared trommel fines sample.

To recover the washed feedstocks, a plastic bowl was initially used to scoop the suspended/floating solids and passed through a 0.5 mm sieve tray. This procedure helped to recover a large proportion of the washed solid feedstocks. However, it was found that some floating solids remained in the water and these were recovered by careful decantation of the liquid through the 0.5 mm sieve tray, while the sediment remained at the bottom of the bucket. The recovered washed feedstocks were each air-dried for 24 hours in the laboratory and then dried in a Swallow oven at 60 °C ± 1 °C for 48 h. The dried washed feedstocks obtained for fast pyrolysis were designated as WPT1 (for the agitated washing with 100% distilled water) and WPT2 (for the agitated washing with 1 vol% surfactant solution). The wastewater was subsequently passed through a 0.05 mm sieve to remove suspended dusts and fines.

To account for the distribution of the original DPT feedstock used for the washing-sedimentation (washing) procedure, the quantities of remaining solids (sediment and dissolved solids) were determined gravimetrically according to USEPA Method 160.3 (APHA, 1992). For the dissolved solids, the filtered wastewater was sampled into clean pre-weighed porcelain crucibles and evaporated to dryness on a water bath. Thereafter, the evaporated porcelain crucibles were dried to constant weight in an oven at 105 °C. The weight of dissolved solids was determined by difference. Five replicate determinations were carried out on each waste water with standard deviations of <1%. The sediments were likewise quantitatively transferred into pre-weighed large porcelain boat with water, evaporated to dryness, oven-dried at 105 °C and weighed.

In addition, the elemental compositions of the ash contents of all three samples were analysed by a simple scan using a Bruker S8 Tiger X-ray Fluorescence (XRF) spectrometer, capable of quantifying elements from sodium to uranium. Firstly, the samples were separately pulverised with mortar and pestle to make fine powders and weighed into a sample cup with Mylar window. The volume of each sample was approximately 1 cm^3. The results of the elements with concentrations ≥ 0.02 wt% are reported in this work.

2.3. Process description for fast pyrolysis of pre-treated trommel fines feedstock

Fast pyrolysis of the pre-treated feedstocks (DPT, WPT1 and WPT2) was carried out using an existing bubbling fluidized bed (BFB) system (Figure 2), which has been fully described previously (Banks, Nowakowski and Bridgwater, 2014). Briefly, the system consisted of a 300 g h^{-1} bench-scale bubbling fluidized bed reactor unit, linked to a dome-bottomed cylindrical hopper-feeder system and a product collection system. The feeder uses a dual screw gravimetric feeding system with variable speed motor for feeding, attached to a fast screw. The pyrolysis chamber is a tubular steel reactor having 41 mm internal diameter and a height of 320 mm. About 150 g of calcined sand of particle size range of 500 – 600 µm was used as bed material, fluidized by a stream of nitrogen gas at a flow rate of 6 L min^{-1} to create the bubbling effect for enhanced heat transfer (Kalgo, 2011; Banks, Nowakowski and Bridgwater, 2014). The product collection system consisted of a water-cooled condenser and two dry ice/acetone-cooled condensers, followed by a cotton wool filter.

Each fast pyrolysis experiment was initiated by deaerating the system with nitrogen flow for 10 min, after which the reactor was preheated using an electrical furnace to a temperature maintained at 500 ºC (to within + 5% accuracy) throughout the duration of each run. Once the temperatures stabilised, the prepared trommel fines feedstock was continuously fed into the reactor at the middle of the fluidised bed by nitrogen entrained flow via an air-cooled feeding tube. The feeding rate was nominally set at 170 g h-1 and each experiment lasted for 1 h. After pyrolysis in the reactor, the pyrolysis vapours including aerosols, water and non-condensable gases, were carried by the nitrogen gas stream through a cyclone to remove entrained solids, which were collected in the char pot. The ensuing vapour stream then passed through the system of two sets of condensers, where the condensable components were collected as liquids. In this work, the primary condensate referred to the liquid recovered from the water-cooled condenser, while any liquid recovered downstream of the water-cooled condenser was regarded as secondary condensate. A cotton wool filter was installed after the last condenser to trap uncondensed vapours before the stream of non-condensable (permanent) gases was directed into a gas meter, where the volume of the exit gas was recorded. A portion of the exit gases was taken by an automatic sampling system into an online gas chromatograph (GC) for gas composition analysis at 3 min intervals. The remainder of the gas was vented through an installed ventilation system.

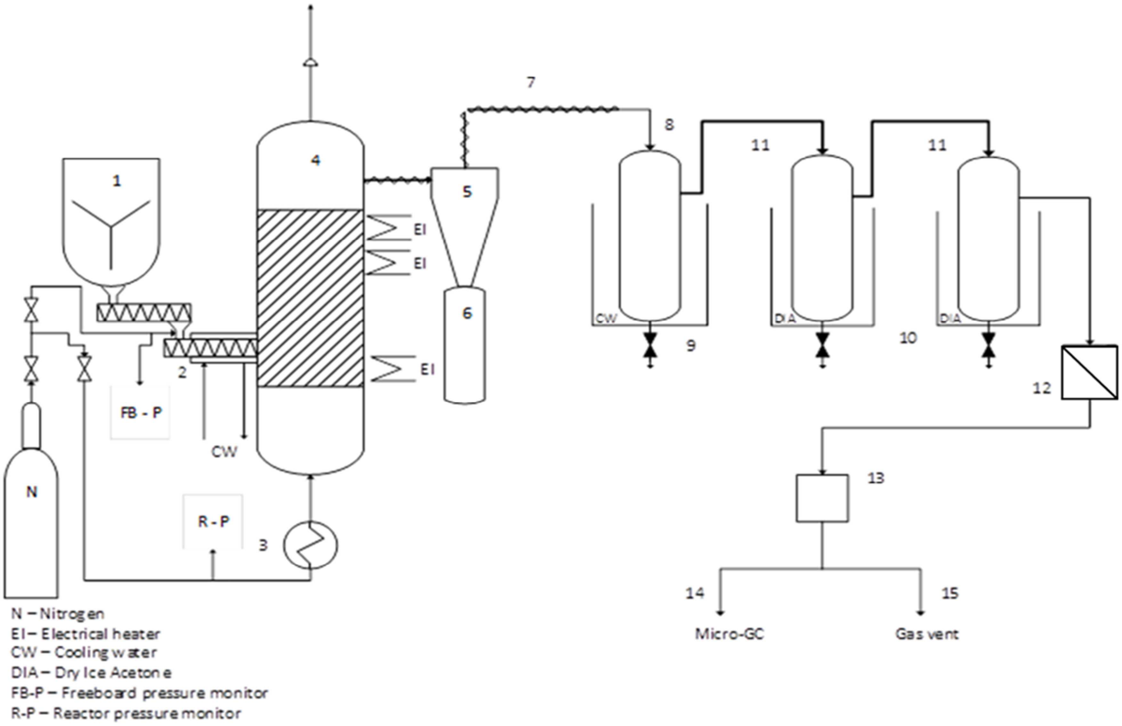

Figure 2. Bench scale 300 g h^{-1} fluidized bed fast pyrolysis rig set-up

Key: 1 - feed hopper with twin screw feeder, 2 – fast screw, 3 – nitrogen preheater, 4 – fluidised bed reactor, 5 – cyclone, 6 – charpot, 7 – metal transition pipe, 8 – glass transition pipe, 9 – water cooled condenser, 10 – dry ice acetone condenser, 11 – ruber transition pipe, 12 – cotton wool filter, 13 – gas meter, 14 – micro-gc, 15 – gas vent

2.4. Characterization of fast pyrolysis products

2.4.1. Analysis of gas products

During a fast pyrolysis experiment, the non-condensable gases were sampled every 3 min into a Varian micro gas chromatograph (Micro-GC) with a thermal conductivity detector (TCD) (Banks, Nowakowski and Bridgwater, 2014). The gas components were separated on two columns; namely Varian CP-5A Molsieve held isothermally at 80 ºC (for H_2, CO, N_2 and O_2) and CP-PortaPLOT held isothermally at 90 ºC (for CO_2 and C_1-C_4 hydrocarbon gases prior to detection. Quantitation was achieved by external standard method by calibrating the detector response using a standard gas mix containing these gases at 3 vol% concentrations in nitrogen. The mass yields of the gas components were calculated using the general gas equation, based on the gas volume composition obtained from GC analysis, total gas volume and the exit gas temperature and recorded pressure. The calorific values (as higher heating values, HHV) of gas product were estimated from the volume percentage of each gas component and their higher heating values, according to Eq.1.

$$HHV\ (\mathrm{MJ}\ kg^{-1}) = \sum_{i=1}^{n}(x_i.HVV_i) \text{ ……………………………………………………………Eq. 1.}$$

where;

i …n = each combustible component in the gas product

x = mass fraction of combustible components in gas product

HHV_i = higher heating value of each component in MJ kg^{-1}

2.4.2. Characterization of liquid products

Each liquid product composed of both aqueous and organic fractions. The liquid products were characterized for their water and solids contents as well as GC-MS analysis of the organic fractions to determine the main compounds present. Elemental analysis and heating values of the liquid products were also determined.

Volumetric Karl-Fischer (KF) titration was used to determine the water content of all the fast pyrolysis primary and secondary condensates. The primary and secondary condensates were dissolved in a known amount of acetone (1:6) prior to analyses. All analyses were performed in triplicate with the water content obtained automatically from the KF titrator. A blank determination using the same amount of acetone was used to correct the final water contents (Banks, Nowakowski and Bridgwater, 2014).

Solids content in the primary condensates were determined using the vacuum filtration technique suggested by Oasmaa and Peacocke (2001). The sample was filtered through a pre-dried and pre-weighed Whatman No. 2 qualitative filter paper with mean pore size of 8 µm. The filter paper with the retentate was then washed with excess amount of acetone until the filtrate became clear. The filter paper with the residue was air-dried for approximately 15 min, placed in an oven at 105 °C for 1 h and cooled in a desiccator before weighing to a constant weight.

Elemental analyses of the primary and secondary condensates were carried out using a CE-440 and Carlo Erba elemental analysers with ±0.3% absolute accuracy (Banks, Nowakowski and Bridgwater, 2014). In the procedure, the liquid samples were mixed with a known amount of acetone (1:6) to obtain the carbon, hydrogen and nitrogen (CHNS) contents. The CHNS composition of the organic fraction of the liquid product was calculated by subtracting the carbon, hydrogen and oxygen contents of the product water and the added acetone. Hence, the CHNS data were obtained on dry, solvent-free basis. Oxygen content was determined by difference, using the percentage composition of CHNS.

Bomb calorimetric determination of the energy content of the liquid products was carried out only on the primary condensates, which had more organic product and less water content than the secondary condensates (please see Figure 4 later). In the procedure, approximately 1 g of the solvent-free primary condensate was burnt completely in an excess oxygen environment in a steel bomb calorimeter (Parr 6100 calorimeter) at constant volume. Each experiment was repeated three times and averages reported (standard deviations < 5%). Results from the experimental determination were compared with those calculated from the elemental composition of the liquid products, using the HHV correlation formula (Equation 2) developed and reported by Channiwala and Parikh (2002). The two sets of results were found to be similar (see Table 4 later), and hence, the correlation was used to calculate the HHV of all the secondary condensates.

$$\mathrm{HHV\,(dry)} = 0.3491\mathrm{C} + 1.1738\mathrm{H} + 0.1005\mathrm{S} - 0.10340\mathrm{O} - 0.0151\mathrm{N} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{Eq. 2}$$

where C, H, S, O, N and A represent mass percentages on dry basis of carbon, hydrogen, sulphur, oxygen, nitrogen and ash contents of liquid products, respectively.

Compositional analyses of organic fractions of the liquid products were performed using a PerkinElmer Clarus 680 GC-MS system (Banks, Nowakowski and Bridgwater, 2014). Samples for GC-MS analysis were prepared by mixing the one volume of the pyrolysis liquids with six volumes of GC grade acetone, followed by filtration using a 0.2 μm pore size Sartorius filter. A sample volume of 1 µL was injected into the GC column via an injection port maintained at 300 °C, with 1:50 split ratio. The GC oven programme was initially held at 50 °C for 2 min, then ramped at 5 °C min^{-1} to 275 °C, and finally held at 275 °C for 3 min, giving a 50-min analysis time. Helium was used as carrier gas at a constant flow rate of 15 ml min^{-1}. Compounds separated on the column were detected by the mass selective (MS) detector held at 250 °C. Mass spectra were obtained using 70 eV ionisation energy in the molecular mass range of m/z = 35 – 300, with a scan time of 0.35 seconds. (Banks, Nowakowski and Bridgwater, 2014). Assignments of the main peaks were made from mass spectral detection (NIST05 MS library), with similarity indexes >85%.

2.4.3. Characterization of solid residues

Solid products obtained from these experiments were distributed into the bed material, char pot and liquid product obtained from the water-cooled condenser. However, in this work, the solid residue in the char pot represented over 90 wt% of the total solid products and was therefore considered of interest for detailed characterization *(see section 3.3.4.2)*. The ash content of this solid residues was determined according to the ASTM D1762-84 method (ASTM, 2013). Approximately 4 - 5 g of solid residue was weighed into each pre-calcined and pre-weighed crucible set (crucible and lid) and placed in a furnace. The samples were ashed at 750 °C for 6 h, followed by cooling in a desiccator to room temperature. After weighing to a constant weight, the ash content was obtained by the difference in mass between the crucible + ash and the empty crucible. The average of five replicate analysis was carried out to account for the heterogeneity of the samples, with standard deviations of <5%. Furthermore, the solid residues were analysed for their ultimate compositions and calorific values using the same techniques used for the liquid products as described in section 2.4.2.

2.5. Fast pyrolysis mass balance calculation

Mass balances (wt. % on dry feed basis) were calculated by comparing the mass yields of final fast pyrolysis products (liquids, solid residues and non-condensable gases) with the mass of feedstock fines feedstock processed. All post-reactor removable parts of pyrolysis (including pipes and condensers) were weighed before and after each run, to determine any weight increase arising from the pyrolysis products. By difference in weight of trommel fines added to hopper before and feedstock left in hopper after each experiment, the amount of feedstock fed can be calculated. The quantity of solid residues included those collected from the char pot, reactor and metal transition pipe, and the solid fines found in the liquid products. The liquid products were collected as two portions; primary condensate and secondary condensate. The yields of products were calculated using the following equations;

$$Gas\ yield\ (wt\ \%) = \frac{\sum mass\ of\ gas\ components\ produced\ x\ 100}{mass\ of pre-treated\ trommel\ fines\ feedstock\ used}\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ \text{Eq. 3.}$$

$$Oil\ yield\ (wt\ \%) = \frac{mass\ of\ oil\ produced\ x\ 100}{mass\ of pre-treated\ trommel\ fines\ feedstock\ used}\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ \text{Eq. 4.}$$

$$Solid\ Residue/Char\ yield\ (wt\ \%) = \frac{mass\ of\ solid\ residue\ or\ char\ produced\ x\ 100}{mass\ of pre-treated\ trommel\ fines\ feedstock\ used}\ \ldots\ \text{Eq. 5.}$$

3.0 Results and Discussions

3.1. Characterization of pre-treated feedstocks

From visual observations, there was no difference between the two sets of washed trommel fines feedstocks. Photographs of the different fractions of DPT obtained after the washing process (with water only) have been provided in the *Supplementary Information (SI1).* The quantitative distribution of the feedstock after the wet pre-treatment procedures are given in Table 1. Nearly 100% of the DPT feedstock was accounted for after the washing procedure. Table 1 shows that overall, the two washing methods gave very similar results, within the margin of errors. Interestingly, both washing methods helped to recover about 78 wt% of organic-rich fractions which were used for fast pyrolysis. These fractions comprised of water-insoluble components of DPT, which were less dense than water. Hence, WPT1 and WPT2 were more fibrous in nature than DPT, which seemed to have some influence on the feeding of the washed feedstock into the pyrolysis reactor (see Table 3 below). The stone/glass and dissolved solids were classified as rejects, being composed mainly of inorganics.

Table 1: Mass balance results from the agitation-sedimentation pre-treatment of DPT trommel fines feedstock

	Washing procedure	
Fractions (wt%)	**Water**	**Water + 1 vol% Surfactant**
Recovered organic-rich feedstock (suspended solids)	78.3 ± 0.9	77.8 ± 0.8
Sediment (stone, glass)	17.7 ± 0.6	17.4 ± 0.7
Dissolved solids	3.8 ± 0.9	4.2 ± 0.7
Total	**99.8 ± 0.3**	**99.4 ± 0.5**

Table 2 presents the proximate and ultimate compositions of the three pre-treated feedstocks. The results however, show that not all the inorganics or ash in the DPT fines feedstock could be removed or separated out by the washing procedure. For instance, lighter inorganic items in the feedstock, such as aluminium sheets and very fine solids were suspended in water along with the organic fraction during the washing-sedimentation process. These were recovered together with the organic solids during the scooping and decantation of floating materials. Hence, they remained as ash in the washed feedstocks.

As shown in Table 2, the ash content of the wet pre-treated feedstocks decreased by 36 - 37% compared to DPT. Consequently, the removal of ash led to an increase in the volatile contents of WPT1 and WPT2. Evidently, the volatile matter contents of the feedstock, which could undergo degradation during fast pyrolysis to give useful products, increased by about 20%. Literature shows that ash removal by water washing or leaching has been reported to be influence by the amount and composition of ash as well as washing conditions, especially temperature and additives (Liu et al., 2011; Deng et al., 2013; Gudka et al., 2016). For instance, using the same washing procedure Deng et al. (2013) found that ash removal efficiencies were lower for high-ash biomass samples such as rice straw and rice hull, which also contained very high silica (SiO_2) contents of over 80%.

While DPT and WPT1 showed similar fixed carbon content (7.52% and 7.28%, respectively), it was lower in WPT2 (6.4%), giving nearly 15% reduction after washing with the surfactant, possibly due to increased floatability of substances with lower fixed carbon contents. The elemental compositions (dry basis) of the feedstocks showed that there were slight improvements in the carbon and hydrogen contents after the washing procedure, due to enrichment of the organic fraction. There were also considerable increases in the calorific values of the washed feedstocks from about 14 MJ kg-1 (DPT) to 18 MJ kg-1 (WPT2).

	Pre-treated trommel fines feedstock		
Parameters	**DPT**	**WPT1**	**WPT2**
Proximate compositions (wt%)			
Ash content [a]	35.1 ± 6.85	22.3 ± 4.46	21.9 ± 4.69
Volatile Matter [a]	54.7 ± 1.50	67.2 ± 1.92	68.1 ± 0.44
Fixed Carbon [a, b]	7.52	7.28	6.40
Moisture content (wt.%)	2.69 ± 0.06	3.22 ± 0.50	3.63 ± 0.32
HHV (Bomb Calorimeter, MJ kg^{-1})	13.8 ± 0.33	**17.5** ± 0.41	18.1 ± 0.32
Ultimate compositions (wt%) [a]			
Nitrogen	2.75 ± 3.16	1.54 ± 0.92	1.89 ± 0.52
Carbon	33.7 ± 6.93	36.4 ± 3.03	39.4 ± 3.56
Hydrogen	4.62 ± 0.92	6.08 ± 0.75	6.22 ± 0.84
Sulphur	0.26 ± 0.20	0.58 ± 0.24	0.54 ± 0.18
Oxygen [b]	23.5	33.1	30.1

a = dry basis; b = calculated by difference

Table 2: Proximate and ultimate compositions of the pre-treated trommel fines feedstocks

3.2. Fast pyrolysis results

3.2.1. Product yields and distribution

Table 3 shows the product yields, product distributions and mass balance closures obtained from the fast pyrolysis of pre-treated trommel fines feedstocks (DPT, WPT1 and WPT2). The product yields were determined on a dry basis, therefore, the water yields presented here were the water (reaction water) generated by the fast pyrolysis reaction excluding the water in the feed. Each experiment was conducted three times and mass balances gave standard deviations within a 5% range. It is worth pointing out that, the more fibrous nature of WPT1 and WPT2 compared to DPT, affected the feeding of the feedstocks into the pyrolyzer. Stones, glasses and sand are much denser and more crystalline than biomass or any floating organic material. Hence the removal of the denser materials as ash by sedimentation led to a reduction of the density of the recovered feedstock. Hence, the reduced density meant that using the same volume of feeding system, less mass of WPT1 and WPT2 were delivered to the reactor compared to DPT at the fixed time of one hour. As shown in Table 3, less quantities of WPT1 and WPT2 were delivered into the reactor after 1 hour compared to DPT, even though a nominal feed rate of 170 g h^{-1} was maintained throughout this work.

The overall mass balance closures for the pre-treated trommel fines feedstock from the fast pyrolysis were between 93 and 98 wt% (dry basis). The pyrolysis process mass balance closures were slightly lower after washing, possibly due to the increased volatile matter contents, leading to increase in the production of unidentified and undetected gases. In contrast, the reaction water product decreased after washing, this might indicate that the presence of certain ash components promoted pyrolysis reactions leading to water formation (e.g. dehydration) in DPT. Hence, removal of such ash components during washing minimized water formation.

Table 3: Mass balance results from the fast pyrolysis of the pre-treated trommel fines feedstock at 500 ⁰C for 1 hour

Parameter measured [a]	**DPT**	**WPT1**	**WPT2**
Quantity of Feed delivered (g)	158.9	109.9	107.7
Liquid Product: Primary condensate (wt%)	12.5 ± 0.40	8.81 ± 0.44	9.02 ± 0.07
Liquid Product: Secondary condensate (wt%)	7.07 ± 0.72	27.6 ± 0.40	25.8 ± 0.39
Liquid Product: Reaction water (wt%)	13.0 ± 0.56	8.30 ± 0.85	8.69 ± 0.60
Total Liquid product (wt%)	**32.6 ± 0.58**	**44.8 ± 0.90**	**43.5 ± 1.06**
Solid Residue: Char port (wt%)	45.5 ± 1.23	30.4 ± 0.34	31.7 ± 0.09
Solid Residue: Reactor bed (wt%)	6.15± 0.85	1.09± 0.56	1.58± 0.34
Solid Residue: Liquid product (wt%)	0.495± 0.16	0.225± 0.42	0.265± 0.23
Total solid residue	**52.1 ± 1.23**	**31.7 ± 0.34**	**33.5 ± 0.09**
Gas (wt%)	**12.9 ± 0.02**	**16.7 ± 0.56**	**15.8 ± 0.36**
Closure (wt%)	**97.6 ± 0.69**	**93.1 ± 0.81**	**92.9 ± 0.61**

[a] dry basis

The total liquid produced from fast pyrolysis of pre-treated trommel fines feedstocks increased after the washing procedure by about 33%, with similar yields from both washed feedstocks (Stefanidis et al., 2015). In particular, WPT1 and WPT2 produce dramatic increases in yields of secondary condensates compared to DPT. In comparison, the liquid yield from DPT was lower than those reported in literature for pyrolysis of RDF and MSW, whereas the washed feedstocks gave comparable yields to MSW (Miskolczi, Ates, Borsodi, 2013; Buah et al., 2007; Chen et al., 2015).

Table 3 also shows that solid residues were the dominant product from the fast pyrolysis of DPT at 52.1 wt%, whereas the WPT1 and WPT2, resulted in much lower solid residues, decreasing by at least 36% compared to DPT. These results were consistent with the reduced ash content in the two washed feedstocks (WPT1, 23.1 wt% and WPT2, 22.8 wt%; dry basis). The gas yield increased slightly after agitated washing and sedimentation, which can be attributed to their increased proportions of volatile matter as shown in Table 2.

3.3. Detailed characterization results of fast pyrolysis products

3.3.1. Effect of pre-treatment methods on gas products

Results in Table 4 show that the gas products contain mainly of carbon dioxide and propylene with small quantities of C_1–C_4 hydrocarbon gases. Apart from propylene and CO_2, the washing procedure did not affect the yields of gas components significantly. Only a slight increase in CO_2 yield was obtained while propylene increased nearly two-fold from the washed feedstock. The formation of propylene during catalytic fast pyrolysis of MSW has been well reported in literature to be due dehydration of biomass-derived sugars or the cracking of polypropylene plastics in the presence of aluminosilicates or zeolite-type catalysts (Fivga, 2011; Sebestyén et al., 2017). Such catalytic materials could be present in the fine ash particles (dust) in the feedstocks, and their presence could be enriched as they floated in water and then scooped with the organic materials during feedstock washing. More interestingly, the increased yield of propylene obtained from the washed feedstocks, led to 3% (WPT1) and 15% (WPT2) increases in the higher heating values of gas products compared to DPT.

Table 4: Yields of gas components during fast pyrolysis of pre-treated trommel fines

Gas component (wt%)	**DPT**	**WPT1**	**WPT2**
Hydrogen	0.01	0.01	0.01
Carbon monoxide	0.08	0.03	0.04
Methane	0.52	0.18	0.20
Carbon dioxide	8.82	11.4	10.4
Ethylene	0.25	0.16	0.22
Ethane	0.24	0.10	0.12
Propylene	2.45	4.55	4.69
Propane	0.41	0.23	0.33
n-Butane	0.16	0.08	0.11
HHV (MJ kg^{-1}) [a]	**14.8**	**15.3**	**17.1**

[a] **Equation 1**

3.3.2. Effect of feedstock pre-treatment method on liquid product characteristics

The liquid products obtained from the fast pyrolysis experiments were characterized to determine their physical and chemical compositions. Fast pyrolysis oils from biogenic feedstock are known to contain water as part of the product (Czernik and Bridgwater, 2004; Oasmaa et al., 2010). Moreover, due to fluidization, fine solids can become entrained in the gas/vapour stream and may contaminate the condensed liquid products; this is particularly so for feedstocks with high ash contents. Photographs of the primary and secondary condensates produced from fast pyrolysis of the three trommel fines feedstocks are given in the *Supplementary Information (SI2)*. The liquids produced exhibited some physical differences between them; for instance, the primary condensate from DPT appeared much more viscous than those from WPT1 and WPT2. In addition, DPT produced a secondary condensate that appeared to be much more watery and lighter than those obtained from the washed feedstocks. The physical appearance of the liquid products may indicate the influence of ash during the fast pyrolysis process, with the high ash content of DPT causing dehydration (Pradhan, 2015) of the feedstocks to give a tarry primary condensate and a watery secondary condensate.

Table 5 shows the results of semi-quantitative XRF analysis of the three feedstocks, which indicates much higher silicon (possibly, as silica) to aluminium (possibly, as alumina) ratio, which may indicate a reduction in acidity. This may have resulted in reduced potential for dehydration reactions, which consequently reduced the formation of tarry products in WPT1 and WPT2 compared to DPT.

Table 5: Results of XRF analysis of DPT, WPT1 and WPT2 trommel fines feedstocks

	Concentration wt%		
Element	**DPT**	**WPT1**	**WPT2**
Calcium	4.23	3.28	3.22
Silicon	3.89	3.48	3.21
Lead	3.51	0.84	0.98
Iron	2.56	1.91	0.49
Potassium	0.79	0.23	0.21
Aluminium	0.75	0.15	0.12
Chlorine	0.7	0.05	0.06
Copper	0.65	nd	0.08
Sulphur	0.42	0.34	0.39
Manganese	0.32	0.19	0.28
Niobium	0.28	0.18	0.18
Phosphorus	0.22	0.27	0.21
Zinc	0.22	0.11	0.08
Magnesium	0.2	0.25	0.24
Titanium	0.16	0.02	0.02
Strontium	0.09	nd	nd
Nickel	0.02	nd	nd
Zirconium	0.02	nd	nd
Total	**19.03**	**11.28**	**9.76**

Table 6 shows the physical and elemental compositions of the liquid products in both the primary and secondary condensates. The results show that in total, the liquid products contained between 34 and 74 wt% of water. While the primary condensates from the three feedstocks contained similar amounts of water (around 5.4 - 6.5 wt%), the secondary condensates were largely different.

The water contents of the secondary condensate obtained from DPT was more than twice those obtained from WPT1 and WPT2, which may be attributed to the influence of the ash during pyrolysis. For instance, water production from DPT could be from decomposition of hydrated salts in the ash and/or from ash-catalysed dehydration of biogenic components in the feedstock. Depending on their ratios, silica and alumina have been reported to cause biomass dehydration during pyrolysis, leading to increased water contents of bio-oils (Pradhan, 2015). Indeed, the washing procedure appeared to have reduced the water contents to levels within the range reported in literature for pyrolysis oils of different biogenic feedstocks, which is typically from 15 – 35 wt% (Elliott 1994; Bridgwater 2012).

The solids contents entrained in the liquid products from all three feedstocks were within similar values, which indicated that majority of the entrained solids was made up of very fine particles which could not be separated by washing and sedimentation. The elemental compositions and heating values of both the primary and secondary condensate liquids produced from all three feedstocks are also presented in Table 6. The elemental composition results show that water washing led to slight increases in the carbon and hydrogen contents of the liquid products, while the oxygen contents reduced. The increase in the carbon and hydrogen contents as well as the calorific values in secondary condensates of WPT1 and WTP2 were considerably higher than in the primary condensates. These results are consistent with the enrichment of organics (including biogenics, plastics and textiles) in the feedstocks after washing. With regards to nitrogen contents, the washing procedures proved to be effective in dramatically reducing the presence of nitrogen compounds in the liquids (both primary and secondary condensates), thereby reducing the potential for NOx emissions during combustion of pyrolysis oils.

Table 6. Physical and chemical characteristics of liquid products obtained from fast pyrolysis of pre-treated trommel fines feedstocks

	Pre-treated trommel fines feedstocks		
Characteristics	**DPT**	**WPT1**	**WPT2**
Primary Condensate (wt%) [a]			
Water content	5.8 ± 0.56	5.39 ± 0.60	6.52 ± 0.74
Solid content	3.58 ± 0.85	2.34 ± 0.74	2.68 ± 0.62
Elemental Analysis (wt%) [b]			
C	62.9	64.0	66.5
H	8.75	11.2	10.7
N	2.95	1.20	1.17
S	0.10	0.12	0.13

O [b]	25.3	23.5	21.5
HHV (Bomb Calorimeter, MJ kg^{-1}) [a]	32.4 ± 0.09	32.5 ± 0.23	33.8 ± 0.41
HHV dry (MJ kg^{-1}) [a, d]	31.2	31.8	32.3
Secondary Condensate (wt%) [a]			
Water content	67.9 ± 2.78	28.7 ± 0.72	31.41 ± 0.36
Elemental Analysis (wt%) [b]			
C	44.7	58.5	57.1
H	6.63	11.2	10.8
S	1.47	0.42	0.50
N	6.36	0.21	0.20
O [b]	40.9	29.7	31.4
HHV dry (MJ kg^{-1}) [a, d]	17.4	25.9	26.4

[a] dry basis; [b] dry-ash-free basis; [c] calculated by difference; [d] Eq. 2

The HHV of the primary condensates were fairly the same (32.4 – 33.8 MJ kg $^{-1}$) for all three feedstocks as shown in Table 6. The total HHV of the pyrolysis oils were close to the value of 35.5 MJ kg^{-1} reported by Buah and Williams (2016) for dewatered oils obtained from the pyrolysis of RDF. The heating values of the primary condensate obtained from these feedstocks were higher than those reported for bio-oil, due to the presence of plastics and textile materials, which carry higher energy contents than biomass (Velghe et al., 2011; Miskolczi, Ates and Borsodi, 2013). For the secondary condensates, there was an increase in HHV after the feedstock washing procedures from 17.4 MJ kg $^{-1}$ (DPT) to 25.9 MJ kg $^{-1}$ (WPT1) and 26.4 MJ kg $^{-1}$ (WPT2). The HHV of the secondary condensates from washed feedstocks were similar to an average of 27 MJ kg^{-1} reported for pyrolysis oils derived from MSW (Velghe et al., 2011). Therefore, the energy contents of the condensates, particularly from the washed feedstocks, show considerable potential for energy recovery of trommel fines using fast pyrolysis.

3.3.3 Indicative yields of major organic compounds in the liquid products

The fast pyrolysis process led to the degradation of the feedstocks to produce a number of organic compounds with carbon chain lengths from C_3 - C_{16} as identified from GC/MS analysis. Examples of GC/MS chromatograms of the organic portions of the primary and secondary condensates from the fast pyrolysis experiments are given in the *Supplementary Information (SI3)*.

Table 7: Peak area % of major organic compounds identified in the primary condensates obtained from fast pyrolysis of pre-treated trommel fines feedstocks

			% Peak Area		
Retention time	**SI%**	**Compound**	**DPT**	**WPT1**	**WPT2**
3.327	95	Glycerol	*	*	*
6.37	90	3-Penten-2-one, 4-methyl-	*		

9.24	93	2-Pentanone, 4-hydroxy-4-methyl-	*		
13.61	95	α-Methylstyrene		*	*
14.81	94	Phenol	**	*	**
17.63	96	Phenol, 2-methyl-	**	**	**
18.64	97	Phenol, 4-methyl-	**		
18.71	98	Phenol, 3-methyl-	**	**	**
19.92	93	Phenol, 3,4-dimethyl-	*	***	***
20.25	92	Naphthalene		***	***
25.06	88	Phenol, 2-methoxy-4-(1-propenyl)-		*	
28.21	93	1,3-Diphenyl propane		*	
29.74	95	1,1-Diphenylbutene	*	****	*****
31.24	99	1,3-Diphenyl-3-methylpropene	***	****	****
35.64	96	n-Hexadecanoic acid		****	***
43.49	96	2,4-Diphenyl-4-methyl-1-pentene	****		
43.66	97	Bisphenol-A		**	
45	85	1-phenyl-1(3-phenyl-3butenyl)cyclopropane	****	******	******

SI: Similarity Index

The condensation system used in the work, clearly aided in separating the organic liquids into heavy and light fractions in the primary and secondary condensates, respectively. Essentially, the primary condensates from all three feedstocks were dominated by phenols, while the secondary condensates contained mostly sugar-derived and furan-type compounds. This kind of staged-condensation system can be useful for separate processing of liquid products into chemicals and fuels (Imran et al., 2016; Johansson et al., 2017). The major organic compounds identified (with similarity index > 85%) in the primary and secondary condensates are shown in Table 7 and Table 8, respectively. Along with their retention times, the indicative concentrations of the various compounds are represented by the asterisks symbols shown, based on peak area percentages.

Table 8: Peak area % of major organic compounds identified in the secondary condensates obtained from fast pyrolysis of pre-treated trommel fines feedstocks

			% Peak Area		
Retention time	**SI%**	**Compound**	**DPT**	**WPT1**	**WPT2**
2.413	96	Pentanone	*	*	*
3.399	94	Acetic acid, 1-methylethyl ester		***	***
4.043	95	1,2-Propanediol, 2-acetate	***	***	***
5.85	94	2,4-Dimethyl-2-oxazoline-4-methanol	*		
6.61	93	Cyclopropane-1,1-dicarboxylic acid	*		
6.82	90	Cyclopentanone	*		
7.606	91	Furan, 3-methyl-	**	**	**
7.652	96	Furfural	***	***	***
8.817	93	1,3-Dioxolane, 2,2,4-trimethyl-	**	**	**

9.207	97	Furan, 2,5-dimethyl-	**	**	*
10.45	96	2-Cyclopenten-1-one, 2-methyl-	**		
11.597	95	2-Furancarboxaldehyde, 5-methyl-		**	**
11.62	86	1,4-Pentanediamine	**		
13.665	93	1,2-Cyclopentanedione, 3-methyl-	**	**	**
15.24	89	Oxazole, 2-ethyl-4,5-dihydro-	**		
24.3	88	(Z),(Z)-2,5-Dimethyl-2,4-hexadienedioic acid	**	*	*
30.832	96	1,6-Anhydro-β-D-glucopyranose (levoglucosan)	*	***	***
31.86	90	Ethyl citrate	**		

SI: Similarity index

In general, the liquid products showed the presence of compounds commonly derived from biomass (e.g. furans and phenols) and plastics (e.g. 1,2-diphenylpropane) (Hall et al., 2009). The liquid products from the washed feedstocks appeared to contain higher yields of the different classes of than those obtained from DPT, which can be attributed to the enrichment of volatile matter. The presence of a few nitrogen-containing compounds in the secondary condensate from DPT corroborated the high elemental nitrogen content earlier reported in Table 6. These compounds were in the form of amines and their derivatives, which were lower in the liquid products from washed feedstocks. The reduction of the nitrogen-containing compounds would indicate that the original nitrogen-bearing materials in DPT were either water-soluble, too dense to float on water or became dense by absorbing water.

3.3.4 Effect of feedstock pre-treatment method on characteristics of char pot solid residues

3.3.4.1 Distribution of the inorganic/ash contents of the pre-treated feedstocks after fast pyrolysis

The catalytic influence of ash on the yields of fast pyrolysis products have been well described in literature; mainly on the extensive cracking of pyrolysis vapour to give higher yields of gas and reaction water (Pradhan, 2015; Mohan et. al 2006; Buah et al., 2007; Zhou et al., 2013; Chen et al., 2014). However, the physical impacts of the solid residues on the pyrolysis system and products also require attention and could provide information on system design for handling high-ash feedstocks. Due to the high contents of inorganic materials in the trommel fines feedstocks (even after washing), it was important to account for their distributions within the fast pyrolysis equipment units. In this work, the inorganic constituents (mostly stones, glass, concrete and ash) present in the feedstocks were distributed between the reactor bed, the char pot and the primary condensates in the water-cooled condenser after the fast pyrolysis experiment as presented in Figure 3.

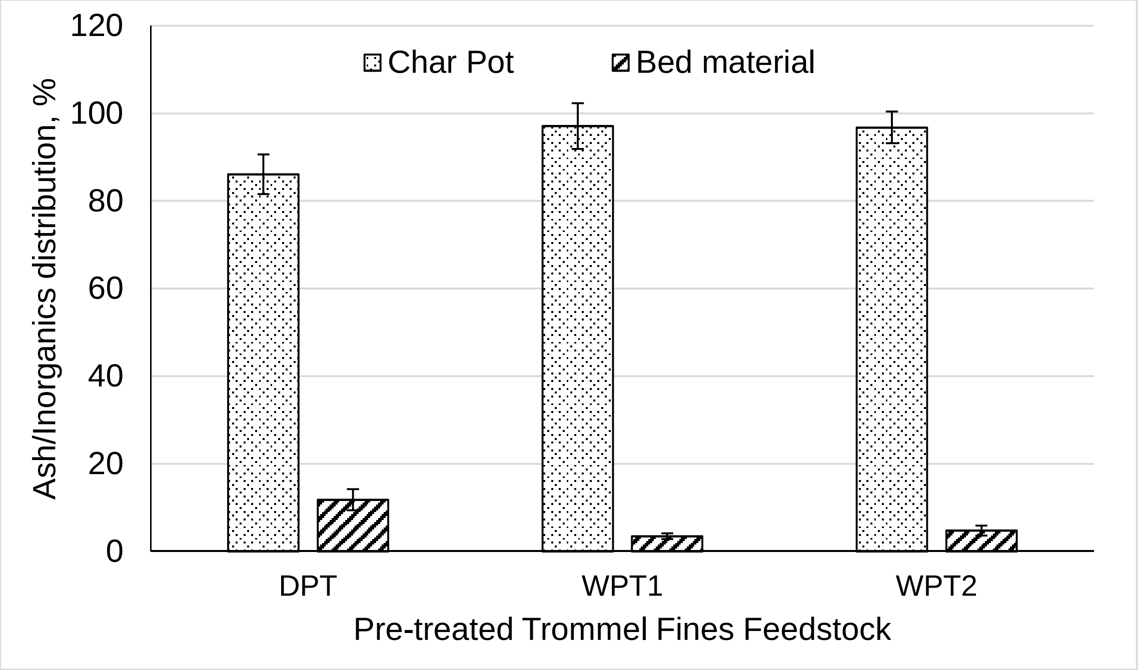

Figure 3: Ash/inorganics balance/distribution after fast pyrolysis of pre-treated trommel fine feedstocks

For all feedstocks, majority of the ash was found in the char pot due to their fine nature, considering that DPT was obtained after initial size reduction and sieving of the raw trommel fines to a particle size range of 0.5 – 2 mm. The ash in the char pot could cause operational concerns due to rapid filling of the char pot, which could lead to large pressure drops. However, more problematic would be the ash deposited in the bed material, which could increase the weight of bed, decreasing bed fluidization, increase the attrition of bed material and even lead to increased vapour residence time due to restriction of gas and vapour flow. Figure 3 thus show that the accumulation of ash in the reactor reduced by at least 60% due to the washing procedure, thereby minimizing any of the negative effects mention above.

To support the reduction in ash accumulation in the bed material, photographs of the reactor bed after pyrolysis of the three feedstocks, after burning-off the char can be found in the *Supplementary Information (SI4)*. There were obvious differences in the size and heterogeneity of inorganic materials left on the bed from DPT compared to the washed feedstocks (WPT1 and WPT2). Hence, the influence of reducing the proportion of inorganics in the feedstock via washing and sedimentation indicated that the reactor bed could be used for extended periods without considerable change in its physical characteristics. Therefore, the reactor system could be designed to periodically draw-off bed materials using the bed weight as control parameter. Whereas for DPT, the observed accumulation and physical characteristics to the accumulated bed material, would require complete changing after short periods of operation. Hence, the ash removal process would also be important in ensuring less disruption in the operation of the pyrolysis operation.

3.3.4.2: Effect of pre-treatment methods on quality of char pot solid residues from pre-treated trommel fines feedstocks

Among the solid residues collected after fast pyrolysis, only those obtained from the char pots could be quantitatively sampled for any further commercial application (e.g. energy recovery via combustion). Hence, only these samples were characterised for their ash contents, elemental composition, and calorific values. Table 9 shows that for all feedstocks, ash dominated the solid residues but with dramatic decreased values from the washed feedstocks. The decrease in the ash contents following the washing procedure, led to increase in char contents by over 230% compared to DPT.

Table 9 also shows the elemental composition of the solid residues on a dry-ash-free (daf) basis, which corroborate the influence of ash reduction in the washed feedstocks. Clearly, ash reduction led to significant increase in the carbon contents of the solid residues. Consequently, the calorific values of the solid residues from the washed feedstocks increased by nearly three times compared to DPT. Hence, energy recovery of the solid residues e.g. via incineration in cement kilns could be possible application of solid residues from the washed feedstocks. The quality of the ash could also possibly be right for use in cement production.

Table 9: Physico-chemical characteristics of the solid residues obtained from char pot after fast pyrolysis of pre-treated trommel fines

Characteristics	**DPT**	**WPT1**	**WPT2**
Char (wt.%) [a]	13.7 ± 0.52	36.3 ± 0.63	31.9 ± 1.43
Ash/inorganics (wt.%) [a]	86.3 ± 1.60	63.7 ± 1.32	68.1 ± 2.11
Elemental Analysis (wt.%) [b]			
C	66.0	85.7	82.7
H	4.17	6.25	6.08
N	2.42	3.55	3.39
S	1.68	1.18	1.35
O [c]	25.7	3.30	6.49
HHV (Bomb Calorimeter, MJ kg^{-1}) [a]	4.12 ± 0.71	13.5 ± 1.27	11.7 ± 0.93

[a] dry basis; [b] dry-ash-free basis, [c] calculated by difference

3.4. Energy yields from trommel fines feedstocks

Due to the focus of this work being energy recovery from trommel fines, it is useful to demonstrate the energy yields from the fast pyrolysis of three feedstocks. The energy yield here refer to the amount of energy contained in the pyrolysis products in relation to the energy content of the feedstocks as shown in Equation 6.

$$\text{Energy yield } \% = \frac{(m\ x\ HHV)solids + (m\ x\ HHV)liquids + (m\ x\ HHV)gas}{(m\ x\ HHV)feedstock}\ x\ 100 \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{ Eq. 6}$$

where, m = mass (g) and HHV = higher heating values (KJ g^{-1})

The results of the energy yield calculations are presented in Figure 4, which shows that the washing procedures increased the amount of energy recovered from the trommel fines feedstock by at least 35% compare to DPT.

More interestingly, WPT1 which was obtained by washing with 100% deionised water, gave the highest total energy yield of 93.6%, which is a 45% increment compared to DPT. The energy yield was slightly lower for WPT2 compared to WPT1, possibly due to the presence of unidentified gas components detected during GC analysis, which did not form part of the energy yield calculation. Hence, using agitated washing with water gave a better feedstock for fast pyrolysis in terms of energy yield and would simplify the treatment of the wastewater from the washing process, compared to using a surfactant. It can be seen from Figure 4 that the liquid products dominated the energy yields for all three feedstock and was a least two times higher than the energy contents of the gas products and solid residues. This was in line with the goal of fast pyrolysis i.e. to convert carbonaceous materials mainly into a liquid product.

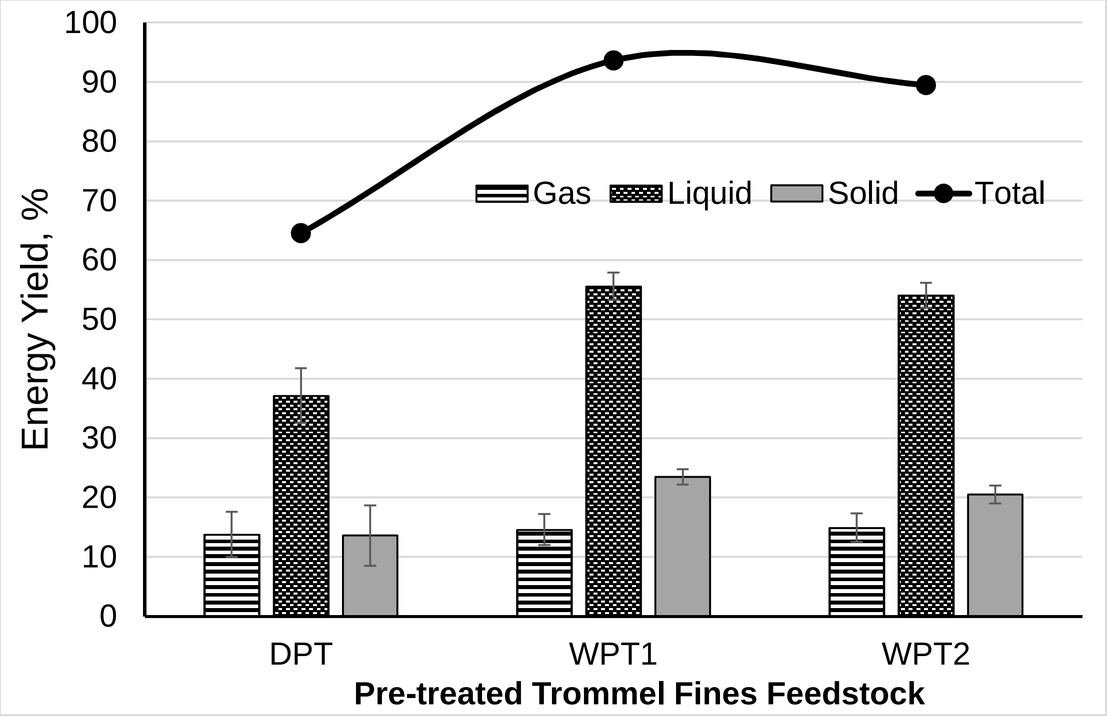

Figure 4: Energy yields and distribution from fast pyrolysis of pre-treated trommel fines

However, the considerable energy contents of the solid residues from WPT1 and WPT2, may make them suitable for thermal and material recovery in cement kilns. The results of this work showed that by adopting a wet pre-treatment process, the operational problematic issues relating to the high ash contents of trommel fines may be resolved. Clearly, the reduction in ash led to considerable increase in volatile matter content and therefore energy recovery via pyrolysis. This was a big step over the dry physical pre-treatment earlier reported (Eke, Onwudili and Bridgewater, 2017), which although improved the feeding characteristics of the feedstock, ash remained a major problem.

4. Conclusions

The influence of aqueous washing of a very high ash trommel fines feedstock on the yields of liquid, solid and gases produced from fast pyrolysis has been experimentally investigated. The total liquid yields (organic and water) increased after the washing procedures, with an organic yield of 36.5 wt.% dry basis. Solid residues emerged as the largest proportion of products due to the original ash contents of the feedstocks but decreased by more than 36% following washing. The addition of a surfactant during the washing procedure did not clearly influence the physico-chemical characteristics of the washed feedstocks, neither did it significantly affect the fast pyrolysis product yields. Overall, the washing procedure, reduced the ash/inorganic contents, increased the proportion of volatile matter in the feedstocks, thereby increasing the overall energy yields from the fast pyrolysis process.

This present work, shows that pre-treatment of high-ash waste can produce an organic-rich feedstock for thermochemical conversion by fast pyrolysis and by extension, incineration and gasification. There is a potential issue with the generation of wastewater from the washing process, which will require treatment However, a sustainable approach could involve the use of non-heavy metal contaminated industrial wastewater streams destined for wastewater treatment plants for the washing process.

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Highlight

- Up to 36% ash was removed from a trommel fines (TF) feedstock by agitated washing and sedimentation
- About 78 wt% organic-rich feedstock was obtained for fast pyrolysis using a BFB bed reactor system
- VM content and pyrolysis liquid product yield increased by 20% and 35%, respectively after washing
- More than 90% of the energy content of washed TF feedstock was recovered in fast pyrolysis products.
- Liquid product gave the highest energy yields by more than two-fold for all three TF feedstocks