

1 **DETERMINATION OF RENEWABLE ENERGY YIELD FROM MIXED WASTE**
2 **MATERIAL FROM THE USE OF NOVEL IMAGE ANALYSIS METHODS**

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1 **Abstract**

2 Two novel techniques are presented in this study which together promise to
3 provide a system able to determine the renewable energy potential of mixed waste
4 materials. An image analysis tool was applied to two waste samples prepared using
5 known quantities of source-segregated recyclable materials. The technique was used to
6 determine the composition of the wastes, where through the use of waste component
7 properties the biogenic content of the samples was calculated. The percentage renewable
8 energy determined by image analysis for each sample was accurate to within 5% of the
9 actual values calculated. Microwave-based multiple-point imaging (AutoHarvest) was
10 used to demonstrate the ability of such a technique to determine the moisture content of
11 mixed samples. This proof-of-concept experiment was shown to produce moisture
12 measurement accurate to within 10%. Overall, the image analysis tool was able to
13 determine the renewable energy potential of the mixed samples, and the AutoHarvest
14 should enable the net calorific value calculations through the provision of moisture
15 content measurements. The proposed system is suitable for combustion facilities, and
16 enables the operator to understand the renewable energy potential of the waste prior to
17 combustion.

18

19 **Keywords-** Biogenic content, renewable energy, mixed wastes, image analysis, energy
20 from waste

21

1 **1. Introduction**

2 The development of renewable energy technologies has become more prominent
3 in recent years. This is due in part to European Union (EU) and global movement away
4 from traditional energy generation from fossil fuels and the associated greenhouse gas
5 (GHG) emissions (Del Río, 2011; Garg et al., 2009; Shafiullah et al., 2012; Tükenmez
6 and Demireli, 2012), and also to the challenging target set by the European Union of
7 producing 20% of electricity from renewable sources by 2020 (Council of the European
8 Union, 2009; Lupa, 2011). Energy produced from biomass (Becidan et al., 2007; Defra,
9 2008; Mabee et al., 2011; Panoutsou et al., 2009; Qiao et al., 2011; Whittaker et al.,
10 2011) and the bio-based fraction of wastes (Séverin et al., 2010; Velis et al., 2012;
11 Wagland et al., 2011) presents a sustainable and secure solution to the renewable energy
12 strategies.

13 Recovering value from waste materials is of key importance for the development
14 of a sustainable future. Whilst the reuse, recovery and recycling of wastes is of interest, a
15 significant proportion of residual waste remains that is either non-recoverable for various
16 reasons, or has no commodity value. Therefore the thermal treatment of residual wastes
17 is a management option that is popular across Europe, and is becoming more prominent
18 in the UK as policy incentivises moving away from landfill disposal and towards the
19 generation of renewable energy.

20 In Europe, national and international targets have been set up for waste recycling,
21 recovery and diversion from landfill (Burnley et al., 2007), which in combination
22 contribute to an integrated waste management system (Grosso et al., 2010). Likewise,
23 existing targets regarding renewable energy production can include energy from biomass

1 and the biomass (or ‘bio-based’) fraction of waste (Wagland et al., 2011). When
2 considering the mixed waste materials, it is critical to understand not only the biogenic
3 carbon content of the waste, but also the energy potential or yield from the bio-based
4 fraction. This is due to the renewable energy targets set (Council of the European Union,
5 2009), and the need to demonstrate the quantity of renewable energy generated from
6 mixed fuels in order to obtain any available financial incentives (such as the renewable
7 obligation certificates in the UK (Ofgem, 2009). Biogenic carbon is defined as the
8 fraction of total carbon present in a material that has been produced naturally by living
9 organisms, but not fossilised or fossil-derived (European Committee for Standardisation,
10 2007). A number of methods exist to determine the biogenic fraction of waste-derived
11 fuels, such as the manual-sorting and selective dissolution test methods (British standards
12 Institute, 2011c; Séverin et al., 2010), although the determination of ^{14}C by accelerated
13 mass spectrometry [AMS] is generally considered to be the most accurate (European
14 Committee for Standardisation, 2007; Fellner et al., 2007). However, these methods do
15 not link the biogenic fraction to the energy content of the sample.

16 One such approach in determining the biogenic content of a mixed waste material
17 would be by determining the physical composition of the mixed wastes, and then
18 matching each component to the biogenic carbon content, as determined by the ^{14}C
19 content. A novel test method has been recently developed by Wagland *et al.* (2012)
20 which can determine the composition of mixed wastes by a simple image analysis
21 technique (Wagland et al., 2012). This approach utilises Erdas Imagine™ v9.3 software
22 to process 12 mega pixel digital pictures by image correction and the placement of a dot-
23 grid over the image. The work described by Wagland *et al.* (2012) assesses a 1 m^2 area of

1 mixed waste; the density of each component is used together with the area covered by
2 each component in order to calculate the percentage composition of the total waste
3 material by weight. A very strong relationship was demonstrated between the hand
4 sorted data and the results yielded by the image analysis method, with a mean correlation
5 (r) of 0.91 ($p < 0.05$) (Wagland et al., 2012).

6 The net calorific value (or ‘lower heating value’) of a fuel cannot be determined
7 analytically, but is calculated from the gross calorific value (‘higher heating value’) and
8 the content of moisture, carbon, hydrogen, oxygen and nitrogen (British Standards
9 Institute, 2011a). However, the accurate determination of the net calorific value of the
10 mixed waste requires an accurate measurement of moisture content across and through
11 the waste volume. Optical technologies are not suitable for penetrating below the surface
12 of the waste, and contact methods are difficult to implement in a waste processing
13 environment. The most suitable non-contact technology for moisture measurement of the
14 waste stream is the microwave moisture sensor: two such examples are the RadarTron
15 2550D (manufactured by ScaleTron) and Hydroprobe (manufactured by Hyronix).
16 However, all currently available moisture sensors offer only single point measurement
17 and provide a limited view of the moisture. This study presents a two-dimensional
18 moisture imaging system, termed NPL AutoHarvest, under investigation for its
19 application to waste moisture quantification with a spatial resolution close to one
20 centimetre.

21 The image analysis tool is used to determine the composition and energy from the
22 biogenic fraction of mixed wastes; the AutoHarvest technology is used to estimate the
23 moisture content of waste samples. This study aims to demonstrate that the two

1 techniques can be combined to accurately determine the potential energy yield from the
2 biogenic fraction of mixed wastes. The biogenic carbon content and the calorific values
3 (gross and net) were determined for each individual component. The moisture content,
4 determined throughout for each component, was used to adjust the net calorific value
5 [NCV]. The NCV accounts for the latent heat of the water vapour formed by
6 evaporation of the moisture within the waste and formed by the combustion of the
7 hydrogen in the fuel. This latent heat is not recoverable in a conventional boiler plant.
8 As such, the NCV represents the energy yield, representing the energy that would be
9 produced in a 100% efficient non-condensing conversion process.

10

11 **2. Methods**

12 ***2.1. Waste materials and preparation***

13 The waste components used in this study were gathered from materials collected
14 from the Cranfield campus of Cranfield University. These included source-segregated
15 components [paper, card, aluminium cans and dense plastic], film plastic, green waste,
16 textiles, inert (rubble) and waste wood. The paper used was office paper, the card used
17 was corrugated packaging cardboard, the dense plastics were PET bottles with a small
18 fraction of HDPE lids, and the film plastics used were black bin bags. The textiles were a
19 mixture of different clothing items and the waste wood was taken from pallets.

20 Each component was then 1) retained for image analysis; 2) dried and dispatched
21 to the National Physical Laboratory [NPL] for microwave analysis for varying moisture
22 content; and 3) dispatched to third party laboratories for analysis.

1 For the image analysis, the waste components were weighed before being
2 combined to produce two different batches, A and B, of mixed waste (42.7 and 45.5 kg
3 respectively). These batches were chosen to ensure that each waste sample was
4 sufficiently different: thus sample A did not include film plastic and inert; whilst sample
5 B did not include textiles. As a result of this selection and mixing, the composition of
6 each of these batches was known prior to image analysis.

7 Representative samples of the waste components (ca. 500 g) to be sent to NPL
8 were dried overnight in an oven at 50°C before being individually placed in air-tight
9 containers and delivered to NPL.

10 The waste components sent to the third party laboratories were not dried before
11 dispatch; they were however prepared by each respective laboratory in accordance with
12 the European standard method statement. Approximately 250 g of each component was
13 sent to Marchwood Scientific for proximate and ultimate analysis; whereas <50 g of each
14 component was used by Beta Analytic for biogenic carbon (¹⁴C) analysis. Along with
15 efforts to ensure that the samples delivered to the third party laboratories were
16 representative of the whole batch, the components were analysed individually and were
17 typically the same type (i.e. PET bottles, office paper etc) and so variation was expected
18 to be minimal.

19

20 ***2.2. Proximate, calorific value and biogenic analysis***

21 The moisture and ash content of the samples, along with the gross calorific values
22 [GCV], were analysed in accordance with the relevant standard methods (British
23 Standards Institute, 2011a, b; European Committee for Standardisation, 2010a) at

1 Marchwood Scientific [Southampton, England]. The net CV [NCV] was calculated from
2 the GCV as defined by the standard method (British Standards Institute, 2011a). GCV
3 analyses are within 5% repeatability, as is required by the standard methodology.

4 The biogenic carbon fraction was measured, calculated and reported for each
5 sample by Beta Analytic [London, England] in accordance with the accepted standard
6 methods (American Society for Testing Materials, 2012; European Committee for
7 Standardisation, 2007; International Organisation for Standardisation, 2013). The
8 technique used by Beta Analytic requires an accelerated mass spectrometer [AMS]. Here
9 the sample is combusted to form CO₂, which is then converted to graphite by passing
10 over a hot Fe catalyst with H₂. The graphite target is then bombarded by Caesium [Cs]
11 ions to release C ions. The rapid detection of ¹²C⁴⁺, ¹³C⁴⁺ and ¹⁴C⁴⁺ ions allows for the
12 calculation of the ratio of ¹⁴C to ¹²C/¹³C (European Committee for Standardisation, 2007).

13

14 ***2.3. Image analysis***

15 Each of the two waste samples produced were spread evenly to represent a typical
16 conveyor belt as used to transport waste in treatment processing facilities. A 1 m²
17 quadrant was placed over each part of the waste, and a digital image was captured of each
18 section. The quadrant was placed so as to ensure that all waste was covered during this
19 process, whilst avoiding overlap between sections.

20 The digital images were then processed using Erdas Imagine (v9.3) to crop and
21 geometrically correct the images before placing an 11x11 dot-grid over the image, as
22 described in a previous study (Wagland et al., 2012). Each dot covering each of the

1 waste component categories was manually selected, and the total number of dots covering
2 each component was counted digitally.

3 In the previous study (Wagland et al., 2012), individual components of fixed
4 volume (30 litres) were weighed to determine the density (g/cm^3) of each component
5 (European Committee for Standardisation, 2010b). However, errors were encountered
6 using this approach, and so in this study the individual components were spread out and
7 subjected to image analysis in order to calculate the mass per dot (kg/dot) for each
8 component. This accounts for the varying thickness of the waste layers, and reduces the
9 errors encountered during the conversion from number of dots to the % composition by
10 weight. The use of a calculated kg/dot over a number of samples (images) means that
11 variations in the thickness of the waste components are essentially averaged out.

12

13 ***2.4. In-line moisture analysis***

14 The dielectric properties of water at microwave frequencies are well documented
15 (Ellison, 2007; Kaatze, 1989). Likewise, the use of microwaves for the measurement of
16 moisture content of materials has been known for some time (Kapilevich et al., 2007;
17 Meyer and Schilz, 1980; Sokoll and Jacob, 2007).

18 The absorption of a microwave beam by a material sample in air follows the Beer-
19 Lambert law (Hecht, 2001):

20

$$21 \quad I_T = I_0 T e^{-ad} \quad (1)$$

22

1 Where I_T and I_0 are the transmitted and incident intensities respectively; α is the
 2 absorption coefficient, and d is the sample thickness. The coefficient T represents
 3 propagation loss at the interface, which may be due to a combination of reflection and
 4 scattering, and is dependent on both the angle of incidence and surface roughness. For a
 5 plane-parallel homogenous sample with faces that are smooth on the scale of the
 6 wavelength and which is positioned normal to the beam, scattering is absent, and T is
 7 given by the Fresnel formula (Hecht, 2001):

8

$$9 \qquad T = 1 - (n-1/n+1)^2 \qquad (2)$$

10

11 Where n is the refractive index of the sample material. When the above conditions
 12 are not met, the value of T will be reduced (except in the special case of Brewster-angle
 13 reflection (Hecht, 2001)). For a multi-component material, e.g. composite or containing
 14 water, the coefficient α must be replaced by $\alpha_1C_1+\alpha_2C_2+\alpha_3C_3+\dots$, where the subscripts
 15 refer to the individual components and C is the fractional concentration of each species.

16 Transmitted power loss in dB is calculated as:

17

$$18 \qquad Loss = -10 \log_{10} (I_T/I_0) = -4.34 \log_{10} T(ad) \qquad (3)$$

19

20 and is additive when the beam passes through several material layers, i.e., for N layers:

21

$$22 \qquad Loss (N) = 4.34 \log_{10} (T_1 + T_2 + \dots T_N) (\alpha_1d_1 + \alpha_2d_2 + \dots A_Nd_N) \qquad (4)$$

23

1 producing a line image of loss distribution. A 2D loss map is generated by passing the
2 material through the sample space on a conveyor.

3 In order to evaluate the moisture content, the measured loss map must be
4 combined with the optical image analysis as described above. The loss of dry material
5 can then be estimated from the knowledge of material type and thickness; the difference
6 between measured loss and loss calculated for dry material would be attributable to the
7 presence of moisture. For a single layer of material, the effective thickness of the water in
8 the beam path can be calculated from:

9

$$10 \quad Loss_{wet} - Loss_{dry} \cong - 4.34 \log_{10} T_{dry} (\alpha_{water} d_{water}) \quad (5)$$

11

12 where the approximate sign is due to the fact that T will be different in wet and dry
13 materials, although the difference is not expected to be large: $T_{dry} \approx T_{wet}$.

14 In order to investigate the practical aspects of moisture measurements and to
15 produce some test calibration curves, a simple phantom was designed and its microwave
16 transmission measured using a single transmitter-receiver channel. The phantom was a 5
17 mm thick cellulose sponge, chosen for its high water retention capability and because
18 cellulose has similar microwave properties to a number of waste materials, such as paper,
19 cardboard, wood and natural-fibre textiles. Moisture content of the sponge was
20 determined by its weight. Figure 2 plots the measured microwave loss as a function of
21 sponge weight, and therefore moisture content, for three test frequencies: 5, 16 and 26
22 GHz. The weight of dry sponge was 0.7 g and its microwave loss was 0.2 dB at all test
23 frequencies. As expected from Equation 5, the relationship between loss and moisture

1 mixed-waste stream as produced by the optical image analysis, compare it with the
2 measured loss, and evaluate the average moisture content of a volume of waste.

3

4 **2.5. Calculations**

5 To calculate the composition of each waste sample, the number of dots counted
6 for each component in each image was multiplied by the kg/dot as calculated previously,
7 to yield the mass (kg) of each component in each image. The sums of mass from each
8 image were then calculated to obtain the total weight of each component in the waste
9 sample, and were presented as weight-percentage composition (% w/w).

10 The biogenic carbon, GCV and NCV were calculated for each of the waste
11 samples from the determined composition using the weighted percentages. Subsequently,
12 the GCV and NCV from the biogenic fraction (GCV_{bio} and NCV_{bio}) were determined,
13 also using weighted averages.

14 The NCV at different moisture levels was calculated by rearranging the formula
15 provided in the standard method (British Standards Institute, 2011a), as shown in
16 Equation 6:

17

$$18 \quad Q_{p,net,m} = \{q_{v,gr,d} - 212.2 \times w(H)_d - 0.8[w(O)_d + w(N)_d]\} \times (1 \times 0.01M) - 24.43M \quad (6)$$

19

20 Where $Q_{p,net,m}$ is the NCV at constant pressure with moisture content (M), $q_{v,gr,d}$ is
21 GCV at constant volume on a dry basis. The hydrogen, oxygen and nitrogen content of
22 the moisture-free sample are shown as $w(H/O/N)_d$.

1 By combining the elements in the curly brackets, a constant (k) was calculated for
2 each component relating to the elemental content. This essentially assumes that the H, O
3 and N content of each component remains consistent, however a previous study by
4 Chester *et al* (2008) demonstrated that the variation between the chemical composition of
5 waste components to be small (Chester et al., 2008). The equation was then adapted
6 accordingly to allow the calculation of NCV at specified moisture content, as shown in
7 Equation 7.

8

$$9 \quad Q_{p,net,m} = (q_{v,gr,d} + k) \times (1 \times 0.01M) - 24.43M \quad (7)$$

10

11 The NCV at specified moisture content could then be calculated, demonstrating
12 how the moisture content measurements described previously would be applicable in
13 practice.

14 The energy from the biogenic fraction was calculated using the guideline method
15 from the Office for Gas and Electricity Markets [OFGEM] (Ofgem, 2011). However,
16 this guidance uses the assumed biogenic fractions as associated with the hand-sorting
17 method (British standards Institute, 2011c), meaning that waste fractions are 100%
18 biogenic (i.e. paper, card, wood etc.), 80% biogenic (leather and rubber), 50% (fabrics)
19 and 0% for plastics. These values are not accurate, and do not agree with laboratory
20 results published elsewhere (Fellner and Rechberger, 2009). Therefore, in this study the
21 OFGEM guidance has been modified to calculate the percentage biogenic energy from
22 the actual ^{14}C data for each waste component, which means that it is possible that certain
23 proportions of the energy from inherently biogenic materials (i.e. wood) is discounted.

1 The biogenic fractions of the waste components generally vary based on the age
2 of the material. As a part of the carbon cycle, ^{14}C is produced in the atmosphere (Marley
3 et al., 2009) and can remain in the atmosphere for a significant period of time prior to
4 uptake from biomass material. The half-life of ^{14}C is 5,730 years (European Committee
5 for Standardisation, 2007; Marley et al., 2009), and so the biogenic content of wood,
6 garden waste and paper is lower than 100% due to the partial decay of ^{14}C . Measured
7 biogenic carbon content of wood-derived materials can be explained if the wood was
8 sourced from a relatively old tree; the wood was taken from the centre-rings of a long-
9 lived tree or if the wood was partially contaminated with petrochemical components
10 (paint, oils or varnish). The biogenic content of card was higher than that of paper and
11 wood, despite also being of woody origin. This is likely to be due to the card being
12 produced from much younger woodlands, as occurs in practices of sustainable forestry. It
13 is also likely that the card used in this study was produced from virgin materials, whereas
14 the paper may have been recycled several times before. It is documented that the
15 precision of the ^{14}C technique is 2% relative standard deviation [RSD] for values between
16 10-100% biogenic carbon content (European Committee for Standardisation, 2007).

17 Plastic is of petrochemical origin, and so it would be expected that the biogenic
18 content would be 0%, however some biogenic material was measured. This could be an
19 error in the analysis as the precision of the ^{14}C technique is quoted as 5% relative
20 standard deviation [RSD] between for values of 0-10% biogenic carbon content
21 (European Committee for Standardisation, 2007). Otherwise, it is possible that a very
22 small proportion of the plastics used in this study were produced from bio-based
23 polymers (bio-plastics).

1 **Figure 5.** Schematic of proposed system on a conveyor belt.
2

3 The conversion of waste components to liquid and/or gaseous fuels (as with
4 gasification and pyrolysis) is not as straightforward as regards the CV, as used in this
5 study. Therefore further consideration would be required. Ofgem has recently suggested
6 that a method of assessing energy produced from biomass-derived material by a
7 gasification process can be adopted by measuring the ¹⁴C ratio within CO₂ in the flue gas
8 (Ofgem, 2011). This method is appropriate for combustion; however for gasification this
9 may not be directly applicable.
10

11 **4. Conclusions**

12 The two image analysis tools presented each demonstrate the potential to be
13 applied, combined in a single system, for estimating the renewable energy potential of
14 mixed wastes in a thermal treatment facility. The proposed system would, however, only
15 be applicable to conventional incineration/combustion processes due to the more complex
16 chemical processes involved in advanced thermal conversion technologies such as
17 gasification or pyrolysis.

18 Alternative applications would be for the determination of mixed waste
19 composition as outlined in a previous study by Wagland *et al.* (2012), or for the
20 certification of SRF prior to delivery to an end-user.
21

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4

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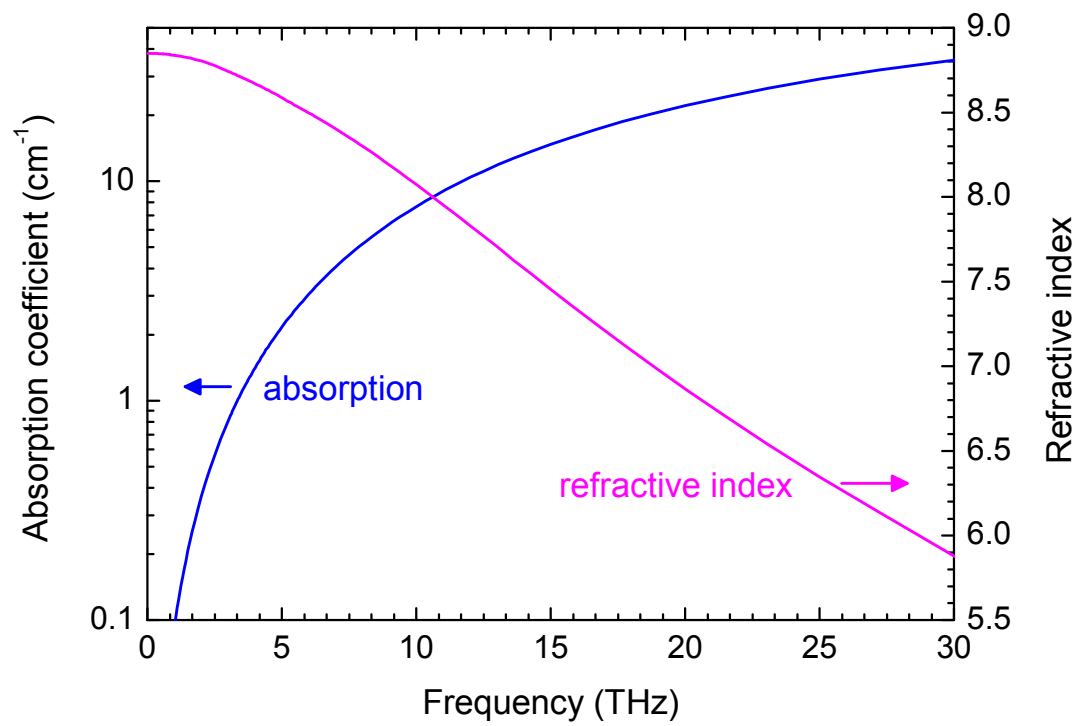
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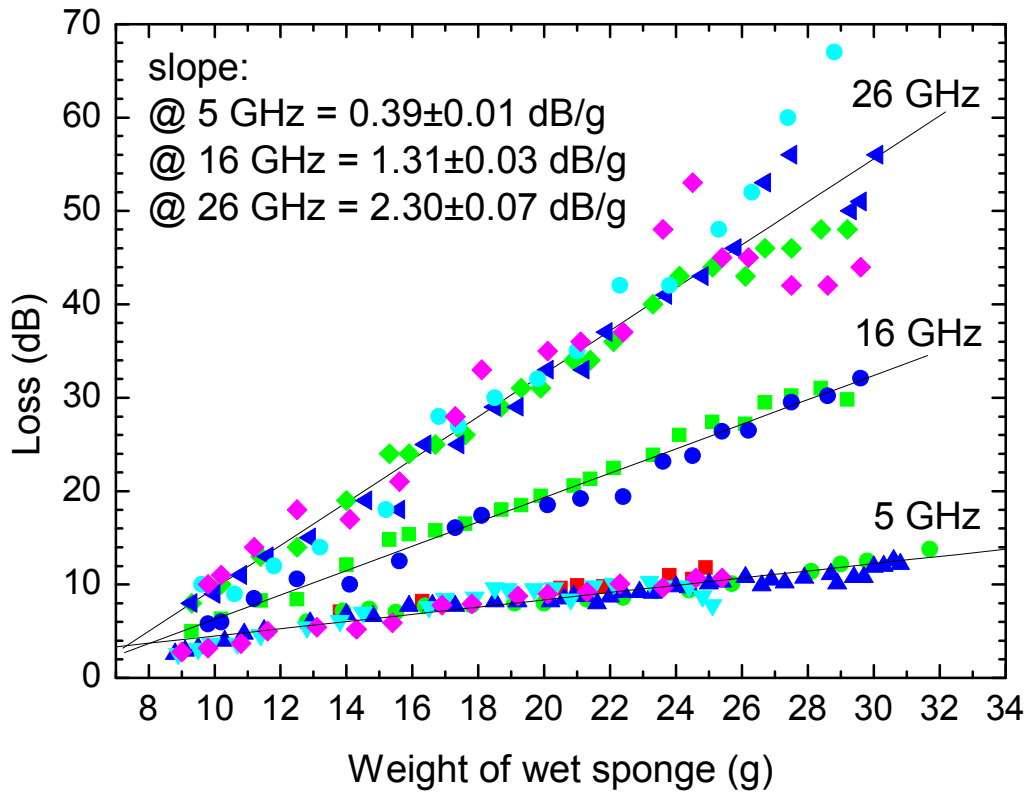
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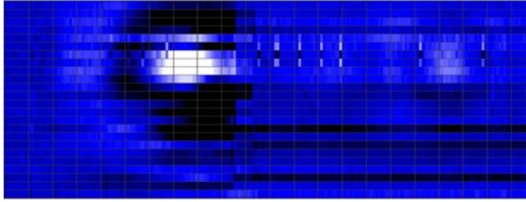
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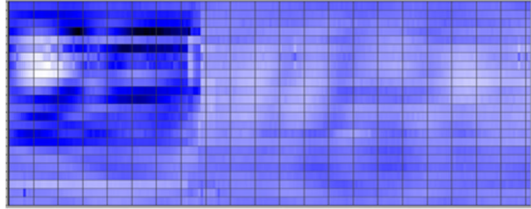




(a)



(b)



(c)

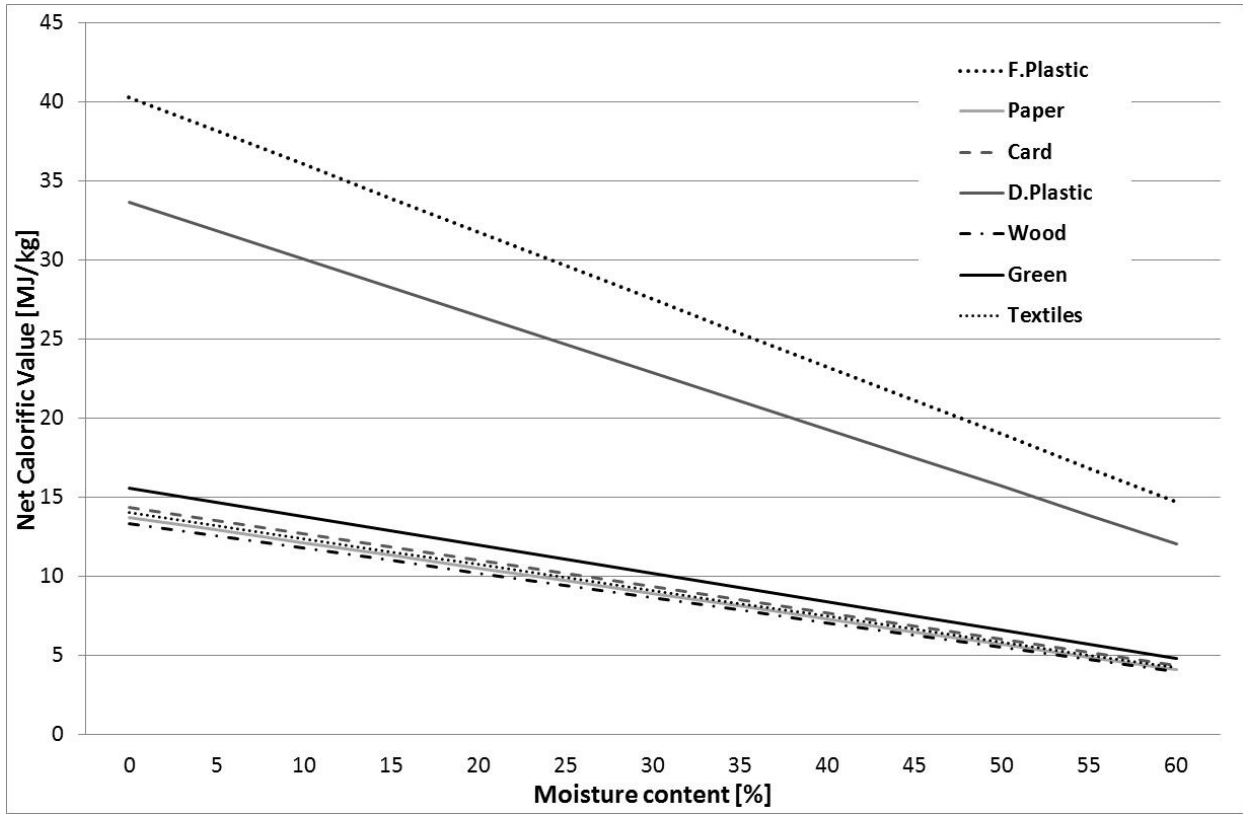
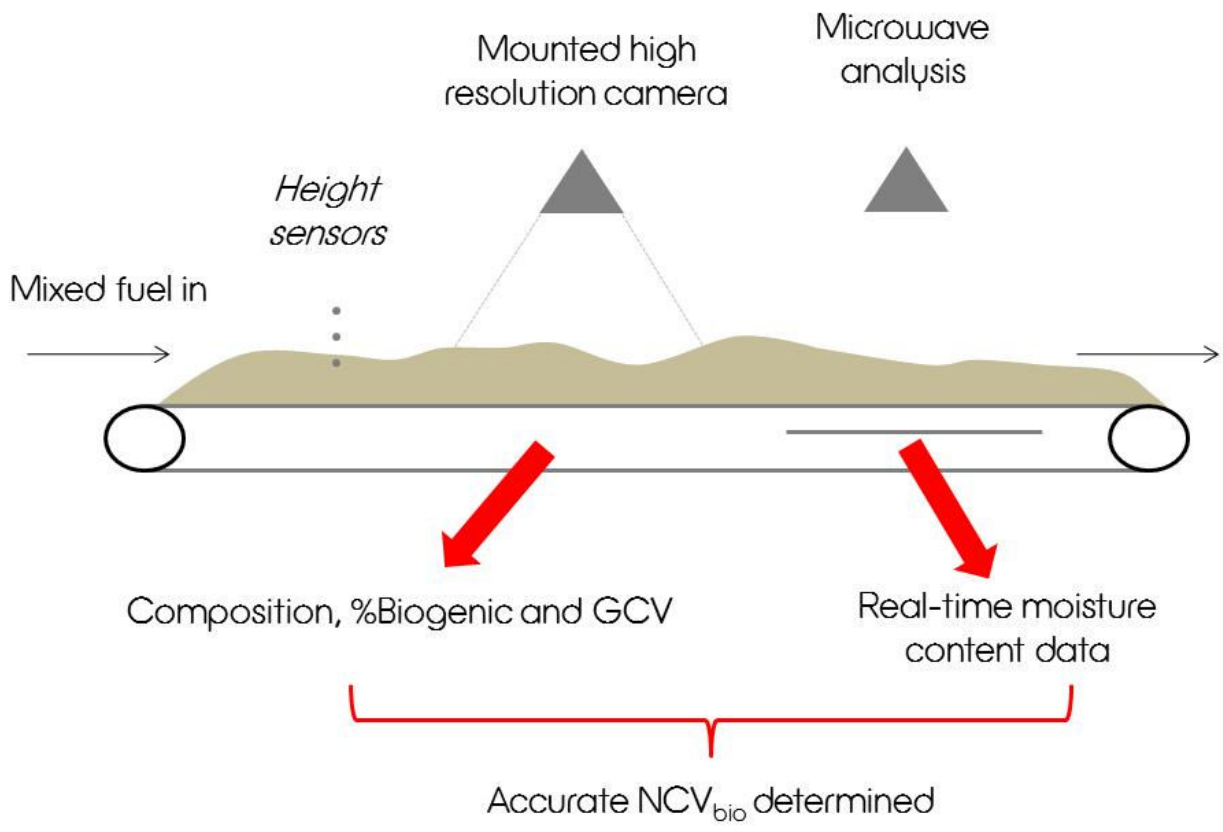


Figure 5



Component	Weight (kg)		% Composition		Ash (%)	Moisture (%)	Gross CV [MJ/kg]	Net CV [MJ/kg]	Biogenic C (%)
	A	B	A	B					
Paper	11.9	17.5	27.9	38.5	0.3	7.2	13,500	12,600	94
Card	12.9	3.6	30.2	7.9	1.2	13.9	13,000	12,100	100
D.Plastic	4.6	1.4	10.8	3.1	0.1	1.6	29,200	27,200	1
F.Plastic	-	0.5	-	1.1	5.4	2.9	41,300	39,100	1
Metal	1.0	1.8	2.3	4.0	-	-	-	-	-
Garden waste	3.4	4.5	8.0	9.8	2.3	25.8	11,800	11,000	96
Textiles	2.2	-	5.2	-	3	6.2	14,000	13,000	86
Wood	6.7	4.2	15.7	9.2	2.4	9.8	13,200	12,300	90
Inert	-	12	-	26.4	-	-	-	-	-
Total	42.7	45.5							

Table 1. Proximate, calorific, ^{14}C and composition data for mixed waste materials.

Component	Weight (kg)		% Composition	
	A	B	A	B
Paper	19.6	23.4	25.7	38.9
Card	20.9	5.4	27.4	9.0
D.Plastic	10.0	1.8	13.1	2.9
F.Plastic	-	0.8	-	1.3
Metal	2.1	2.2	2.8	3.7
Garden waste	6.7	4.1	8.8	6.8
Textiles	4.1	-	5.4	-
Wood	12.9	3.8	16.9	6.3
Inert	-	18.7	-	31.0
Total	76.4	60.2		
Correlation (r)	0.992	0.988	0.993	0.988

Table 2. Component weight and % composition determined by image analysis

Material	Thickness of water layer (mm)	Loss when dry (dB)	Loss when wet (dB)	Loss due to water (dB)	Calculated thickness of water (mm)
Wood	0.006±0.001	3.5±0.2	3.6±0.2	0.1±0.3	0.02±0.08
Cardboard	0.033±0.002	0.1±0.2	0.3±0.2	0.2±0.3	0.05±0.08
Fabric	0.33±0.01	0.3±0.2	1.6±0.2	1.3±0.3	0.31±0.07

Table 3. Moisture content of different materials calculated from microwave loss.

		Renewable gross CV [MJ/kg]	Renewable net CV [MJ/kg]
Component	Paper	12,700	11,800
	Card	13,000	12,100
	D.Plastic	292	272
	F.Plastic	413	391
	Metal	-	-
	Garden waste	11,300	10,500
	Textiles	12,000	11,200
	Wood	11,900	11,100
	Inert	-	-
% Renewable energy	Sample A	74.69	74.69
	Image analysis Sample A	70.72	70.71
	Sample B	80.25	80.09
	Image analysis Sample B	79.61	79.44

Table 4. % renewable energy from each waste sample, determined from the known composition and from image analysis. CVs quoted on an ‘as received’ basis.

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Determination of renewable energy yield from mixed waste material from the use of novel image analysis methods

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