BIOSOLIDS AND MICROALGAE AS ALTERNATIVE BINDERS FOR BIOMASS FUEL BRIQUETTING

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Abstract

Binders can be employed to improve the particle adhesion, compressive strength, abrasion resistance and energy content of densified biomass, such as briquettes. They may also reduce the energy cost of producing such briquettes, by reducing the compaction pressure, conditioning temperature and the wear on production equipment.

This study explored and compared the effects of three different binders, including starch, enhanced treated biosolids and microalgae, on density, durability, energy content and combustion characteristics of fuel briquettes produced from blends of rice husks, corn cobs and bagasse, in a multilevel factorial design experiment.

Briquettes had relaxed unit densities of 1.9 to 3.3 times the loose biomass bulk density, and were stronger than briquettes from the individual materials, with an average unconfined compressive strength of 125 kPa. An unconfined compressive strength of 175 kPa was achieved for a 2:4:1 blend of rice husks, corn cobs and bagasse with the microalgae binder at a compaction pressure of 31 MPa. Statistical analysis of the results showed that the addition of biosolids and microalgae binders significantly improved briquette density, while the addition of starch reduced briquette density, and biosolids reduced briquette strength.

Of all the briquettes produced with the three binders, those containing the microalgae binder were found to be most durable, with a higher energy value, slower mass loss during briquette combustion, and a higher afterglow time. Since microalgae may be grown using CO_2 from biomass combustion, discovery of their advantages as a binder in briquetting is particularly welcome.

Key words: biosolids; microalgae; starch; biomass; briquettes

1 INTRODUCTION

Biomass densification into fuel briquettes offers many advantages, such as easier transportation and storage of biomass, more uniform feeding into conversion equipment, and improved thermal conversion, when compared with loose biomass. The density and strength of fuel briquettes is of great importance, as poor quality briquettes may disintegrate and crumble back to their parent materials when handled, processed or stored [1]. This may cause emission of fines during transportation, handling and processing of these briquettes, and negate the advantages of briquetting.

The addition of binders to loose biomass residue before densification has been studied as a way of addressing such drawbacks and reducing production costs [e.g., 30,31,57]. However, due to the negative effects of the use of some binders in both densification [30] and briquette combustion [61], it is necessary to develop more effective and sustainable binders for biomass briquetting.

The specific objectives of this paper were:

1. To investigate the potential of using starch, treated biosolids or microalgae as a binder for briquetting.

2. To investigate the effect of the proportions of rice husks, corn cobs and bagasse, addition of a starch, biosolids or microalgae binder, and compaction pressure, on briquette durability-related properties, energy density and combustion characteristics.

2 BACKGROUND

2.1 Rice husks, corn cobs and bagasse

Rice, corn and sugarcane are examples of major crops that result in generation of huge amounts of waste from their cultivation and processing. In the year 2012, around 148 Mt of rice husks were generated from 740 Mt of global rice production [2]; in the same year, approximately 173 Mt of corn cobs were produced from 1020 Mt of corn production [2]; while 549 Mt of bagasse were produced from 1830 Mt of sugarcane [3]. Although most sugar refineries combust the bagasse to support the energy demand of the plant, excess amounts of this high calorific residue still remain unutilised.

Table 1 compares energy, ash and moisture contents, bulk density, porosity, water absorption and composition of rice husks, corn cobs and bagasse, as gathered from sources in the literature [4,5,6,7,8,9,10-19]. The total annual generation of rice husks, corn cobs and bagasse has an estimated energy content of 16 EJ, which represents about 2.9% of the world total primary energy consumption [20].

2.2 Binding properties of biomass residues

Although many biomass residues possess natural binding agents [23], additional binders are often added to improve binding during densification into briquettes.

Despite the advantages of using binding agents in biomass briquetting, problems have been encountered with some types of binders when fuel briquettes are converted to energy, including air emissions from pollutants in untreated materials, deposit formation and corrosion of equipment [61]. Other binders may have resource problems, e.g., starch, which is also a food product. There is therefore a need to explore better and more environmentally friendly binders for briquetting of loose biomass.

2.3 Binders for fuel briquette production

Binders commonly used in briquetting include starch, molasses, lignosulphonates (in animal feed processing), sulfonate salts made from lignin in pulp [24,25,26], or biomass wastes that are naturally rich in binding components, e.g., rice bran & sawdust [27]. Recent research has focused on developing new, cheaper and more sustainable binders, as well as optimising the ratio of binder to loose biomass. A variety of effects of binders on briquette quality have been reported:

Chin & Siddiqui [28] reported a decrease in the relaxed density of briquettes with an increase in binder (starch and molasses) ratio for sawdust and coconut fiber, yet an increase in relaxed density of briquettes with an increased ratio of the same binder for peanut shell and palm fiber. Singh & Singh [29] reported an increase in briquette strength with increased addition of a molasses and sodium silicate binder in briquettes from rice straw.

Furthermore, Muazu & Stegemann [30] used starch in briquetting of different blends of rice husks and corn cobs, and reported a statistically significant negative effect of starch binder on briquette density but a positive effect on compressive strength. This was attributed to the low density of the starch/water gel, in comparison with the residues that it replaced, as well as the possible expansion of briquettes due to heat development during densification. Oladeji &

Enwerenmadu [31] also showed a reduction of corn cob briquette density with increased addition of a starch binder.

Emerhi [32] used three different organic binders including cow dung, wood ash and starch in briquetting of sawdust, to assess the effect on the calorific value of the produced briquettes. Results showed that starch-bound briquettes produced the highest calorific value while ash-bound briquettes had the lowest calorific value. Sivakumar et al. [33] showed that briquetting sawdust with a cow dung binder could be optimized to increase the thermal efficiency and methane content of the product gas in a downdraft gasifier.

2.3.1 Starch, biosolids and microalgae

Table 2 compares the energy, ash, moisture and volatile matter contents, bulk density, and composition of starch, biosolids and microalgae binders as gathered from literature sources [34,55,56,59,62-71,76,77].

Starch in its pure form is a tasteless and odourless white powder which can be extracted from various kinds of crops such as rice, wheat, cassava, yam, and potato. Chemically refined starch has been treated after extraction from the source crop to modify some of its properties, for example, to enhance its solubility in cold water, or improve whiteness.

Starch has two major components: amylose and amylopectin [34]. These polymers are very different structurally, amylose being linear and amylopectin highly branched. Addition of water and heat to starch granules causes swelling, which results in the formation of intermolecular hydrogen bonds between the amylose and amylopectin, followed by loss of the individual crystalline structure of the two components [37]. This leads to formation of a viscous solution that undergoes retrogradation, i.e., gelling, during cooling or storage. The ratio of amylose to amylopectin influences its viscosity, shear resistance, gelatinization, texture, solubility, tackiness, gel stability, cold swelling and retrogradation of the starch [34,35]. Amylose and amylopectin are therefore natural binding compounds present in various biomass materials.

Apart from its value as a food, starch has various applications as a binder in non-food industries such as textiles, cosmetics and pharmaceuticals, explosives, paper, construction, etc. Its high energy content, and chemical and structural properties make it a promising binding agent for fuel briquetting. The viscosity of hydrated starch increases its shear and tensile strengths. The fluidity and viscoelasticity of the produced solution [37] gives it the ability to occupy the void spaces present within and between biomass particles, forming solid bridges that become stronger upon air-drying.

Biosolids are the residue from anaerobic digestion of waste activated sludge from municipal wastewater (i.e., sewage) treatment. Biosolids contain valuable organic matter and high contents of natural binding compounds such as lignin and protein (Table 2), which are useful in solid compaction processes [56]. The increase in temperature during densification causes thermosetting of lignin to produce more durable briquettes [73]. Application of heat also denatures protein and results in formation of new bonds with other proteins and starch molecules [24]. The synergistic effect of lignin and protein during densification, had positive impact on briquette durability, in the co-pelletization of dewatered biosolids and biomass [56].

Untreated biosolids contain pathogenic organisms present in municipal wastewater [36]. Therefore, it has become a requirement to treat biosolids before disposal, application on farm land or other applications. Conventional treatment destroys at least 99% of the pathogens; this has been superseded by enhanced treatment which ensures that 99.99% of pathogens are destroyed [37]. Since the treatment of biosolids affects their composition, it might be expected to also influence their binding characteristics.

Microalgae are a large group of photosynthetic, heterotrophic single-celled organisms from different phylogenetic groups, representing many taxonomic divisions. They are distributed worldwide, inhabiting fresh- and seawater ecosystems [39], and are easy to cultivate. Since they capture carbon during growth, can be grown using wastewater, and can have a high lipid content, their potential use as biofuels has been the subject of considerable attention in recent years. The efficient recovery of the energy and carbon remaining in algal residues after lipid extraction is important for improved environmental and economic sustainability of algal biofuels [40].

Algal residue has a potential application in material binding due to its high content of protein, and a considerable content of lignin (Table 2). In the presence of moisture, algal residue releases a protein binding substance that acts as glue between loose material particles, forming solid bridges and filling voids [41]. For example, freshwater microalgal biomass was found to increase the mechanical strength of paper pulp [41].

3 MATERIALS AND METHODS

1. Preparation and characterisation of raw materials

Bulk samples of air dried rice husks, corn cobs and bagasse were sourced and collected from local farms and milling sites in Niger state, Nigeria. Rice husks were used as received from the milling site, since they have a particle size of 2 mm or smaller, which can readily undergo densification. The mass median diameter ("D50") of the rice husks was 0.7 mm. Corn cobs and bagasse were used with a particle size of <1.6 mm, based on preliminary experiments which found that larger particles (2-10 mm) were less easily compacted. Corn cob and bagasse particles obtained using a hammer mill fitted with a 1 mm screen were blended with larger particles (1-1.6 mm) that had been manually crushed. The mass median diameter of the resulting blend for both corn cobs and bagasse was 0.8 mm.

Unrefined cassava starch was obtained from a local market in Niger state, Nigeria, in a dry powder form with 6.8% moisture content. Enhanced treated biosolids were collected from a UK municipal wastewater treatment plant as a filtercake with a solids content of 21% wet mass. The specific enhanced treated biosolids used in this study was also free of bad odour. Whole microalgae (*chlorella sorokiniana*) were grown in our laboratory and centrifuged to obtain a concentrated slurry with a solids content of 25% wet mass. It was expected that the binding characteristics of this slurry would be similar to that of algal residue following lipid extraction, as the lipid content of our algae was relatively low (<10%).

The three binders were prepared into paste by mixing with normal water at room temperature for biosolids and microalgae binders, while starch was prepared using warm water to provide the gel like paste.

Characterisation of rice husks, corn cobs and bagasse included determination of bulk density by BS EN 15103 [42], moisture content by BS EN 14774-2 [43], particle size by DD CENT/TS 15149-2 [44], water absorption by adaptation of BS EN 772-21 [45] and specific gravity using a Micromeritics helium pycnometer (ACCU Pyc 1330). The porosity of materials was determined using equation 1.

$$\text{Porosity} = (1 - \frac{\rho}{SG}) X\ 100 \text{............} (1)$$

where

ρ = *density of material (kg/m^3 dry basis)*

SG = specific gravity of material (kg/m³)

The starch, biosolids and microalgae binders were prepared separately by mixing each individual solid binder into a paste with water at a mass ratio of 2:3, for 5 minutes prior to addition to the blends of rice husks, corn cobs and bagasse [30]. The inherent water contents of the biosolids and microalgae were included in this ratio.

2. Experimental design and analysis

A factorial experimental design method involving 16 runs was employed for production of briquettes. The variables investigated in this study were chosen based on their influence on briquette properties from previous work by the authors [30]; these included material ratio (M), i.e., percentage masses of rice husks, corn cobs and bagasse in the blends, binder addition (B), i.e., mass of starch (ST) or biosolids (BS) or microalgae (AL) binder and water (W) added as a percentage of the rice husks, corn cobs and bagasse blend, and compaction pressure (P). The response variables measured were green (immediately after extrusion from the mold) and relaxed (after 24h curing) density, unconfined compressive strength, calculated energy density, and the combustion profile of the briquettes.

The $2^2 3^1$ multilevel level factorial design that was used for briquette production is shown in columns 2 to 6 and 8 of Table 5, which also shows the measured responses. Two levels were selected for material ratio (40% rice husks: 40% corn cobs: 20% bagasse, or 25% rice husks: 65% corn cobs: 10% bagasse; columns 2 and 3 of Table 5). Thus the effects of rice husks and bagasse are confounded, as both were higher when the corn cob content was lower, and vice versa. Two levels were also selected for the compaction pressure (19 or 31 MPa; column 8 of Table 5), while three levels were selected for the binder (17% starch, biosolids or microalgae; columns 4, 5 and 6 of Table 5). The quantity of water in the binder paste for each experimental run is shown in column 7 of Table 5. The effect of water was confounded with that of the starch, biosolids or microalage used in the experiments, however, the effect of water separately with and without binder, was evaluated in our previous work with starch binder [30]. Table 5 shows that Runs 1 to 4 were repeated, whereby the first replicate was run together with the runs for the biosolids, and the second replicate was run together with those for the microalgae.

Statistical effects of variables and their interactions on the responses were calculated based on the individual replicates, corresponding to the averaged results shown in columns 9, 11 and 13 of Table 5 [46]. Effects of the variables and interactions between the variables on a response are estimated as the differences between the averages for each level of a variable or interaction, and the total average response. Normal probability plots of the effects can be used to visualize the significance of the effects of individual variables on the responses [46]. The estimated effects can be read from the abscissa, against the standard deviation of the normal distribution on the ordinate. The scale of the ordinate has been adjusted such that a normal distribution appears as a straight line, i.e., points that lie on the straight line may be a result of normal random variability, whereas those that deviate from the straight line indicate significant effects of these variables or interactions on the response. Analysis of variance was also used to determine the statistical significance of the observed effects [46].

3. Briquette production and curing

Biomass and binder blends were weighed out in the proportions indicated in columns 2 to 7 of Table 5 and densified using hydraulic compression, as previously described [30]. The briquette diameter was 32 mm, and the green lengths ranged from 25 to 33 mm before relaxation, while the relaxed lengths ranged 33 to 43 mm. The briquette masses ranged from 16 to 19 g. The briquettes were cured for 24 hours at 23 ± 2^{o}C and relative humidity of 50 ± 5 % before testing. Figure 1 shows sample briquettes produced from the blends of rice husks, corn cobs and bagasse with different binders.

3.1 Briquette characterisation

The methods used to measure the response variables are summarized in Table 3, apart from the combustion test, which is further described below. All tests were repeated for three briquettes.

An atmospheric combustion test (adapted from [50,51]) was carried out in the laboratory by placing a single briquette in the centre of a steel wire mesh grid resting on fire retardant bricks, allowing the free flow of air through the briquette. The combustion rig was positioned on top of a digital mass balance to record the briquette mass throughout the combustion process. Smoke was allowed out through an extraction hood.

Individual briquettes were ignited using a laboratory ignition blow torch powered by propane gas (Calor gas 340) as shown in Figure 2 The blow torch was left in until the briquette was well ignited and had entered into its steady state burn phase [50]. The briquette mass was recorded every 3 minutes until less than 10% of the briquette remained. The afterglow time was recorded as the amount of time within which a red glow was observed after the ignition flame disappeared, i.e., the period in which useful heat is evolved.

The remaining residue from briquette combustion was further heated in a Carbolite laboratory muffle furnace at 600^{o}C for 4h, to obtain the residual combustible fraction and total non-combustible (ash) portions in a complete combustion.

4 RESULTS AND DISCUSSION

4.1 Properties of loose rice husks, corn cobs and bagasse

Table 4 shows the properties of the rice husks, corn cobs and bagasse measured in this study.

The properties of rice husks and corn cobs have been discussed in previous work by the authors [30]. The moisture content of the bagasse appears to be very low compared with that reported in the literature (Table 1). This may be attributed to air drying at source and during hammer milling [7]. The specific gravity of bagasse is slightly lower than that of rice husks and corn cobs, corresponding to the lower ash content. The high ash content of corn cobs can be attributed to the type of biomass species and possible contamination from soil during cultivation and handling of residue [e.g., 87]. The loose bulk density falls within the range reported in Table 1, but is lower than that of rice husks and corn cobs, corresponding to a higher inter-particle porosity. In contrast, the water absorption and percentage saturation of available pore space were far less than for the rice husks and corn cobs, and the reported values in the literature. During the water absorption test, water was observed to rapidly penetrate between the particles of bagasse, but quickly separated from the residue at the filter stage of the absorption test. The slight oversaturation of the porosity observed in bagasse is associated with swelling (% volume change in Table 4) that occurs in most lignocellulosic materials when immersed in fluids such as oil [52] and water, including also the rice husks and corn cobs.

These results again indicate significant variability in the properties of lignocellulosic biomass, as also reported by Muazu & Stegemann [30], and which is potentially caused by factors including growth conditions, cultivation methods, and post-harvesting handling of the crop. Our results suggest that the post-harvest handling of the crop is particularly significant.

4.2 Briquette density and compressive strength

Columns 9, 11 and 13 of Table 5 show the average green and relaxed densities and compressive strengths of briquettes obtained for each run of the multilevel factorial design experiment; the standard deviations for the three replicates of each test are shown in columns

10, 12 and 14. The green and relaxed densities refer to the specific unit density of an individual briquette.

The relaxed densities obtained for the twelve runs with different proportions of the three raw materials and three binders ranged from 463 to 577 kg/m^3. These relaxed densities were up to 1.9 times the average bulk density of the loose rice husks and corn cobs and up to 3.3 times the bulk density of loose bagasse.

The compressive strengths obtained for the twelve runs with different proportions of the three raw materials and three binders ranged from 70 to 175 kPa. Briquette moisture contents ranged from 10 to 12% mass. These values comply with the recommended moisture specification of ≤12% by CEN/TS 14961, the European standard for solid fuel quality [54].

4.3 Energy density of starch, biosolids and algal bonded briquettes

Column 15 of Table 5, shows the estimated energy densities of briquettes produced using starch, biosolids and microalgae binders, with the blend ratio of rice husks, corn cobs and bagasse.

From Table 5Table 5, the use of a higher proportion of corn cobs, which have a higher calorific value, yielded briquettes with higher calculated energy densities for all three binders. (Table 1). The influence of the bagasse calorific value was relatively minor, as a result of the relatively small difference in the mass proportion of bagasse residue in the 40/40/20 and 25/65/10 blends of rice husks, corn cobs and bagasse.

Briquettes produced with starch binder had the lowest energy densities while briquettes produced with the algae binder had the highest energy densities for both blends of rice husks, corn cobs and bagasse. Although untreated biosolids have a high calorific value [56,59], enhanced treated biosolids were used in this study to avoid health hazards [1.4.1, 37]. Enhanced treatment of biosolids may be associated with a reduction in energy density.

4.4 Effects of briquetting variables on response variables

Figure 3a to c presents the normal probability plots of the main (individual) and interaction (two-factor and three-factor) effects of the material ratio, binder content/type and compaction pressure, on the green densities, relaxed densities and compressive strengths of the briquettes produced in the multilevel $2^2 3^1$ factorial design experiment (Table 5). The effects that deviate from the straight lines in the probability plots are the most significant. The magnitudes of the effects, and the probabilities that they are attributable to random error, *p*, determined based on the F-statistics calculated in the analysis of variance (ANOVA), are shown in Table 6. An effect is generally considered as statistically significant when $p < 0.05$ [46].

The use of the lower content of rice husks and bagasse (i.e., higher corn cob content) in the biomass blend, had a significant positive effect on briquette relaxed density and compressive strength ($p = 0.001$ and $p = 0.001$, respectively). The corn cobs particles were smaller, and findings by other authors [7,30,31] indicate that briquettes produced from smaller particles sizes exhibited less relaxation; this may be attributable to lower compressible intraparticle porosity. Also, bagasse has a high moisture content and rich natural binders. Therefore, addition of these components was expected to improve the briquette density and strength. However, a mild exothermic reaction, attributed to degradation of residual sugar present in the bagasse [53], caused immediate drying after densification, which reduced the mass, and therefore the density of the briquettes. Small cracks were also physically observed on the briquettes containing the higher proportions of rice husks and bagasse, which may have reduced their strength. The presence of cracks was also related to greater expansion/relaxation of the briquettes.

In contrast with the negative effect of the starch binder observed in previous work by the authors [e.g., 30, 31], the use of biosolids and microalgae binders increased briquette green density and relaxed densities ($p = 0.02$) and ($p = 0.035$). This may be attributable to the high protein content of microalgae and biosolids (Table 2), which is known to improve binding in densified fuels [56,57]. Additionally, the use of biosolids and microalgae binders did not result in swelling during densification. This is consistent with findings by Jiang et al [56] for untreated biosolids binder used in pellet production and Ververis et al [40] for use of a microalgae binder in paper pulp production. The addition of starch and microalgae had positive effects on briquette compressive strength ($p = 0.001$), but there was apparently no interaction effect of binder and material ratio on compressive strength ($p = 0.38$).

The use of the higher compaction pressure of 31 MPa had a significant positive effect on green density ($p = 0.001$) but this effect was not apparent for compressive strength, while the interaction of compaction pressure with binder and material ratio both had negative effects ($p = 0.05$ and $p = 0.04$) on briquette green and relaxed density respectively. This agrees with findings from previous work by the authors [30] and the literature [28].

Overall, the values of relaxed density obtained in this study are slightly less than those obtained in a previous study by the author [30]. This may be due to the increased quantity of binder present in the blend (17% mass of residues compared with 10%), which increases the overall moisture content and porosity. This agrees with findings by Mani et al [58] that a lower moisture content of 5-10% results in good quality briquettes, and Kaliyan & Morey [7] also suggest a moisture content less than 15%.

4.5 Combustion characteristics of starch, biosolids and algal bonded briquettes

The combustion profiles of briquettes produced containing the biomass blends with starch, biosolids and microalgae binders, i.e., percentage mass loss over time, can be viewed in Figure 4

Figure 4 shows that briquettes produced with the biosolids binder burned more quickly than briquettes produced with starch, which in turn burned more quickly than those made with microalgae. Figure 5 shows that the afterglow times of the briquettes tend to increase as a function of their relaxed densities, with the highest density and afterglow time associated with the microalgae binder. The error bars indicating the standard error suggest that real differences in both afterglow time and density exist.

It is postulated that the combustion rates of the briquettes are associated with their morphological characteristics (4.2), and particularly the presence of air in the void spaces of the briquettes containing biosolids. This agrees well with findings by other authors [e.g., 50,51] for waste newspaper briquettes and peanut shells, and indicates the importance of binder type in biomass densification as well as the thermal conversion of densified fuels.

For efficient combustion, the release of heat must be controlled to keep the fuel burning [74] and for efficient capture of useful energy, and solid fuel must burn as completely as possible. The briquettes made with microalgae have the advantage of a higher energy density, compared with the starch and biosolids binders. The proportions of uncombusted organic matter remaining in the char for briquettes made with starch, biosolids and microalgae indicated comparable completeness of combustion, with 6.5, 7.5 and 6.8 % of the mass of original briquettes remaining, respectively.

5 CONCLUSIONS

This study has identified and demonstrated the suitability of using enhanced treated biosolids and microalgae as binders for durable briquette production from blends of rice husks, corn cobs and bagasse. The physical and combustion characteristics of briquettes produced with biosolids, microalgae and starch binders, were evaluated. A range of good quality briquettes that conform to CEN/TS 14961[54] can be produced with the addition of biosolids, microalgae or starch binder to the blends of rice husks, corn cobs and bagasse.

Statistical analysis of the results showed that the addition of microalgae to the blends of rice husks, corn cobs and bagasse, and higher compaction pressure had positive effects on briquette density and strength. The addition of biosolids also improved briquette density, but had a negative effect on briquette compressive strength. Starch addition enabled achievement of measurable unconfined compressive strengths in comparison with no binder addition, but significantly reduced the green and relaxed densities of the briquettes.

In comparison with the biosolids and starch binders, the use of microalgae binder increased the energy density of briquettes, which also burnt more slowly in combustion tests. Since microalgae may be grown using CO_2 from biomass combustion, discovery of their advantages as a binder in briquetting is particularly welcome.

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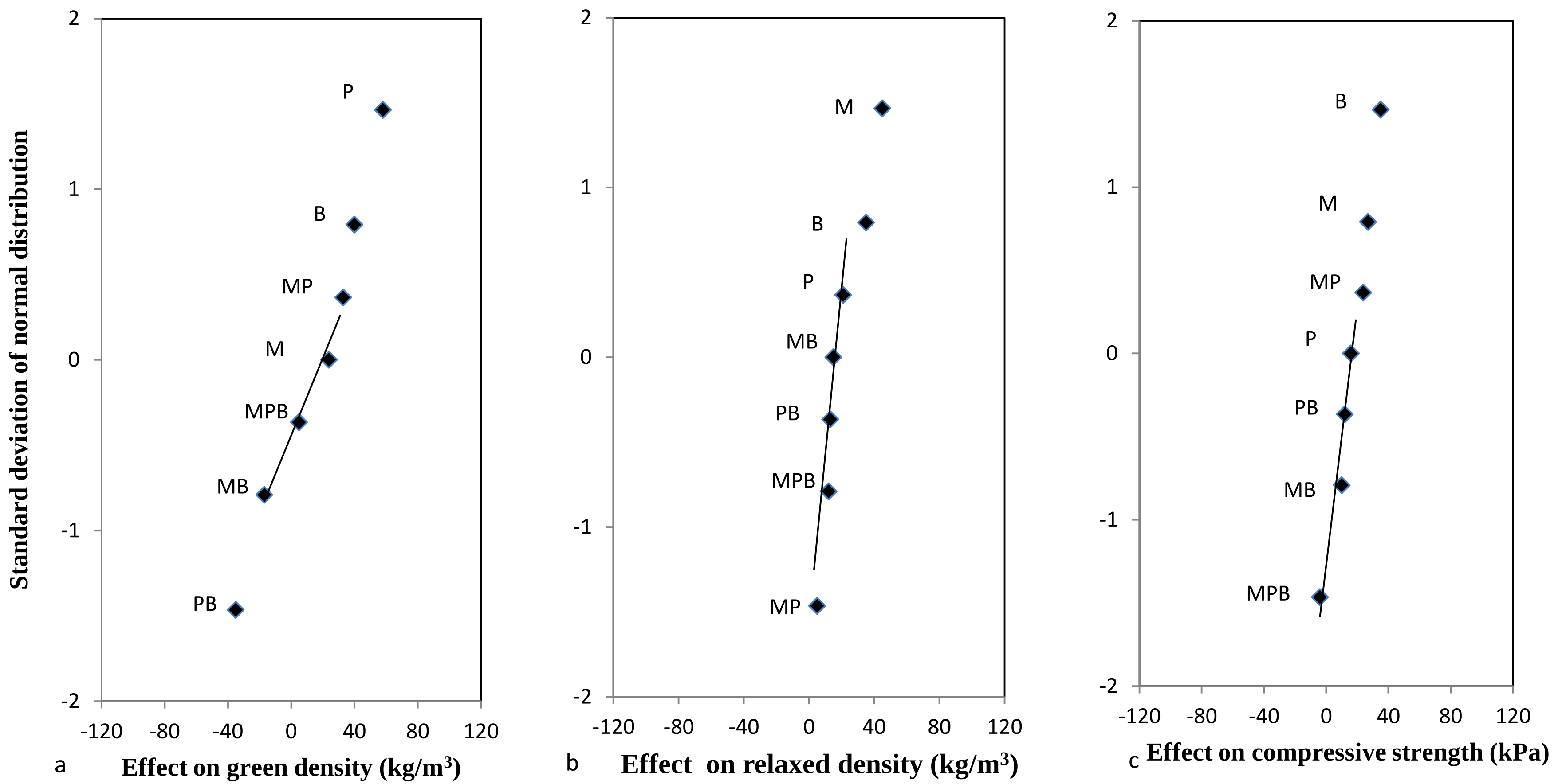
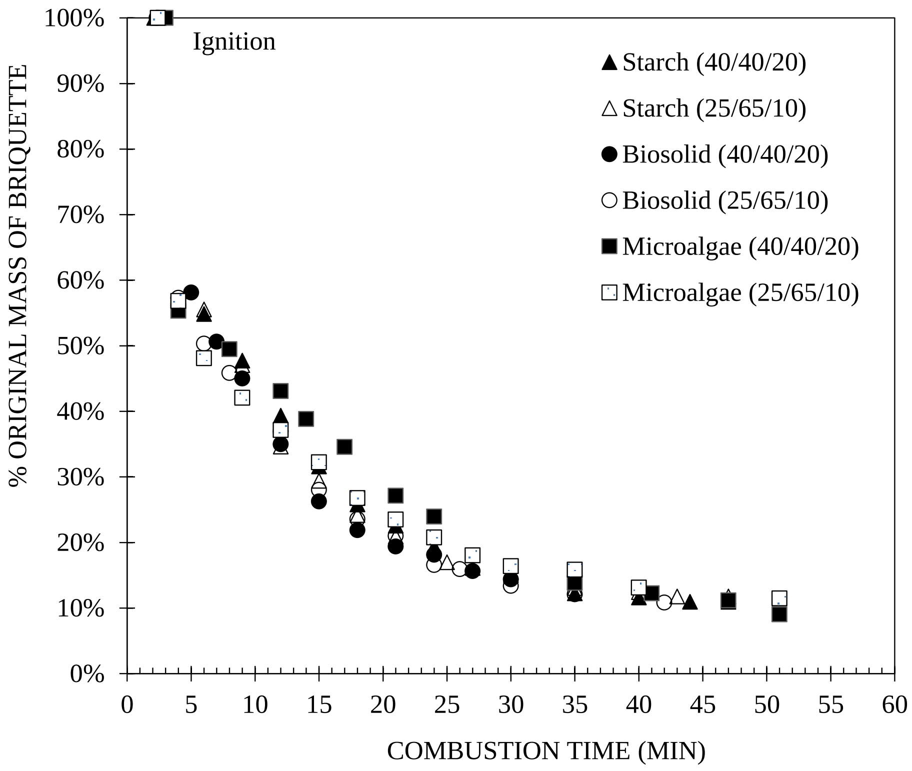
LIST OF FIGURES

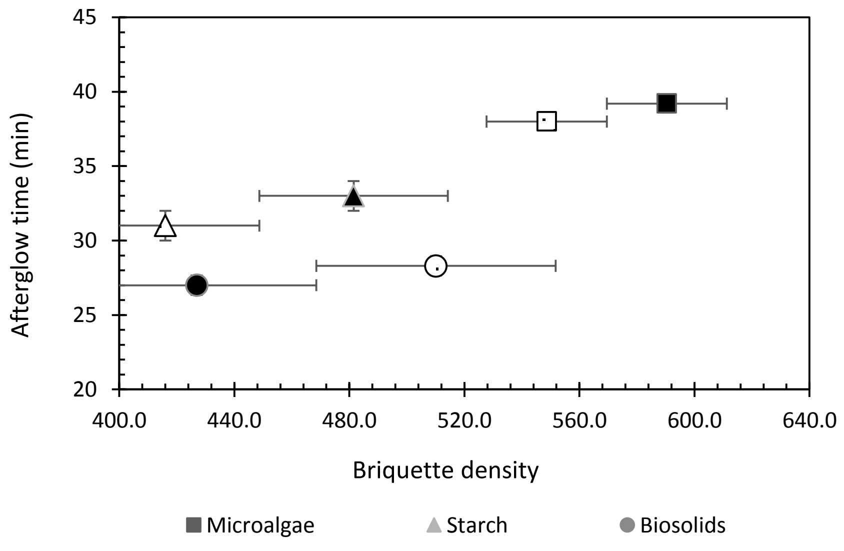
 CALOR Gas		



Standard deviation of normal distribution
2
1
0
-1
-2
P
B
MP
M
MPB
MB
PB
-120
-80
-40
0
40
80
120
a
Effect on green density (kg/m3)
M
B
P
MB
PB
MPB
MP
b
Effect on relaxed density (kg/m3)
B
M
MP
P
PB
MB
MPB
c
Effect on compressive strength (kPa)



100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Ignition
Starch (40/40/20)
Starch (25/65/10)
Biosolid (40/40/20)
Biosolid (25/65/10)
Microalgae (40/40/20)
Microalgae (25/65/10)
% ORIGINAL MASS OF BRIQUETTE
0
5
10
15
20
25
30
35
40
45
50
55
60
COMBUSTION TIME (MIN)



45
40
35
30
25
20
Afterglow time (min)
400.0
440.0
480.0
520.0
560.0
600.0
640.0
Briquette density
Microalgae
Starch
Biosolids

Table 1: Comparison of basic properties of rice husks, corn cobs and bagasse

Properties	Rice husks	Corn cobs	Bagasse	Reference
Calorific value (MJ/kg dry mass)	16	18	19	[4,5,6,8,9]
Ash content (% dry mass)	20	<3	2-10	[4,5,8,11,12,78]
Moisture content (% undried mass)	8-12	20-55	45-55	[4,5,7,9,11,12]
Bulk density (unprocessed) (kg/m^3 dry mass)	100-150	160-210	100-200	[5,7,11,12,13]
Bulk density (ground to <0.85 mm) (kg/m^3 dry mass)	331-380	282	NA	[4,11,12]
Porosity (% dry volume)	63-73*	68	NA	[11,12]
Water absorption (% dried mass)	105	327**	186	[21,10,13]
Lignin (% dry mass)	19.2	15.3	18-24	[15,19]
Protein (% dry mass)	1.8	2.7	3.0	[22,14,16,17]
Starch (% dry mass)	<1	1.61	NA	[14,18]
Volatile matter (% dry mass)	62 - 66	76.3	85.5	[8,9,79]
Sulphur (% dry mass)	0.04 -0.08	0.01-0.72	0.06	[8,9,80]
Chlorine (% dry mass)	0.12	0.17 -0.26	0.03	[8,81]

*range of 4 different types including long and short grain rice

**average water absorption of whole small cobs

NA = not available

Table 2: Comparison of basic properties of starch, biosolids and microalgae

Properties	Pure untreated starch	Biosolids	Microalgae	Reference
Calorific value (MJ/kg dry mass)	18	6-19	15-23	[59,64,65,70]
Ash content (% dry mass)	0.08-0.2	31	10	[56,63,67,69]
Moisture content (% undried mass)	4-11	5-11	7	[56,62,63]
Volatile matter (% dry mass)	NA	39-57	67	[56,67,71]
Bulk density (kg/m^3 dry mass)	617	400-800	370-435	[62,68,72]
Lignin (% dry mass)	NA	10-10.3	2	[41,69,76]
Protein (% dry mass)	0.23	10-15	7-64**	[63,69,76,77,55]
Amylopectin (%)	0-70*	NA	NA	[34]
Cellulose	NA	1	7.1	[41,76]
Hemicellulose (% dry mass)	3.72	NA	16.3	[41,76]
Fat (% dry mass)	0.075	13	2-10	[63,69,71]
Nitrogen (% dry mass)	NA	3.3 -3.7	1.6 -6.8***	[82,85]

Properties	Pure untreated starch	Biosolids	Microalgae	Reference
Sulphur (% dry mass)	NA	0.18 -3.6	0.4 -1.0***	[82, 83]
Chlorine (% dry mass)	NA	0.02	1.97	[84,85]
Calorific value (MJ/kg)	17.5	10.1 -16.2	18.59	[59,82,85]
Lipid (%)	NA	NA	21.3 -30.8	[82,86]

NA = not available

* The remainder of the starch is assumed to be amylose

**Value obtained from different strains of microalgae

***Range is for green and mixed green algae of different strains

Table 3: Briquette characterisation methods

Briquette Property	Method Summary	Standard Test Method	Reference
Green (1) & relaxed (2) densities	Ratio of cylinder mass to volume (1) immediately after compression and (2) after 24h curing	DD CEN/TS 15405:2010	[48]
Moisture content	Mass lost in drying at 105ºC±2	BS EN 14774-2	[43]
Unconfined compressive strength	Failure loading of axially loaded cylinder	ASTM C39-96 (adapted)	[49]
Energy density	Proportionally weighted sum of average component energy density from the literature multiplied by the relaxed density		adapted from Table 2, [50]
Water absorption	Mass gained after soaking in water at room temperature	BS EN 772-21	[45]

Table 4: Feed material properties (averages of three measurements)

Raw feed sample	Rice husks	Corn cobs	Bagasse
Ash content (% dry mass)	19.6	4.1	3.0
Moisture content (% undried mass)	7.0	6.8	8.1
Specific gravity	1.50	1.46	1.38
Bulk density (undried mass, kg/m^3)	354	278	173
Porosity (% of uncompacted volume)	76	81	87
Water absorption (% dried mass)	160	289	90
(% saturation of porosity)	109	251	4
(% volume change)	29	40	20
Particle size (mm)	<2	<1.6	<1.6

ND = not determined

Table 5: Briquette densities and strengths measured in a factorial design experiment to study effects of material ratio, binder content and compaction pressure

Run	VARIABLES							RESPONSES*							
	Material ratio (M) (% dry mass in blend**)		Binder (B) (% dry mass added to blend**)				Pressure (P) (MPa)	Unit Green Density (kg/m^3)		Unit Relaxed Density (kg/m^3)		Compressive Strength (kPa)		Energy Density (kJ/m^3)	
	rice husks	corn cobs	starch	biosolids	algae	water		Average	SD	Average	SD	Average	SD	Average	SD
1-1	40%	40%	6%	0%	0%	11%	19	752	24	470	14	125	12	1175	7
2-1	25%	65%	6%	0%	0%	11%	19	714	37	489	30	119	10	1164	9
3-1	40%	40%	6%	0%	0%	11%	31	782	12	465	25	102	6	1175	7
4-1	25%	65%	6%	0%	0%	11%	31	858	6	515	20	155	13	1164	9
1-2	40%	40%	6%	0%	0%	11%	19	722	16	463	8	118	14	1169	4
2-2	25%	65%	6%	0%	0%	11%	19	698	23	491	10	104	17	1162	9
3-2	40%	40%	6%	0%	0%	11%	31	779	11	470	21	121	6	1169	4
4-2	25%	65%	6%	0%	0%	11%	31	840	4	503	19	159	23	1162	9
5	40%	40%	0%	6%	0%	11%	19	759	19	520	20	94	7	1196	5
6	25%	65%	0%	6%	0%	11%	19	796	29	500	30	101	8	1185	12
7	40%	40%	0%	6%	0%	11%	31	759	29	463	27	70	15	1196	5
8	25%	65%	0%	6%	0%	11%	31	859	21	577	20	146	27	1185	12
9	40%	40%	0%	0%	6%	11%	19	822	17	473	21	124	21	1247	5
10	25%	65%	0%	0%	6%	11%	19	809	36	544	40	150	13	1237	6
11	40%	40%	0%	0%	6%	11%	31	836	13	502	32	137	15	1247	5
12	25%	65%	0%	0%	6%	11%	31	826	46	571	37	175	31	1237	6

* Average of three responses; SD is standard deviation

** Blend is rice husks/corn cobs/bagasse without binder; % of bagasse in blend can be obtained by subtraction of the sum of the % masses of rice husks and corn cobs from 100%.

Table 6: Probabilities that effects are attributable to random error based on analysis of variance

Factor	**Green density**		**Relaxed density**		**Compressive strength**	
	Effect (kg/m^3)	**Probability, *p***	**Effect (kg/m^3)**	**Probability, *p***	**Effect (kPa)**	**Probability, *p***
M	24	0.07	45	0.001	27	0.001
P	58	0.001	15	0.06	16	0.06
B	40	0.02	35	0.035	35	0.001
M*P	33	0.01	21	0.04	24	0.001
M*B	-17	0.055	13	0.57	10	0.38
P*B	-35	0.05	5	0.21	12	0.66
M*P*B	5	0.19	12	0.056	-4	0.1

Shading indicates statistically significant effects, $p<0.05$