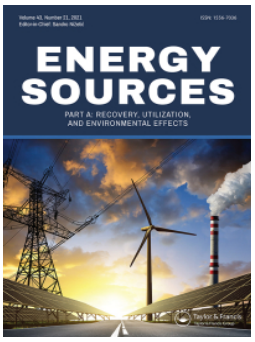

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Briquetting as a means of recovering energy from organic market waste

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ABSTRACT

Municipal Solid Waste is causing pollution and health hazards in cities around the world. In Kenya, existing and emerging cities are experiencing increased populations with increase in organic market waste. Organic market wastes can be used to produce briquettes. This study aimed to formulate available organic market waste into briquettes of optimal energy or calorific value. The study used locally fabricated technologies such as manual screw press, ram-piston and using bare human hands. Taguchi method was used based on controllable factors: Ratio of raw material; percentage (%) of binder; Size of raw material and method of production. Out of nine (9) experiments, laboratory results showed that the sixth (6th) and ninth (9th) formulations yielded briquettes with high calorific value of 20,540 kJ/kg and 18,962 kJ/kg, respectively. A further confirmatory experimental test was carried out based on Qualitek-4 software optimal simulated conditions. The test revealed that a mixture of carbonized market waste of particle size 2–5 mm; ratio of one part charcoal dust, two parts sawdust, and one part maize stover; with 30% of binder made using manual ram piston yielded briquettes of high calorific value of 21,633 kJ/kg against Qualitek-4 simulated value of 21,771 kJ/kg. In addition, Greenhouse gases evolved: CO and $PM_{2.5}$ concentrations are within World Health Organization (WHO) and Kenya Subsidiary Legislation on critical limits allowable for human exposure. These indicates that organic market waste can be used to produce briquettes with acceptable quality using locally available technologies.

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Market waste; briquettes; taguchi; kibuye; kisumu; calorific value

Introduction

Globally, organic market waste is increasing day by day (Raharjo et al. 2018). To address this menace, a sustainable approach for turning organic market ‘waste’ into a ‘resource’ in the form of alternative fuel can be employed. Recovering energy from organic market waste will subsequently help address other cross-cutting issues in current and upcoming cities in terms of ensuring: efficiency in market waste collection and disposal; production of quality briquettes of high calorific value with zero or minimal evolution of greenhouse gases, among others. Furthermore, this will enable cities meet Sustainable Development Goals (SDGs) namely: reduction of adverse per capita environmental impact of cities/towns by paying attention to air quality and municipal waste management (Vaidya and Chatterji 2020); substantial reduction in number of deaths and illnesses from hazardous chemicals and air, water and soil pollution and/or contamination (Federico 2020).

Organic market waste from Kibuye Market, largest market in East and Central Africa, is partly collected by County and private stakeholders for final disposal (Ngusale and Oloko 2018). A large

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share of organic market waste is strewn all over and/or openly burnt within the market area or surrounding environs. This not only pollutes the environment but also forms a breeding ground of disease causing organisms such as mosquitoes and rodents. In addition, haphazard deposited organic market waste blocks drainage systems thus causing floods during rainy season. Therefore, turning organic market waste into sustainable fuel briquettes will enable local cities and/or countries comply with international treaties on sound waste management practices. Fuel briquettes are common alternative fuel currently in use in many jurisdictions in Kenya (Ngusale et al., 2014). This is as a result of studies showing that fuel briquettes made from certain organic waste formulations (derived from markets, households, institutions, among others) have appealing properties namely: low greenhouse gas, low production cost and readily availability (Ngusale et al. 2017). However, for effective utilization of organic market waste, optimal choice of briquette parameter formulations must be ascertained. This study majorly focused on calorific value as the performance parameter. Taguchi approach was used to determine least possible number of tests required for optimal performance parameter of fuel briquettes produced. Several research studies have been conducted on fuel briquettes made from organic waste fractions. For instance, Chou et al. analyzed optimum conditions using Taguchi method for preparing solid fuel briquette of rice straw by a piston-mold process and found that the size of smashed rice straw is the most influential factor to solidify fuel briquette (Chou et al. 2009a). Žandeckis et al. evaluated combustion performance and its association to the analysis of the quality of different types of herbaceous-based briquettes mixed with wood and deduced that some types of non-wood biomass have a positive effect on briquette production and the combustion processes (Žandeckis et al. 2014). Yank et al. developed a low cost system to produce biomass briquettes from rice husks in the context of a rural village and found that briquette formulation (type of binder, binder content, water addition, and bran content) did not significantly influence the calorific value (Yank, Ngadi, and Kok 2016). Sen et al. investigated influence of binders on physical properties of fuel briquettes produced from cassava rhizome waste and found that briquettes produced from cassava rhizome charcoal with molasses, starch gel and concentrated slop as binders in proportion of 6:4 and 7:3 yielded higher calorific values from 21,670 to 24,367 kJ/kg, respectively (Sen, Wiwatpanyaporn, and Annachhatre 2016). Rahaman et al. investigated the effect of particle size, pressure and mold diameter on the physical characteristics of rice straw briquettes and found that the use of sawdust as binding material at 3:1 and 1:1 mixing ratios increased heating value by 6–7.2%, respectively. (Rahaman and Salam 2017). Jha et al. investigated optimization of binder for improving strength and shatter index of briquettes using design of experiments and deduced that they are dependent on agglomeration technique (Jha and Dutta 2019). The references highlighted focused solely on briquettes made from organic waste with influence from either technology or binder used. A study on optimizing various parameters while using different organic market waste ratios to produce briquettes is lacking. More so, locality of where the organic waste fractions are derived is not explicitly mentioned e.g. market, households or institutions. Besides, an overall study on using Taguchi approach to ascertain calorific value from different formulations of organic market waste has not been undertaken. Taguchi approach was used as is a structured approach for determining the 'best' combination of inputs to produce a product (Athreya and Venkatesh 2012). Basically, Taguchi approach analyzes the best trend with fewer experimental data. Therefore, using Taguchi, this study elucidated the 'best' optimal conditions for preparing fuel briquettes from three mostly readily available organic market waste: sawdust; charcoal dust and maize stover. A confirmatory experimental test was carried out based on elucidated optimal conditions in Qualitek-4 software.

Materials and Methods

(1) Study site

The experiment was carried out in Kibuye at Kibuye demonstration site, Kisumu located between latitude 00°02‟N and 00°11‟S and longitude 34°35‟E and 34°55‟E.

(2) Materials used to make briquettes

The materials consisted of organic market waste (obtained from Kibuye market) such as maize stover, sawdust and charcoal dust. These materials were selected based on their relative abundance in the market. Molasses used as a binder was sourced from Kibos sugar factory in Kisumu.

(3) Material preparation

The three main organic market waste materials were collected from Kibuye market and taken to Kibuye demonstration site for pre-sorting. This entailed removing plastics, stones and other unwanted materials that could contaminate or compromise quality of specific market waste. Sorted waste were then dried and placed in labeled sacks for easier identification and avoid confusion. Thereafter, specific labeled sacks were weighed to ascertain the amounts prior to carbonization (carbonization was specifically carried out on uncarbonized market waste).

The uncarbonized waste fractions were therefore carbonized in a home-made updraft kiln shown in Figure 1. Recovery rates for carbonized waste fractions were: 60 kg of dry saw dust yielded 22 kg of carbonized materials while 75 kg of dry maize stover yielded 28 kg of carbonized materials as shown in Table 3.

The three specific market waste sieved with mesh of sievers of varying diameters: less than 2 mm, 2–5 mm and 5–10 mm are shown in Figure 5. The sieved components of varying diameters were placed in specific labeled sacks for easier identification. Molasses binder was prepared at different concentration of 10%, 20% and 30% as per ratio of market waste formulation. For example for every 10% or 20% or 30% of required binder, 4 kg of waste were used (4 kg was based on number of experiments to be done). Binders were required to supplement lignin in order to pelletize/solidify non-woody feedstock (Tumuluru, Conner, and Hoover 2016). Pre-weighed amounts of market waste used are shown in Table 3. Thereafter, market waste formulation and molasses binder were carefully mixed to obtain a paste and then placed in locally fabricated briquette machine shown in Figure 2. These two locally fabricated technologies include: manual screw press and manual ram-piston press. Details on principle of operation of the machines are supplied elsewhere (Ngusale et al., 2014). Briquettes made using machines in Figure 2 were sun dried for 3–5 days. The drying period was influenced by prevailing weather condition, shape and size of briquettes.

(4) Experimental design

Taguchi method was adopted in this study to optimize design parameters so as to significantly minimize overall testing time and experimental costs (Davis and John 2018). Using orthogonal array specially designed for Taguchi method, optimum experimental conditions were easily determined. The study considered four controllable factors, each having three levels as shown in the Table

Figure 1. Updraft carbon kiln and carbonized market waste.

Figure 2. Manual screw press and its overhanging screw shaft (left) and ram-piston press (right).

Table 1. Controllable factors and their levels.

Factor	Description	Level 1 (CD:C-SD:C-MS)	Level 2 (CD:C-SD:C-MS)	Level 3 (CD:C-SD:C-MS)
1	Ratio of raw material	2:1:1	1:2:1	1:1:2
2	% of binder used	10%	20%	30%
3	Size of raw material used	<2 mm	2–5 mm	5–10 mm
4	Method of production	Manual Screw press	Manual ram piston	Hand-made

Table 2. Test conditions.

Test/condions	Ratio of raw material (CD:C-SD:C-MS)	% of binder used	Size of raw material used	Method of production
1	2:1:1	10%	<2 mm	Manual Screw press
2	2:1:1	20%	2–5 mm	Manual ram piston
3	2:1:1	30%	5–10 mm	Hand-made
4	1:2:1	10%	2–5 mm	Hand-made
5	1:2:1	20%	5–10 mm	Manual Screw press
6	1:2:1	30%	<2 mm	Manual ram piston
7	1:1:2	10%	5–10 mm	Manual ram piston
8	1:1:2	20%	<2 mm	Hand-made
9	1:1:2	30%	2–5 mm	Manual Screw press
10 (Confirmatory)	1:2:1	30%	2–5 mm	Manual ram piston

1. An L-9 (3^4) orthogonal array capturing different test conditions is illustrated in Table 2. The arrays are highly fractional orthogonal designs used to estimate main effects using a few experimental runs. It is important to note that carbonized raw materials were used in the following ratios: level 1 (2 parts of charcoal dust (CD): 1 part of carbonized saw dust (C-SD): 1 part of carbonized maize stover (C-MS)); level 2 (1 part of CD: 2 parts of C-SD: 1 part of C-MS) and level 3 (1 part of CD: 1 part of C-SD: 2 parts of C-MS).

(5) Analysis of briquettes made

Taguchi method entails analyzing the best trend with fewer experimental data to optimize a process or experiment. Therefore, an analysis of signal-to-noise (*S*/*N*) ratio is needed to evaluate experimental results or processes. Three types of *S*/*N* ratio analysis are applicable: (1) lower is better (LB), (2) nominal

Table 3. Three main market waste, recovery rates after carbonization and amounts used for briquetting.

Collected Materials	Raw materials (kg)	Recovery after Carbonization (kg)	Recovery after sieving		Used for briquetting	
			Size (mm)	Weight (kg)	Size (mm)	Weight (kg)
Charcoal dust	120	Already carbonized	< 2	14	< 2	4
			2–5	8	2–5	4
			5–10	8	5–10	4
Sawdust	60	22	< 2	10	< 2	4
			2–5	5	2–5	4
			5–10	4	5–10	4
Maize cobs stover	75	28	< 2	6	< 2	4
			2–5	5	2–5	4
			5–10	5	5–10	4

is best (NB), (3) higher is better (HB) (Chou et al. 2009b). Main target of this study being to maximize calorific value of solid fuel briquette, S/N ratio with HB characteristics was required, which is given by,

$$\frac{S}{N} = -10\log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{Y_i^2}\right) \tag{1}$$

Where, n is the number of repetitions under the same experimental conditions, and Y represents the result of measurement, e.g. Y is calorific value of solid fuel briquette.

A simulation was carried out on obtained calorific values (1–9) in Qualitek-4 application. Basically, Qualitek-4 application automatically designs experiments based on user-indicated factors and levels. Simulation analysis can be performed using standard or signal-to-noise ratios of results. This study aimed to optimize test conditions to S/N ratio of optimal calorific ratio (also known as 'large is best'). The obtained optimal conditions were then used to produce briquettes whose calorific value was measured using a bomb calorimeter.

Further emissions performance tests (based on water boiling test protocol version 4.2.3) were carried out on briquettes produced at optimal conditions in a LEMS hood system assembly at KIRDI as shown in Figure 3. Briquette samples to be tested were put in a standard Kenya Ceramic Jiko (KCJ), shown in Figure 4. This 'Jiko' was used as common utility end-use device in most households in Kenya (Silk et al. 2012).

Results and Discussion

(1) Taguchi method used to produce briquettes

The manual screw press and ram-piston machines produced briquettes of cylindrical and rectangular shapes, respectively. Hand-molded briquettes were circular in shape as they took mold shape of palms when molding. Every batch of made briquettes was solely based on 4 kg of specific market waste of specific size plus standard binder required. Made briquettes were then dried in open sunshine on specially made drying racks as shown in Figure 6.

In Table 4 the HB for calorific value as per equation 1 is the 6th experiment with calorific value of 20,540 kJ/kg followed by the 9th experiment with 18,962 kJ/kg. A confirmatory experimental test (10th experiment) carried out based on simulated optimal conditions in Qualitek-4 software yielded an optimal calorific value of 21,633 kJ/kg, against Qualitek-4 simulated value of 21,771 kJ/kg. Substitution of experimental repetitions and results into equation 1 was not necessary given the importance of calorific value as earlier mentioned.

(2) Analysis of briquettes made

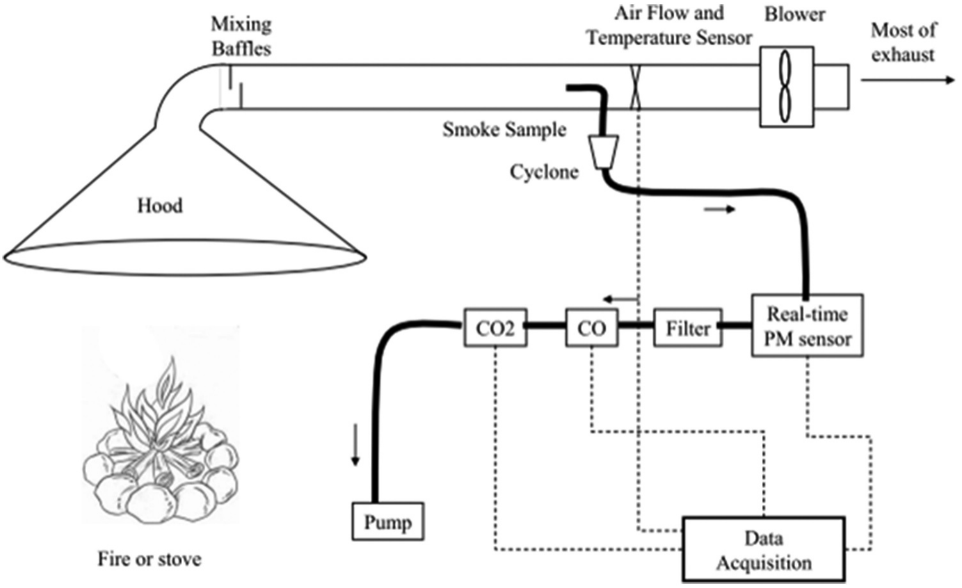

Figure 3. Laboratory Emissions Monitoring System (LEMS) Hood system. Adapted from Aprovecho (Aprovecho Research Center, 2013).

Figure 4. Standard Kenya Ceramic 'Jiko'.

For briquettes to be commercialized, the minimum calorific value threshold is at least 17,500 kJ/kg (Sindhu et al. 2017). Experimental compositions 2, 4, 5, 6, 9 and confirmatory test surpasses this threshold, with experiments 6 and 9 yielding high calorific value of 20,540 kJ/kg and 18,962 kJ/kg, respectively, as shown in Figure 7. This implies that most of the briquettes formulations made can be commercially used for making an alternative source of fuel of acceptable quality. Individual calorific value for CD is between 28,000 and 30,000 kJ/kg while C-SD is between 23,000 and 24,000 kJ/kg

Figure 5. Specific market waste against different sievers.

Figure 6. Different shapes of briquettes made from different waste compositions.

(Rotich 1998). Calorific value for C-MS is 20,910 kJ/kg (Sriprasoed, Patikarnmonthon, and Kamwilaisak 2016). However, these individual calorific values do not influence optimal calorific value yielded as depicted in experiments 6 and 9. For instance, experiment 6 was formulated on 1:2:1 (CD: C-SD: C-MS, respectively) while experiment 9 was formulated on 1:1:2 (CD: C-SD: C-MS, respectively).

Also, most briquettes made attained acceptable operating moisture content of 8–12% as depicted in Figure 8. Confirmatory test yields an optimal calorific value of 21,633 kJ/kg with higher fixed carbon of

Table 4. Experimental data of analyzed briquettes.

Experiment No.	Moisture Content ($\%^{w}/_{w}$)	Volatile matter ($\%^{w}/_{w}$)	Total ash content ($\%^{w}/_{w}$)	Fixed carbon ($\%^{w}/_{w}$)	Calorific value (kJ/kg)	Sulfur	Bulk density (g/cm^3)
1st	7.19	43.96	27.33	21.52	15,721	0.45	0.69
2nd	8.80	32.44	17.35	41.41	18,133	0.42	0.88
3rd	8.52	39.69	16.98	34.81	17,024	0.56	0.91
4th	7.67	36.47	14.06	41.80	18,137	0.29	0.73
5th	8.14	64.73	16.17	10.97	17,568	0.23	0.65
6th	8.65	59.31	21.66	10.38	20,540	0.26	0.68
7th	9.11	38.13	12.88	39.88	16,885	0.58	0.62
8th	7.37	41.98	23.63	27.02	15,227	0.41	0.97
9th	8.59	35.76	13.66	42.00	18,962	0.30	0.67
10th	(Confirmatory)	5.6	29.10	14.53	52.95		21,633
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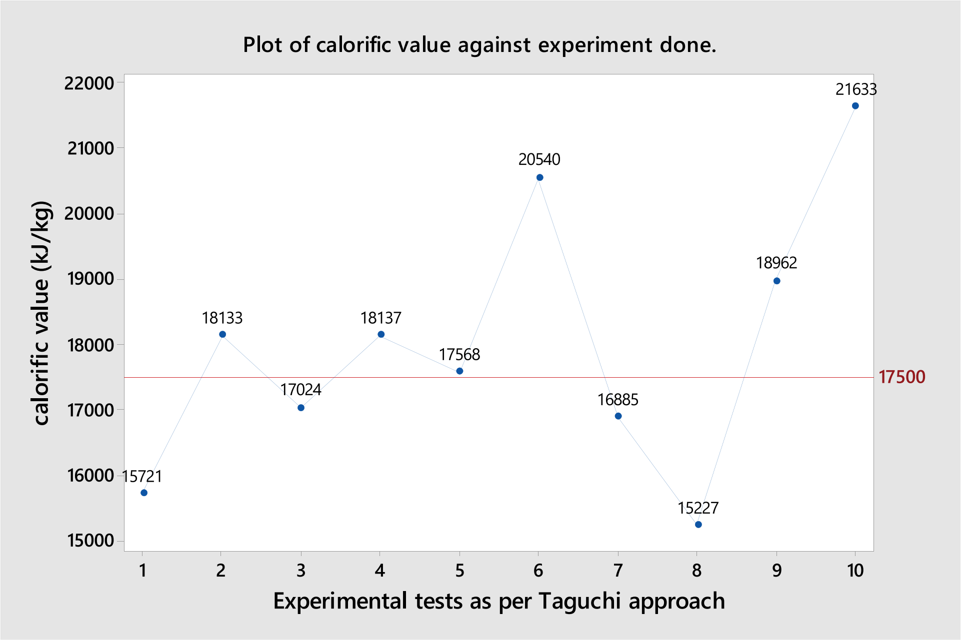

Figure 7. Calorific values of nine experiments carried out.

52.95%, lower volatile matter of 29.10% and lower ash content of 5.6%. This is in agreement with a study that ascertained a good and efficient fuel briquette depends on high fixed carbon, low volatile matter and low moisture content (Asamoah et al. 2016).

Molasses was used as a binder given its ready availability in Kisumu. Besides, a research shows that briquettes bonded with molasses exhibit better combustion characteristics (Chirchir, Nyaanga, and Githeko 2013). However, this study does not agree with previous studies that the lower the binder ratio, the better the briquette and an increase in binder content decreases calorific value (Chirchir, Nyaanga, and Githeko 2013; Piboon, Tippayawong, and Wongsiriamnuay 2017). For instance, Chirchir, Nyaanga, and Githeko (2013) deduces that the calorific value for a composite briquette (rice husk, bagasse and charcoal dust) decreases from 26,800 to 25,200 kJ/kg with increase of molasses binder from 10% to 25%, respectively. Piboon, Tippayawong, and Wongsiriamnuay (2017), used locally available algae for densification of corncobs and found that using algae at 20% or less improved the energy density of densified corncobs. As illustrated in Figure 9, experiments 1, 2 and 3 with a binder of 10%, 20% and 30% yields calorific values of 15,721, 18,133 and 17,024 kJ/kg,

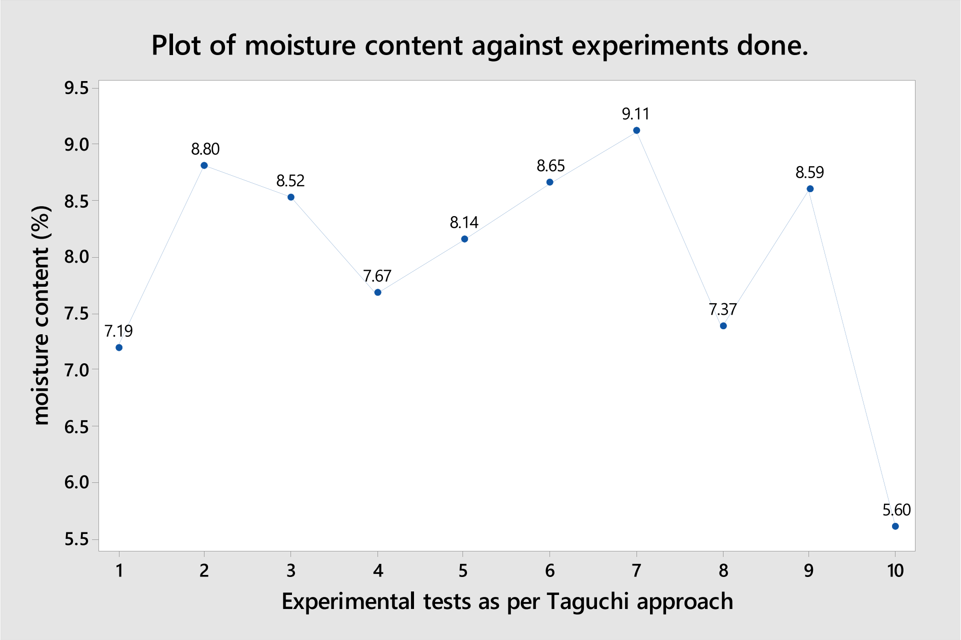

Figure 8. Moisture contents of nine different briquettes made.

respectively. In comparison to experiments 4, 5 and 6 with calorific values of 18,137, 17,568 and 20,540 kJ/kg, respectively. This implies that for every briquette produced several factors influence final calorific value, binder content notwithstanding. Regarding experiments 6 and 9 with calorific values of 20,540 and 18,962 kJ/kg, respectively, the following can be deduced: ratio of raw material compositions differs (one part of CD: two parts of C-SD: one part of C-MS vis-a-viz one part of CD: one part of C-SD: two parts of C-MS, respectively); size of raw materials used differs (less than 2 mm vis-a-viz 2–5 mm, respectively) and technology used differs (manual ram-piston vis-a-viz manual screw-press machine, respectively). Regarding the ratio of raw materials used, a study shows that wood-derived wastes have high volatile materials while agro-based derived wastes have low volatile materials (Falemara et al. 2018). Experiments 1–6 were formulated with blends of charcoal dust and sawdust of high proportions (wood waste) compared to experiments 7–9 whose high proportion was maize stover (agro-wastes). Thus experiments 1–6 exhibit high volatile matter ranging from 32.44% to 64.73% while experiments 7–9 exhibit low volatile matter ranging from 35.76% to 41.98%. However, a blend of raw materials in the confirmatory test appears to neutralize the effect of high and low volatile matter yielding lowest volatile matter of 29.10%. Low volatile matter is significant as it translates to low amounts of evolved emissions during burning (Falemara et al. 2018). Also, the blend in the confirmatory test considerably reduces ash content to 5.6%, thus reducing the amount of heating value required for combustion (Sotannde, Oluyege, and Abah 2010). Low ash content indicate good quality briquettes (Grover and Mishra 1996). On the other hand, briquettes with high ash contents evolves high dust emissions, affects combustion volume and even efficiency of combustion (Katimbo et al. 2014).

Furthermore, there appears to be no relationship between calorific value vis-a-viz bulk densities as shown in Figure 10. Experiments 1, 2 and 3 slightly brings out a direct proportionate increase of calorific value with bulk density. However, experiments 7, 8 and 9 bring out an indirect relationship whereby as calorific value increases, the bulk density decreases.

The study further shows an indirect relationship between volatile matter and calorific value. However, this relationship is violated at experiments 6 and 7 as shown in Figure 11. Furthermore,

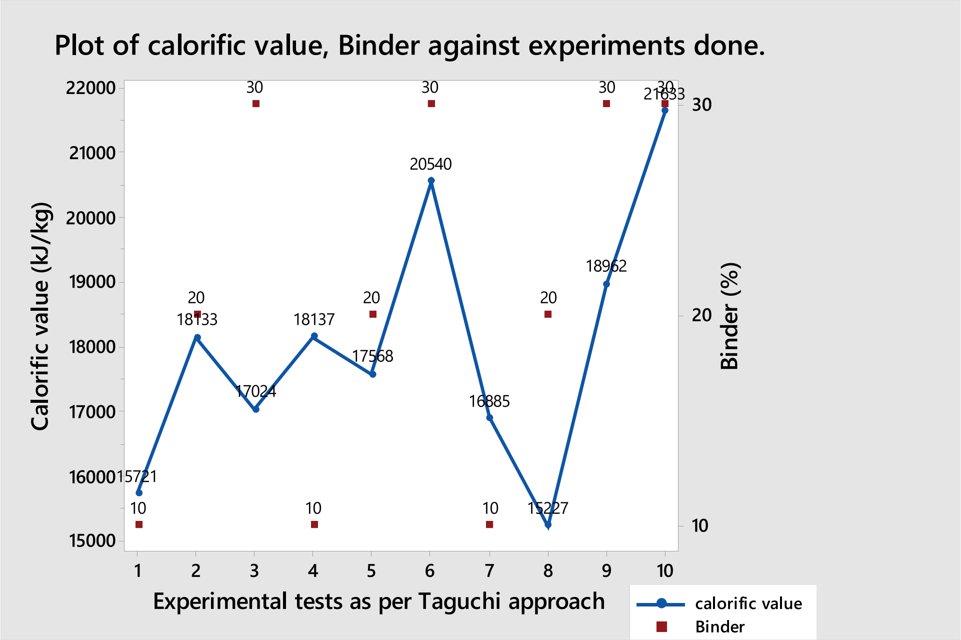

Figure 9. Relationship between calorific value and binder against nine experiments carried out.

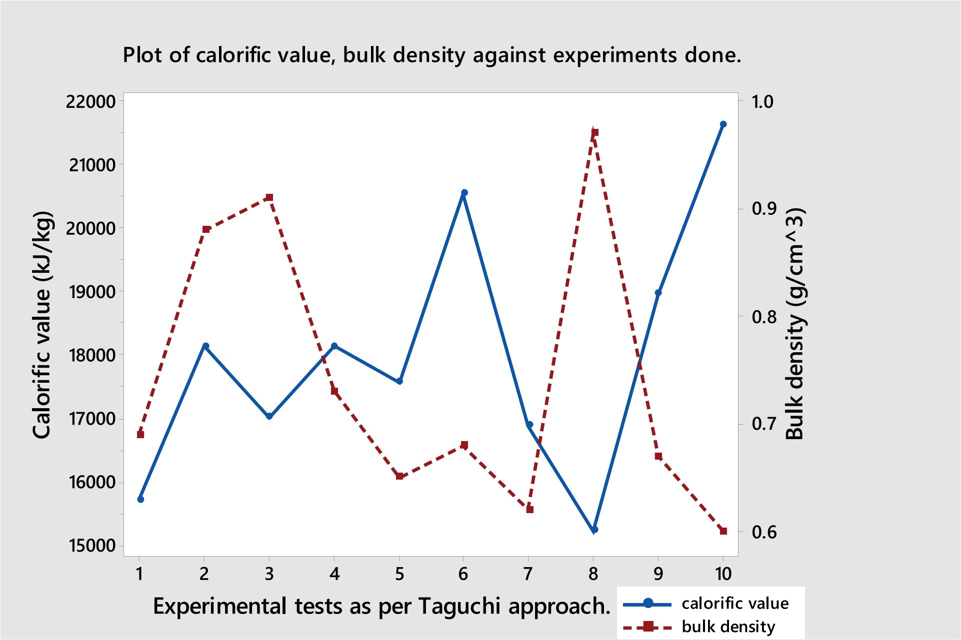

Figure 10. Relationship between calorific value and bulk density against nine experiments carried out.

fixed carbon is directly proportional to calorific value, however, this relationship is violated between experiments 5, 6 and 7. From Figure 11, between experiments 4 and 5, there are drastic rises and drops of volatile matter and fixed carbon, respectively. For these, the changes could be attributed to increase in binder usage from 10% to 20% for experiments 4 and 5, respectively. Also, a drop in bulk density

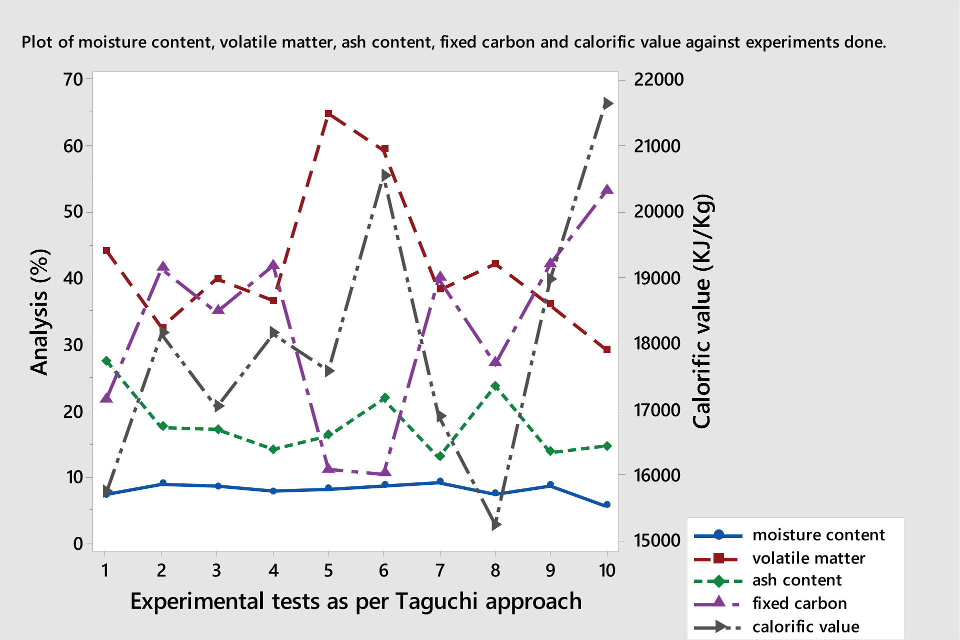

Figure 11. Interaction between moisture content, volatile matter, ash content, fixed carbon and calorific value against experiments done.

from 0.73 to 0.65 g/cm^3, respectively. Size of raw materials for experiment 4 (2–5 mm) and 5 (5–10 mm) could also influence these changes.

Similarly, drastic drops and rises of volatile matter and fixed carbon, respectively, can be seen between experiments 6 and 7. For these, the changes could be attributed to decrease in binder usage from 30% to 10% for experiments 6 and 7, respectively. Also, a drop in bulk density from 0.68 to 0.62 g/cm^3, respectively. The size of raw materials for experiment 6 (less than 2 mm) and 7 (5–10 mm) could also influence these changes.

Given the similarities in two cases: increase in binder usage for 4 to 5 and a decrease in binder usage for 6 to 7, then can deduce that these changes are as a result of binder usage. Also, changes in the size of raw materials between the two cases can attribute to drastic drops and increases. Bulk density appears to have no influence given its continued drop in the two cases.

Another key observation, ash content is indirectly proportional to calorific value content. This affirms previous researches on coal fuel that as ash content increases, calorific value decreases (Yuliza, Nazir, and Djalal 2013).

The technology used for manually producing briquettes has no great influence on calorific value as shown in Figure 12. However, this study shows that certain raw material formulations work best with specific technologies for better calorific values. This refutes previous studies that high compaction pressures result in briquettes of high calorific values. Probably, high pressures improve on handling characteristics of solid briquettes.

(3) Confirmatory test at optimal condition

A simulation test done in Qualitek-4 to ascertain expected calorific value at optimum conditions yielded 21,771 kJ/kg. This calorific value could be realized at the following conditions: Ratio of raw materials – 1:2:1 (1 part of CD: 2 parts of C-SD: 1 part of C-MS); Percentage binder – 30%; Size of raw materials – 2-5 mm; Method of production – ram-piston, as depicted in Table 5.

A confirmatory experiment done based on optimal conditions in Table 5, yielded a calorific value of 21,633 kJ/kg. This proved the value obtained in Qualitek-4 at optimal conditions of 21,771 kJ/kg. Also, obtained proximate analysis test results conform to local national standards. For confirmatory,

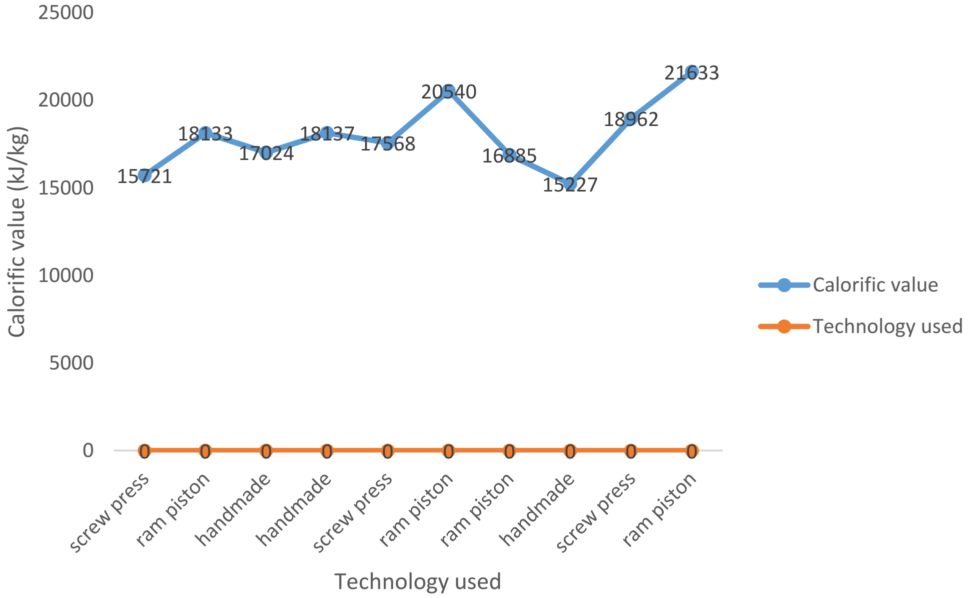

Figure 12. Influence of technology used on calorific value of briquette produced.

moisture content (5.6%); volatile matter (27.1%); ash content (14.53%); fixed carbon (52.95%). Local national standards, moisture content (≤10%); volatile matter (≤25%); ash content (≤27%); fixed carbon (≥44%).

Experimental tests to ascertain greenhouse gas emissions evolved while utilizing briquettes (obtained at these optimum conditions) in standard KCJ at the household level yielded data shown in Table 6. Emissions from both KCJ and chimney were captured through LEMS system (shown in Figure 3) to ascertain total emissions. This entailed real-time data collection using the hood method as is highly recommended in providing sufficient data for field measurements (EPA, PCIA, A 2013). Based on the protocol used, the most important pollutants to measure are carbon monoxide (CO) and particulate matter (PM) due to their short and long-term health effects (EPA, PCIA, A 2013). As previously highlighted herein, low volatile matter content in the optimally produced briquettes should emit low or minimum levels of pollutant as depicted in Table 6.

Indoor air pollution (mostly occasioned by burning of solid fuels) was vital in this study as it is a leading cause of health-related complications and even death (World Health Organization 2015). For $PM_{2.5}$, WHO allows human exposure limit of 25 μm/m^3 (25 ppm or 25 mg/L) for 24 hours (World Health Organization 2015). From Table 6, $PM_{2.5}$ to simmer falls within WHO critical limit implying that meals/foods requiring simmering would best utilize these briquettes in KCJ without compromising human health. This is quite significant for cereal and/or leguminous meals that require long periods of cooking like ‘githeri’ or mixture of maize and beans which are common traditional meals in Kenya (De Groote and Kimenju 2008). However, Kenya Subsidiary Legislation does not highlight critical for human exposure at residential level, it only provides for human exposure limit for 24 hours of 75 μm/m^3 in industry (Government of Kenya 2014).

Table 5. Optimal conditions for optimal calorific value.

Factor	Level of description	Level	Contribution
Ratio of raw materials	1:2:1	2	0.279
Percentage of binder	30%	3	0.301
Size of raw materials	2–5 mm	2	0.198
Method of production	Ram piston	2	0.224

Table 6. Total emissions evolved while utilizing briquettes made at optimal condition in a kitchen set-up.

Cooking Emissions	Units	Test 1	Test 2	Test 3
CO TO BOIL	mg/L	9.99	10.11	10.42
CO To Simmer	mg/L	10.62	10.70	7.48
CO TO COOK	mg/L	20.61	20.81	17.89
PM2.5 To Boil	mg/L	57.67	69.31	32.68
PM2.5 to Simmer	mg/L	15.88	18.53	10.94
PM2.5 to Cook	mg/L	73.55	87.85	43.63
Average CO/CO2 Ratio for Boil	%	16.6%	17.0%	16.3%
CO/CO2 Ratio for Simmer	%	15.0%	13.5%	12.0%

For CO, WHO allows a critical limit of human exposure of 30 ppm (30 mg/L) for one hour (World Health Organization 2015). Obtained CO concentrations in Table 6 based on average time limit of 34 minutes (standard deviation of 2.0) show that these briquettes evolve lower levels of CO.

Potential challenges and possible solutions for commercializing briquettes made from market waste include:

1. Availability and affordability of molasses binder mainly sourced from sugar factories situated within Kisumu – at times price per liter is expensive discouraging local upcoming briquette users from using it. A previous study indicated that most producers use clay soil as a binder whose inertness makes produced briquettes very smoky (Ngusale et al., 2014). Affordability of alternative clean fuels is clearly captured in SDG 7 and thus cheap binders such as starch can be explored as alternative to molasses (Franco, Power, and Whereat 2020).
2. Kenya as a country lacks specific standards on alternative fuels such as fuel briquettes (Ngusale et al., 2014). Taguchi approach could help in developing specific formulations for different waste materials in specific locality. For example, in this study the confirmatory experimental formulation (s) can serve as standard for preparing fuel briquettes from market waste within Kisumu region. This would ease briquette production of either skilled or unskilled producers in terms of attaining optimal performance parameter such as calorific value. This will contribute toward Kenya's government on achieving Big Four Agenda: improved innovation on product development as domiciled within the pillar of manufacturing (one of Big Four Agenda) (KAM 2018).
3. Lastly, Kenya has inadequate policy provision on uptake of fuel briquettes – policy mainly captures conventional energy sources plus renewable sources such as solar, wind, hydro, geothermal, biogas (MOEP, 2018). There is need for a clearly defined legal and regulatory framework on how fuel briquettes are to be produced and utilized at both local and commercial levels. The framework at national level can then be cascaded downwards to county and/or cities as anchored in the new constitution of Kenya (Republic of Kenya 2010).

Conclusion

The study demonstrates the feasibility of preparing briquettes from market waste given various compositions using Taguchi method. Results show that a mixture of carbonized market waste: of particle size 2–5 mm; ratio of one part charcoal dust, two parts sawdust and one part maize stover; with 30% of binder made using manual ram piston yields briquettes of high calorific value of 21,633 kJ/kg against Qualitek-4 simulated value of 21,771 kJ/kg. In addition, Greenhouse gases evolved: CO and $PM_{2.5}$ concentrations are within WHO and Kenya Subsidiary Legislation on critical limits allowable for human exposure. Therefore, this study affirms that market waste such as charcoal dust, maize stover and saw dust, when prepared and mixed in right proportions can commercially produce briquettes thus offering an alternative source of fuel to charcoal and/or fuelwood.

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