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1 author:

Sunil L. Narnaware
College of Agricultural Engineering & Post Harvest Technology (Central Agricultural University))

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Gasification: An alternative solution for energy recovery and utilization of vegetable market waste

Sunil L Narnaware[1], NSL Srivastava[1] and Samir Vahora[2]

Abstract

Vegetables waste is generally utilized through a bioconversion process or disposed of at municipal landfills, dumping sites or dumped on open land, emitting a foul odor and causing health hazards. The presents study deals with an alternative way to utilize solid vegetable waste through a thermochemical route such as briquetting and gasification for its energy recovery and subsequent power generation. Briquettes of 50 mm diameter were produced from four different types of vegetable waste. The bulk density of briquettes produced was increased 10 to 15 times higher than the density of the dried vegetable waste in loose form. The lower heating value (LHV) of the briquettes ranged from 10.26 MJ kg^{-1} to 16.60 MJ kg^{-1} depending on the type of vegetable waste. The gasification of the briquettes was carried out in an open core downdraft gasifier, which resulted in syngas with a calorific value of 4.71 MJ Nm^{-3} at the gasification temperature between 889°C and 1011°C. A spark ignition, internal combustion engine was run on syngas and could generate a maximum load up to 10 kW$_e$. The cold gas efficiency and the hot gas efficiency of the gasifier were measured at 74.11% and 79.87%, respectively. Energy recovery from the organic vegetable waste was possible through a thermochemical conversion route such as briquetting and subsequent gasification and recovery of the fuel for small-scale power generation.

Keywords

Vegetable market waste, briquettes, gasification, downdraft gasifier, syngas, power generation

Introduction

Waste generation, waste disposal and waste utilization for energy recovery have become foremost concerns in developed as well as developing countries. Waste to energy (WtE) is widely recognized as the process of generation of energy in the form of heat or electricity. The rise in urban population with its improved standards of living, in the absence of an effective management mechanism, contributed significantly to the rise in quantity and variety of solid waste generation. These wastes have heterogeneous compositions consisting of both biodegradable and non-biodegradable material. Organic biodegradable waste can be utilized for bio-energy production and this has received a worldwide acceptance as a waste disposal method while maintaining environmental integrity. Bioenergy is a promising, inexhaustible, sustainable source to cope with the global issues such as the deterioration of the environment and perennial escalating fuel prices and has been the motivation for a rise in the use of biomass fuels as a substitute for both space heating and electricity generation (Luque et al., 2008). In India, the biomass available is basically the waste generated from the agriculture, forest, municipal or different food processing industries. Vegetable and fruit waste is one of the major parts of such waste generated at different stages. Owing to its biodegradable nature, vegetable waste starts to decompose very fast, creating an environmental nuisance and a threat to human health.

India is the second largest producer of fruits and vegetables in the world, with a combined production of 251.86 Mt (88.97 Mt of fruits and 162.89 Mt of vegetables) during 2013–2014 as per Vision-2050 (Indian Institute of Horticultural Research, 2014). In the Indian horticulture sector, substantial pre- and post-harvest loss occurs at different stages of handling, transport, storage, processing and distribution of produce. About 60% to 70% of vegetables in India are sold by small retailers and farmers, which incurs about 25% losses. According to Agricultural Statistics at a Glance (Agricultural Statistics at a Glance-2010, 2010), during 2008–2009, India produced 69.453 Mt of fruits and 133.071 Mt of vegetables; out of which about 25–30% of fruits and vegetables were spoiled or wasted in handling, transport and in retailing. According to NAAS Policy Paper-49 (Agricultural Waste Management, 2010), out of the total production of 202.52 Mt of

[1]Thermochemical Conversion Division, Sardar Patel Renewable Energy Research Institute, Gujarat, India
[2]Bioconversion Divisions, Sardar Patel Renewable Energy Research Institute, Gujarat, India

Corresponding author:
Sunil L Narnaware, Thermochemical Conversion Division, Sardar Patel Renewable Energy Research Institute (SPRERI), Vallabh Vidyanagar 388 120, Gujarat, India.
Email: narnawaresunil@yahoo.com

fruits, vegetables and other horticultural crops in India in 2008–2009, the estimated availability for processing and was about 83.34 Mt, which was only 41.15% of total production. India, with rich agricultural resources, accounts for about 30% waste of its total production (Verma et al., 2011). Regarding the global scenario, the study suggests that roughly one-third of food produced for human consumption is lost or wasted, which amounts to about 1.3 billion tonnes year^{-1}. It is estimated that about 45% of the annual fruit and vegetable of global production is wasted (Food and Agriculture Organization, 2012) and have the highest wastage rates among any food products. Regarding food losses in developing countries, more than 40% loss occurs at post-harvest and processing levels, while in industrialized countries, almost the same losses occur at retail and consumer levels (Gustavsson et al., 2011).

Organic waste generated from the vegetables can be transformed into viable beneficial products, organic fertilizers and animal feed via bioconversion (Verma et al., 2011) and has been recognized as a valuable and lucrative energy resource (Lesteur et al., 2010; Yu and Huang, 2009). Vegetable waste, due to its high biodegradability nature (Viturtia et al., 1989) and high moisture content (75% to 90%), is considered as a good substrate for bio-energy recovery through anaerobic digestion and could be an appealing option in the future (Khalid et al., 2011). A major limitation of the anaerobic digestion of vegetable waste is the rapid acidification due to the lower pH of waste and the larger production of volatile fatty acids (VFA), which reduce the methanogenic activity of the reactor (Bouallagui et al., 2005). Also, the aerobic processes are not preferred for vegetable wastes because preliminary treatment is required to minimize organic loading rate (Landine et al., 1983). Vegetable waste is disposed of at municipal landfills or dumping sites (Srilatha et al., 1995) or also dumped on open land, emitting a foul odor and causing health hazards.

However, the feasible alternative option to deal with the solid vegetable waste is to convert it into high-density briquettes, which give flexibility in storage, transportation as well as the use as per requirement. Briquetting, in general, is a densification process of producing higher bulk density material from original material of low bulk density by compaction (McMullen et al., 2005; Obernberger and Thek, 2004). Bulky biomass is reduced to better volume to weight ratio by compressing in a die at high temperature and pressure. Densification can increase the bulk density of biomass from an initial bulk density of 40 kg m^{-3} to 200 kg m^{-3} to a final compact density of 600 kg m^{-3} to 1200 kg m^{-3} (Adapa et al., 2007; McMullen et al., 2005; Obernberger and Thek, 2004), improving its handling and storage characteristics, enhancing the volumetric calorific value and reducing transportation costs (Holm et al., 2006; Kaliyan et al., 2009). Briquetting of waste biomass can be done by bringing its moisture content to the specific level, pulverizing and mixing it with some kind of binder or by direct compacting. The adhesive properties of thermally softened lignin are considered to provide the binding effect to the briquettes made of lingo-cellulosic materials (Granada et al., 2002). Because of their uniform shape and size, the briquettes can be easily adopted in direct combustion or co-firing with coal, gasification, pyrolysis and in other biomass-based conversions (Kaliyan and Morey, 2009). One specific use of the briquettes is for gasification. Gasification, a thermochemical route of biomass conversion, is a highly efficient way to utilize biomass among other conversion routes. The operational flexibility and higher efficient conversion of biomass makes gasification useful for application for small- or medium-scale power generation. Gasification is the conversion of a fuel source into a gaseous product that can be used in heat, power or combined heat and power applications (Ouadi et al., 2013). Studies on gasification of different waste biomass briquettes in an open core downdraft gasifier such as jatropha seed husk briquettes (Singh et al., 2008), crop residue briquettes made from cotton stalk, pigeon pea, sugarcane, baggasse, saw dust briquettes (Pareek et al., 2012), biomass waste briquettes (Singh et al., 2007), groundnut shell briquettes (Bhoi et al., 2006) are a few examples. The open core downdraft gasifier has capability to operate on a wide range of fuels such as smaller sized wood pieces, coconut shell and agro residue briquettes. The system enables high conversion efficiency because of uniform air-flow distribution from the top as well as from nozzles. The uniform passage of air and fuel down the gasifier keeps local temperatures from becoming too high or too low while the average temperature is high. The cylindrical construction permits easy fuel feeding and continuous flow without causing bridging or channeling (Kaupp and Guass, 1984; Mukunda, 2011).

The present study focuses on the utilization and environment-friendly disposal of the vegetable waste generated at vegetable markets through the thermochemical conversion process. The vegetable waste is converted into environmental-friendly and low-cost briquettes without using any external binder, and furthermore they were used to test the feasibility of gasification of vegetable waste briquettes for power generation using an internal combustion engine.

Material and methods

Vegetable waste and production of briquettes

Four different types of vegetable waste were received from different sources such as city vegetable markets, directly from farmer's fields (where they used to throw away stems and leaves of cauliflower/cabbage) and the vegetable processing industry. Basically, most of the vegetable waste collected consisted of the left-over parts after the usable part was taken out. The type and the quantity of vegetable waste generation varied with the growing season. In total, 8 t of raw green vegetable waste consisting of four different types of vegetables, namely cauliflower (*Brassica oleracea)* and cabbage leaves (*Brassica oleraceaca*), coriander stalks and leaves (*coriandrum sativum)*, field beans (*dolichos lablab*) and green pea pods (*pisum sativum*) were collected. The physical condition of the vegetable

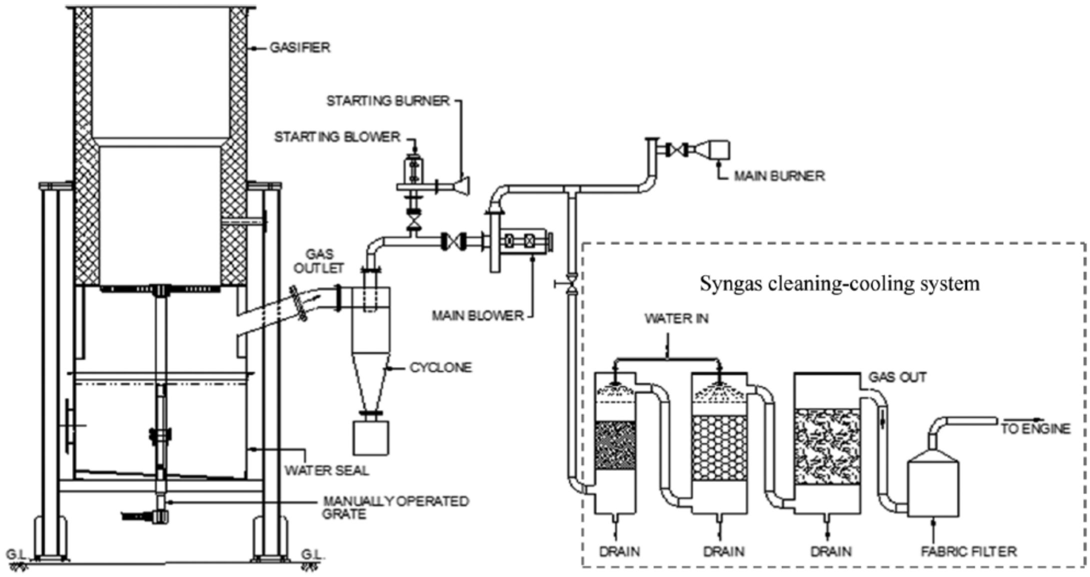

Figure 1. Schematics of gasifier and cleaning-cooling system.

waste was fairly clean and no further cleaning or segregation was required. The proximate analysis of the collected waste was conducted in the biomass laboratory of the Sardar Patel Renewable Energy Research Institute (SPRERI), while chemical compositions were determined at the Animal Nutrition Research Laboratory of the Anand Agricultural University, Anand (Gujarat).

Bulk density plays an important role in transportation and storage efficiency (Karunanithy et al., 2012) as well as influencing engineering design of transport equipment, storage and conversion processes (Woodcock and Mason, 1987). For briquetting, the feed material should have low moisture content and be in powder form. The collected vegetable waste had high initial moisture content and needed to be reduced below a suitable limit required for briquetting because the moisture percentage in the biomass feed is a critical factor to the briquetting machine. Generally, at 8% to 10% moisture content in the biomass feed, the briquettes will have 6% to 8% moisture and are strong and free of cracks, making the briquetting process smooth (Grover and Mishra, 1996). But when the moisture content exceeds more than 10%, the briquettes are poor and weak and the briquetting operation is erratic. So, to reduce the moisture content, the vegetable waste was spread on a polyethylene sheet and dried under the sun, as this is the cheapest drying method. The briquetting process requires size reduction for achieving proper compaction, strength and durability (Grover and Mishra, 1996). Therefore, the dried vegetable waste was ground using a hammer mill (7.5 kW) with 5 mm sieving screen. A commercially available piston-ram press (punch and die) type briquetting machine; of output capacity 500 kg h^{-1} (Hi-Tech Agro Project Pvt. Ltd, India), was used for producing briquettes of 50 mm diameter. The machine used a 22 kW three-phase electric motor. The briquettes were analyzed to determine physical properties such as bulk density and true density. The heating value of all four types of briquettes was determined using a bomb calorimeter (Scientronics Instruments, New Delhi, India). The compressive study of the production of briquettes from the vegetable market waste has been reported by Srivastava et al. (2014).

Gasification experiment

Gasification system. Figure 1 shows a schematic of an open core downdraft gasifier used for the gasification experiment of the vegetable briquettes as fuel. The gasifier system of capacity 50 kg h^{-1} was designed and developed by SPRERI for the gasification of fuel wood and agro residue briquettes. The gasifier was a cylindrical reactor shell fabricated from the mild steel and provided with the thermal insulation of the refractory cement (Insulyte 11) on the inner side to prevent the outer shell from heating and thermal deformation. The effective height of the reactor was 1.6 m starting from the grate to the open top. The effective internal diameter of the reactor was 0.63 m at the lower part, i.e. up to 0.80 m height from the grate, whereas the remaining upper part had an internal diameter of 0.80 m. The difference in the diameter was due to the thickness of the insulation provided based on the temperature profile of the different zones during operation. The lower part had an insulation thickness of 135 mm, whereas the upper part had a 50 mm thick insulation. A cast iron grate provided the support to the biomass and passage for syngas as well as removed the discharge (ash and charcoal) during operation. The grate area (0.273 m^2) was designed for the specific gasification rate (SGR= 180 kg h^{-1} m^{-2}) and fuel consumption rate (FCR = 50 kg h^{-1}). The gasification air was drawn from the air tuyers and open top with the help of an induced air blower operated in suction mode. Four air tuyers of 25 mm diameter were provided on the periphery of the reactor at a constant height of 0.443 m from the grate and placed at 90^{o} to each other. The fuel regime where the air was introduced through the air tuyers formed a partial oxidation zone which provided all the necessary heat energy required for other thermochemical processes such as reduction, pyrolysis and drying. The gasifier used two induced air blowers: a starting blower and a main blower for sequential operation of

Table 1. Specification of gasifier system, syngas engine and electrical generator.

System	Parameters	Description/ specification
Gasifier	Gasification concept	Downdraft open core
	Biomass consumption rate	50 kg h^{-1}
	Thermal input	850 MJ
	Thermal output	625 MJ h^{-1}
	Gas conditioning system	Packed bed scrubber, cloth filter
	Ash removal system	Manual
	Air feeding	Tuyers and open top
Engine	Type	4-stroke, spark ignition, natural aspirated
	Speed (RPM)	1500 (25 Hz)
	Number of cylinders	3
	Displacement	3308
	Bore × stroke	110 × 116
	Compression ratio	10:1
Generator	Output	24 kW
	Voltage	430
	Frequency	50 Hz

the gasifier. The start-up blower used for initial starting of the gasifier prevented the main blower from condensing the tar formed during initial start-up of the gasifier, thus reducing maintenance. When the temperature reached ⩾ 300°C; the operation of the gasifier switched to the main blower. A water seal tank of mild steel was provided at the bottom of the gasifier for collecting the discharge and simultaneously provided an air seal to the syngas passage. The discharge collected in the water tank was removed periodically. The specification of the gasifier system is given in Table 1.

Syngas cleaning-cooling system

It is of great importance that the syngas delivered to an engine must be free from dust and should contain the absolute minimum of corrosive constituents. Syngas generation in the gasification process is associated with the generation of impurities such as tar and solid particulate matter consisting of ash and carbon particles; generally carried with the gas stream. For power generation application, these impurities need to be eliminated to the specified limits before feeding into any combustion system. The gas quality for successful internal combustion (IC) engine operation has been postulated as 50 mg N m^{-3} for the particle and less than 100 mg N m^{-3} for the tar (Knoef and Koele, 2000). In the present experiment, the syngas cleaning-cooling system consisted of a hot gas cyclone; packed bed wet scrubber and fabric filter. At the initial stage of cleaning, the raw syngas was passed through the hot gas cyclone, which removes most of the coarser solid particles of ash and carbon from the hot gas stream. Later, it was introduced in the wet packed bed scrubbing system where it comes in direct contact with scrubbing water. Wet scrubbers have the ability to remove gaseous pollutant and solid particles while simultaneously cooling the gas, which makes them ideal for stationary engines (Kaupp and Gauss, 1984). The wet scrubber consisted of three cylindrical packed bed filter columns made of mild steel connected in series, as shown in Figure 1. The first and second cylindrical filter columns were filled with raschig rings (SS-304, Ø: 10 mm and L: 10 mm) and charcoal pieces as a packing material, respectively, and provided the water spray at the top. The purpose of the packing material is to break down the liquid flow into a film with a high surface area and to increase the contact surface area between the gas and water, which increase the cleaning efficiency. The third filter column was filled with coconut coir, which helped in adsorbing the moisture carried with cooled gas. The water drain at the bottom of the filter column helped in removing the water used during syngas scrubbing and prevented the filter columns from flooding. A safety filter (fabric filter) was connected inline after the third filter column to trap micro particles if any were carried along with the syngas. The design capacity of the system was suitable for 10 kW_e power generation systems.

Syngas engine

A natural gas, spark ignition IC engine was adapted to run on syngas and was directly coupled with an electric generator. The specifications of the syngas engine and generator are depicted in Table 1. After cleaning, cooling and premixing with air, the syngas was fed into the engine. The intake flow was monitored with the help of an inline connected pre-calibrated orifice meter and regulated with the help of the control valve. The electric resistive load bank was used to test the electrical power generated. Output voltage and current across three phase and frequency were measured.

Gasification experiment

The gasifier was operated according to the test procedure prescribed by Ministry of New and Renewable Energy (MNES, 2000). The major parameters monitored during the experiment

Table 2. Physical characteristics of vegetable waste at different stages.

Material	Green vegetable waste		Dry vegetable waste		
			Loose form		Powder form
	MC, % wb	Bulk density, kg m^{-3}	MC, % wb	Bulk density, kg m^{-3}	Bulk density, kg m^{-3}
Cauliflower/cabbage leaves	85	221	9.18	44.2	320
Coriander stalk & leaves	87	282	9.78	50.4	436
Field Beans	85	241	8.96	52.5	425
Green pea pods	70	188	9.00	60.0	400

were FCR, gas flow rate, calorific value and equivalence ratio (ER). Initially the gasifier was set to starting blower until the temperature of the exit syngas reached ⩾ 300°C; the operation of the gasifier then switched to main blower. The syngas from the main line was taken to the engine through a bypass line. The material was fed manually on an hourly basis from the open top. Ash accumulated on the grate was removed by rotating the grate at regular intervals depending on the pressure drop across the reactor bed. The temperature at various points inside the reactor at 525 mm and 1125 mm height from the grate, partial oxidation zone and gasifier outlet was measured using K-type (Chromel–Alumel) temperature sensors. The amount of the gasification air was measured with the help of the anemometer. The pressure drop of systems and subsystems was measured using a U-tube water manometer. The gas flow rate of the engine was measured using a pre-calibrated orifice meter. The quantity of the tar and solid particulate matter in the syngas before entering into the engine was measured with a field sampling device designed by IIT, Bombay. The volumetric composition of the different gases in the syngas was determined using gas chromatograph (NETLE, Baroda) and subsequently the calorific value was determined. The gas samples for analysis were collected at the gas outlet with the help of gas balloons.

Gasification efficiency

Thermal performance of the gasifier is defined by cold gas efficiency and hot gas efficiency. The cold-gas efficiency is the energy input over the potential energy output. If $M_f$kg of solid fuel is gasified to produce $M_g$kg of product gas with a calorific value of CV_g, considering LHV_f as the lower heating value (LHV) of the solid fuel, then the cold gas efficiency is expressed as

$$\eta_{\text{cg}} = \frac{M_g CV_g}{LHV_f M_f} \tag{1}$$

Considering the sensible heat of the hot gas into account, the hot gas efficiency, η_{hg}, can be defined as

$$\eta_{\text{hg}} = \frac{M_g CV_g + M_g C_p (T_h - T_c)}{LHV_f M_f} \tag{2}$$

where C_p is specific heat of syngas; T_f and T_c are the hot gas temperature and cold gas temperature of the syngas.

Results and discussion

Properties of vegetable waste

The raw green vegetable waste obtained from different sources had high initial moisture content (MC) in the range of 70–87% and bulk density in the range of 188 kg m^{-3}–282 kg m^{-3} respective of their types. After open sun dying, the initial moisture content was reduced to ⩽ 10%. About 1350 kg of dried material was obtained from the 8000 kg of green waste material. The bulk density of dried vegetable waste was as low as 44.2 kg m^{-3}, 50.4 kg m^{-3}, 52.5 kg m^{-3} and 60.0 kg m^{-3} for cauliflower/cabbage leaves, coriander stalk and leaves, field beans and green pea pods, respectively. The dried vegetable waste was pulverized into a powder form, which increased the bulk density substantially (7–8 fold) for each type of vegetable waste. The physical characteristics of the vegetable waste at different stages are shown in Table 2.

Table 3 shows the results of proximate analysis and chemical analysis of different vegetable wastes. Proximate analysis shows that the vegetable waste had the volatiles and fixed carbon almost in the same range of other lingo-cellulosic material. The percent content of the cellulose and hemicellulose were significantly lower than lingo-cellulosic biomass. Generally, lingo-cellulosic material has the lignin content in the range of 20–30% (Karunanithy et al., 2012), while vegetable waste had lignin in the range 3.23–4.51%. However, vegetable species and lingo-cellulosic biomass are different: the calorific values were almost in the same range reported in some studies (Bhoi et al., 2006; Pareek et al., 2012; Singh et al., 2007), which might be due to the carbon content.

Particle size distribution

Particle size distribution and particle size are the important factors that affect the bulk properties of feedstock. Particle size affects the true density of feedstock (Zhou et al., 2008) and percent of fines influence densification and durability of briquettes and is an important parameter which impacts the quality and binding of briquettes (Grover and Mishra, 1996). Particle size analysis showed that the particle size in the range 0.595–0.841 mm consisted of a major fraction of powdered vegetable waste, i.e. more than 58%, whereas more than 90% fraction is below

Table 3. Physical and chemical properties of dried vegetable waste powder.

Parameters	Cauliflower/ cabbage leaves	Coriander stalk and leaves	Field beans (*papdi*)	Green pea pods
Volatile matter (%)	69.64	78.00	76.72	72.48
Fixed carbon (%)	12.21	18.48	18.61	20.63
Ash content (%)	18.15	3.47	4.22	6.27
Cellulose (%)	11.43	15.93	22.10	20.50
Hemi-cellulose (%)	11.00	11.38	25.78	26.00
Lignin (%)	3.23	4.51	4.28	3.92

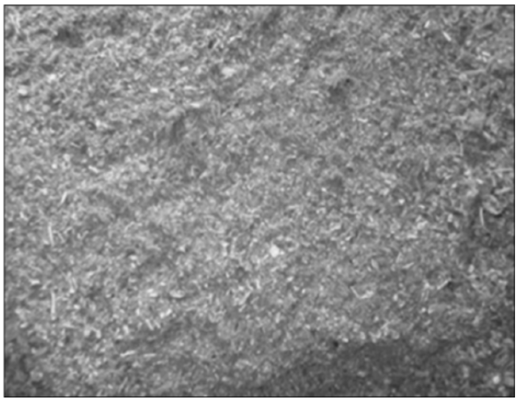

Figure 2. Dried vegetable waste in pulverized form.

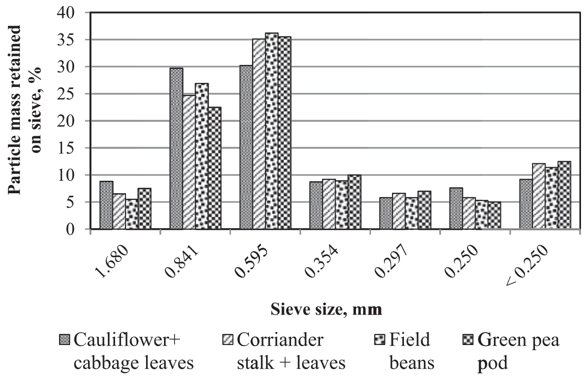

Figure 3. Particle mass retained on mesh (%).

1.68 mm. Because of the softer nature of the vegetable leaves waste than the agricultural waste such as stalks; straws, etc., they tend to generate more fines during the process of grinding. Figure 2 shows the vegetable waste in powdered form and Figure 3 shows the particle size distribution measured for different vegetable waste powder.

Briquette production

Figure 4 shows the briquettes produced from the dried vegetable waste powder. Although the lignin content in all four vegetable wastes was less than that of lingo-cellulosic biomass as discussed earlier, better quality briquettes were produced without using any external binding agents. Starch, sugar and pectin content were high in food grade vegetables, which might have compensated for low lignin content which helped in binderless briquetting.

The diameter of the briquettes produced was 50 mm for all types of vegetable waste. The bulk density of the briquettes produced was found to be 509 kg m^{-3}, 747 kg m^{-3}, 685 kg m^{-3} and 557 kg m^{-3} for cauliflower/ cabbage leaves, coriander stalk and leaves, field beans and green pea pod respectively. Figure 5 shows the variation in the bulk density of all the four types of vegetable waste in different form at different stages. The true density of briquettes varied between 1058 kg m^{-3} to 1319 kg m^{-3}. Figure 6 shows the percent change in bulk density and true density of all the four types of vegetable waste in different form at different stages, considering the density of the collected wet vegetable waste as a base. The negative value shows that, after drying the wet vegetable waste, the bulk density reduces significantly

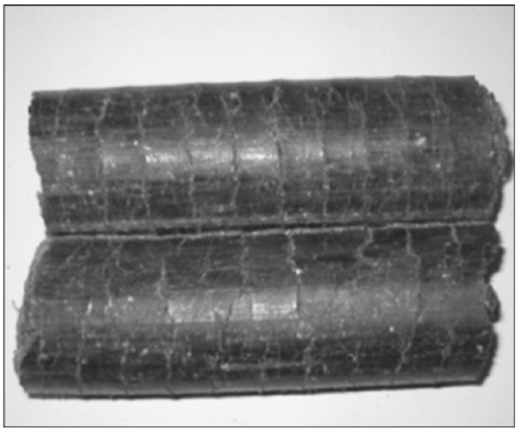

Figure 4. Briquette sample produced from vegetable waste.

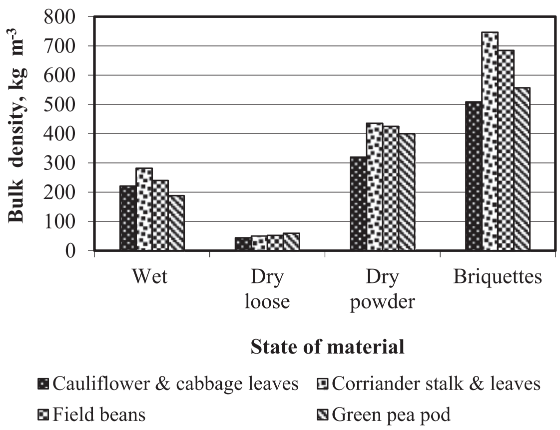

Figure 5. Bulk density at different states.

as most of the moisture was removed during sun drying. The bulk density and true density, as depicted in Table 4, had well within the values of bulk density reported in several studies (Colley et al., 2006; Gilbert et al., 2009; Srivastava and Vyas, 2010) and true density (Adapa et al., 2009; Colley et al., 2006; Lehtikangas, 2001; Lindley and Vossoughi, 1989) for the other briquettes.

The high percent increase in true density was because vegetable waste was ground into finer particles due to its soft physical nature, which gave higher quality compaction (Kaliyan and Morey, 2009). The bulk density of briquetted vegetable waste increased almost 10 to 15 fold over the loose dried vegetable waste. The measured calorific value (LHV) of the briquettes, which ranged between 10.26 MJ kg^{-1} to 16.60 MJ kg^{-1}, as depicted in Table 4, shows that calorific value of the vegetable waste briquettes is comparable to other woody biomass and briquettes (Bhoi et al., 2006; Pareek et al., 2012; Singh et al., 2007).

Gasification

As the major focus of the study was to test the feasibility of the gasification of the briquettes prepared from the vegetable waste. The system was operated at an average fuel consumption rate (FCR) of 48 kg h^{-1}, which generated the syngas at a 100 N m^3 h^{-1} to 105 N m^3 h^{-1} flow rate. The specific gasification rate was found to be 176 kg h^{-1} m^{-2}. The temperature of the oxidation zone was varied between 889°C to 1011°C, whereas the gas temperature at the outlet of the gasifier was varied between 345°C to 456°C. The temperature variations at different level in the gasifier and variation in pressure drop are shown in Figure 7. During the operation of the gasifier, the temperature profile varied with respect to time as a function influenced by the ER, fuel feed rates and syngas flow rate. It is notable that varying the feed rate of biomass or air induced changes in the temperature profile, which caused a change in the process regime inside the gasifier and pressure drop across the fuel bed regime.

The important operating parameter that decides the gasification process was the air to fuel ratio, generally referred to as ER. The amount of gasification air varied between 90 to 97 Nm^3 h^{-1}, at which the ER was measured at 0.33. Considering the average gas generation at 100 N m^{-3} h^{-1}, and syngas exit temperature of 400°C, the cold gas efficiency of the gasifier using vegetable briquettes was found to be 74.11%, while the hot gas efficiency was 79.87%.

The thermochemical processes involved in the gasification of the vegetable waste briquettes are the same as occurred in gasification of other fuels such as wood or agro residue briquettes. In general, the important requirement from the viewpoint of gasification is the thermal stability, i.e. the property of the briquette retaining its shape without disintegration during the thermochemical process. It has been found that moisture content less than 10 % and the density in excess of 650 kg m^{-3} would qualify the briquettes to be used in the gasification system. The higher the density, the better would be the quality of briquettes with respect to the integrity and resistance to crumble inside the reactor. Also, it is essential to avoid condensation of moisture on the upper surface of fuel after shut down of the gasifier as this would result in loose disintegrated material inside the reactor and increase in the pressure drop, finally resulting in poor gas quality (Dasappa et al., 2011).

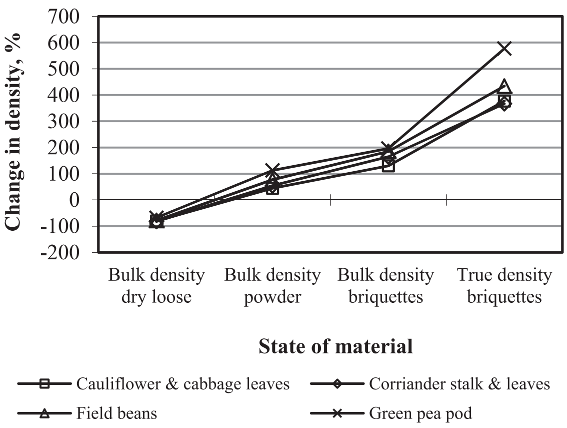

Figure 6. Percent change in density at different states.

Syngas analysis

The volumetric composition in the syngas is mainly the function of equivalence ratio and temperature at oxidation zone. The volumetric compositions, and hence the calorific value of the syngas, were measured at every 30-minute interval and are depicted in Figure 8. It can be seen that the volumetric compositions and calorific value of syngas showed good agreement with the composition of syngas produced from the other woody biomass (Bhoi et al., 2006; Pathak et al., 2008). The average composition of CO, CH_4, H_2 and CO_2 were 17.9%, 1.5%, 16.7% and 11.4%, respectively, accounted the calorific value as 4.71 MJ N m^{-3}, which showed that the heating value of the syngas satisfied the minimum requirement of the power generation engine. Tar and

Table 4. Physical and thermal properties of briquettes.

Parameters	Cauliflower/ cabbage leaves	Coriander stalk/ leaves	Field beans *(papdi)*	Green pea pods
Diameter (mm)	50	50	50	50
Bulk density (kg m^{-3})	509	747	685	557
True density (kg m^{-3})	1058	1319	1285	1274
Calorific value (MJ kg^{-1})	12.39	13.70	16.60	10.26

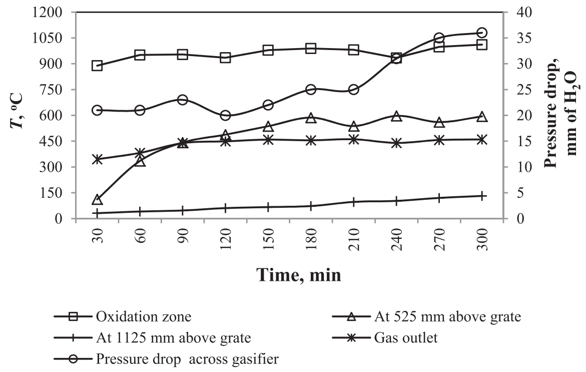

Figure 7. Temperature variation and pressure drop across gasifier.

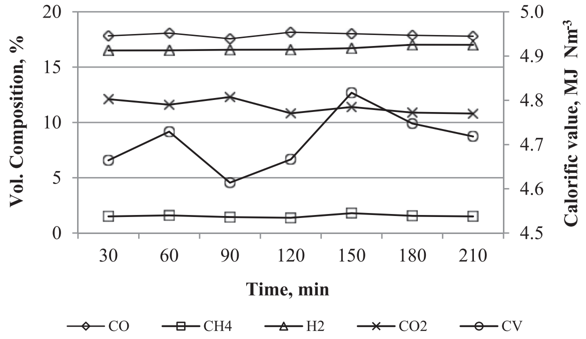

Figure 8. Volumetric composition and calorific value of syngas.

suspended particulate matter (SPM) which were determined as 85.2 mg N m^{-3}, were cumulatively assessed before entering into the engine at the permissible limit for small gas engines (Knoef and Koele, 2000; Pathak et al., 2007).

Performance of power generation unit

The syngas was fed into the engine and the electrical power produced from the generator was spent on a resistive electrical load bank which had the facility of putting the load stepwise. Air fuel ratio was maintained by a gas mixture valve, while the gas flow rate was controlled with the help of manually operated valve. A maximum load of 10 kW$_e$ could be given on engine genset. The operation could be done for three hours without any difficulty. The voltage, current and the frequency were maintained at 420 (±2%), 12.7 (±2 %) and 50 (±1%), respectively. More loads could not be given as the syngas cleaning-cooling system had a design capacity of 10 kW$_e$. The stable and continuous operation of gasification systems for about four hours showed that the briquettes produced from the vegetable waste could be used in a gasifier system for power generation with a syngas engine.

Conclusions

The study investigated the energy recovery and utilization of vegetable waste through briquetting and gasification in the fixed downdraft gasifier. Briquetting could be a possible method for waste-to-energy generation from vegetable waste and can be a good feed material for gasification. The trend in gasifier system performance was similar to the feedstock such as wood and other briquettes. However; the briquettes can have other thermal applications, for example in boilers and cookstoves etc. The volumetric percentage of all combustible constituents and calorific value was comparable to that of wood and could be fed to the engine to generate the electrical power. The study revealed that the thermochemical process such as briquetting and gasification can be applied as an alternative method to utilize vegetable market waste.

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