Jatropha – Potential of biomass steam processing to convert crop residues to bio-coal and thus triple the marketable energy output per unit plantation area

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ABSTRACT

Jatropha curcas cultivation is being undertaken mainly for fuel oil production, but it also results in biomass residues such as fruit husks, seed shell, seed cake or kernel meal, together making up > 80% of the dry fruit weight. Additionally, plant biomass from crop management is also generated. The various biomass residue fractions have gross energy contents ranging from 13 MJ/kg to over 18 MJ/kg. The conversion of these residues into marketable products would contribute to broadening the circumstances under which the jatropha crop is profitable. Biomass Steam Processing (BSP) is a steam assisted thermochemical conversion process, which aims to increase the energy density of lignocellulosic feedstock. Basically, during this process biomass is heated to a temperature of 250–400 °C in a steam atmosphere at atmospheric pressure. It converts biomass residues efficiently into bio-coal in a relatively short time period of about 1 h. In the current investigation, BSP was deployed to transform different potential jatropha crop and seed processing residues into marketable high quality bio-coal. The energy density of jatropha residues could be raised considerably, resulting in an estimated total marketable energy yield of 90 GJ per year per hectare of a 5-year-old jatropha plantation compared to a total yield of 30 GJ per year when jatropha oil alone is marketed, as currently practiced.

1. Introduction

1.1. Jatropha plantations as a promising source of biomass

The demand for alternative non-petroleum fuels, whose production does not conflict with global food security, has driven research into plants such as the tropical shrub *Jatropha curcas*. Jatropha plant attracts interest as it was observed to be growing on a wide variety of soils and climatic zones, including in nutrient depleted poor soils and under apparently water deficient conditions (Basili and Fontini, 2012; Francis et al., 2013). Jatropha seed contains comparatively high amount of oil that could be extracted mechanically or by solvent extraction methods for biodiesel or bio-aviation-spirit production (Francis, 2016; Gonzales, 2016). These properties taken together led to the identification of an opportunity to produce good quality biofuel or its feedstock without interfering with food production.

The present interest in jatropha cultivation is based on the assumption that it can grow and produce seeds at a commercially viable level on land that is not fully suitable for conventional agriculture (Basili and Fontini, 2012; Lama et al., 2018). Even with availability of standardised seeds from plant breeders and agricultural best practices, seed productivity alone might be insufficient to make the jatropha crop profitable on the poor soils usually used and available for its cultivation because of low seed productivity on such soils (Kgathi et al., 2017). Oil forms only 17–18% by weight of the dried fruits of *Jatropha curcas* and the remaining > 80% of fruit biomass has considerable energetic potential (Kongkasawan et al., 2016; Singh et al., 2008). By growing elite jatropha plants and by optimizing the mechanical extraction process, an increase in oil yield of up to 25% by weight of dried fruits would be conceivable (Kumar and Das, 2018; Romuli et al., 2017). Nevertheless, valorisation of the by-products other than oil including fruit husk, seed shell, kernel meal and pruned twigs have been identified as essential components contributing to the potential of jatropha as a profitable crop (Gonzales, 2016).

Abbreviations: BSP, biomass steam processing; HTC, hydrothermal carbonisation

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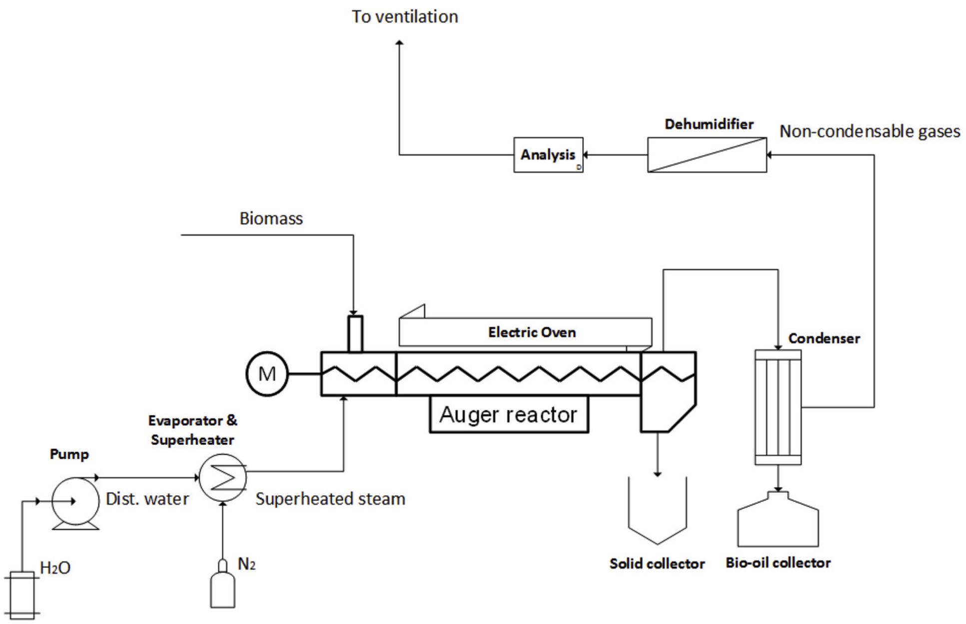

Fig. 1. Schematic process flow diagram of the BSP with technical plant.

1.2. Biomass steam processing (BSP) to treat biomass residues

Due to the low energy density of biomass residues, the economical transport radius of this energy carrier is limited (Cheng, 2010). Therefore, energy densification is essential for lignocellulosic biomass to be an effective bioenergy feedstock. Current methods for exploiting the potential energy from biomass are often based on the initial conversion to secondary products such as bio-coal, bio-oil or syngas which contain higher amount of energy per volume (Steinbrück et al., 2015). Newer thermochemical conversion processes often aim to promote the efficiency and flexibility to allow a wide range of feedstock as input. However, they are all following an identical objective: increasing the energy density and modifying the fuel characteristics of the product.

Biomass steam processing (BSP) is a steam assisted thermochemical conversion, carried out at 250–400 °C and under atmospheric pressure. The use of steam to carbonise biomass has been tested successfully in a screw reactor for reaction times between 15 and 150 min (Steinbrück et al., 2012). In contrast to conventional pyrolysis, BSP needs no pretreatment such as drying before being processed. Thus, a wide variety of lignocellulosic biomass regardless of their moisture content can be used as BSP feedstock. This process has been developed by Prof. Bockhorn's research group at the Engler-Bunte-Institute of Karlsruhe Institute of Technology (KIT) supported by Energie Baden-Württemberg AG (EnBW, Karlsruhe, Germany) (Steinbrück et al., 2012, 2015). The latter holds a patent on the technology (patent no. EP2390301).

This paper investigates the potential of the Biomass Steam Processing (BSP) for efficient conversion of different residues from jatropha e.g. by-products of seed processing and pruning residues into economically valuable bio-coal that has different commercial applications. The importance of marketing residues for broad-based profitability of jatropha as a crop is outlined.

2. Materials and methods

2.1. Collection of jatropha by-products

Jatropha residue fractions e.g. oil cake, seed shell, fruit husk and dried twigs were delivered by EnBW AG from their jatropha project in Madagascar. The project runs a 450 plus ha jatropha plantation established on degraded lands that were previously left barren. All of the obtained materials were in a sun-dried condition as it is usually stored. The oil cake was produced by pressing dry jatropha whole seeds along with shell using a conventional screw press (Karl Strähle GmbH & Co. KG, D-73265 Dettingen/Teck) with one tonne per day seed throughput capacity, which is available at the plantation site in Madagascar. The dehusking of the dried fruits and the deshelling of the seeds were done manually to produce enough quantities of these two fractions for the experiment. Before admitting into the BSP reactor, larger pieces of the oil cake mass and seed shells were broken up, the fruit husk was roughly crushed and the twigs were cut into small 2–3 cm long strips.

2.2. Jatropha curcas agronomic data

The agronomic data of jatropha presented here is taken from the seed production and research farm of Jatropower AG (Baar, Switzerland) near Coimbatore, Tamil Nadu state, India, where one of the authors (GF) is intensively involved. The total area of the farm is about 2 ha. Standardised seeds of Jatropower's commercial accession (JP1010) were planted in this farm at a spacing of 3 m × 3 m (totalling about 1100 plants per ha). The climatic and soil conditions at the farm are as follows:

- rainfall: average below 400 mm p.a., split in two seasons June-August and October-January.
- soil pH: 7.8
- soil nutrient status: deficient in organic matter content, nitrogen and micronutrients such as Fe and Zn (according to the soil testing laboratory of the Dept of Agriculture, Government of Tamil Nadu, assessment based on their reference soil values for oilseed crops).
- irrigation was provided at the rate of 14 litres every 14 days per plant during rain free months.

The experiments were done from the year 2012 to 2016.

2.3. The BSP pilot plant

The Biomass Steam Processing was done in a pilot plant established at the Engler-Bunte-Institute of Karlsruhe Institute of Technology (KIT).

The plant consists of a custom built continuous screw reactor with an inner diameter of 40 mm and effective length of 1000 mm designed to operate BSP with up to 0.5 kg.h^{-1} biomass throughput. The screw has an axle diameter of 17 mm and a pitch of 40 mm. The reactor zone

Table 1
Possible production of various products and by-products from a 5-year old Jatropha plantation per ha and year.

Product/residue[2]	Plantation	Crushing of whole seeds	Extraction of deshelled seeds
Pruned twigs[1]	9000 kg		
Dry fruits	4500 kg		
Dry Seeds	2813 kg		
Fruit husk	1687 kg		
Oil		788 kg	985 kg
Oil cake with shell		2025 kg	
Seed shell			1055 kg
Kernel meal			773 kg

[1] fresh mass.
[2] average proportions calculated based on actual measurements and analysis of seeds obtained from the agronomic trial.

is placed in an electrical oven, 900 mm in length and the BSP reactor has an inner volume of 1.03 L. Fig. 1 gives a schematic representation of the technical scale of the BSP set-up. Water at room temperature is pumped by a diaphragm pump from a storage vessel into the evaporator. The water flows through a 6 mm (OD) electrically heated steel tube and the steam generated is heated further to reaction temperature before it is being injected as superheated steam into the reactor. A continuous and steady flow of steam is confirmed in a dry run before the start of the experiments. A hopper is connected to the reactor and the solid biomass is fed continuously to the reactor. The reactor can be set to the desired reaction temperature between 250 and 350 °C. Steam feed temperature is constantly monitored by a K-type thermocouple at the steam inlet of the reactor. Temperature inside the reactor is monitored online by three K-type thermocouples, located 275, 500 and 727 mm along the reactor. In addition, the temperature of the injected steam as well as the outlet gas from reactor is measured online in order to control the temperature of the reactor more effectively.

The actuator speed for the desired residence times of the feedstock between 6 and 150 min is determined at room temperature. By changing the speed of screw rotation, the residence time of feedstock can be adjusted easily. At the end of the reactor, there is a collector vessel for the solid product. The purge stream is directed to a condenser for offline aqueous phase analysis. The non-condensable stream is connected to an online analyser to measure the CO to CO_2 ratio before the filtration of the exhaust.

All jatropha residues were treated under the same process conditions at 250, 275, 300, 325 and 350 °C with a retention time of 30 min.

2.4. Analytical methods

The physical properties of jatropha fruits and its fractions were determined as follows: Twenty fruits were randomly taken from the harvested fruit lots. These were then cracked using a mechanical cracker to obtain the husks and seeds. The seeds were then cracked again to obtain seed shells and kernels. After each cracking step, the different fractions were carefully weighed using a digital balance to calculate percentages of each fraction.

The oil contents of the seed kernels and seed cake were determined using the Soxhlet method, with petroleum ether as solvent. The total oil content of the seeds was estimated from the % of kernels in the seeds. The physical properties and oil contents were determined from a representative pooled sample of the harvested fruits and the values presented is the average of 2 determinations from this pooled sample.

The raw feedstock and solid reaction products were analysed by means of C,H,*N,*S-elemental analysis (Vario eL, Elementar, Germany). Ash content of the samples was determined by heating approximately 1.0 g of samples according to ISO 1171:2010, a general ash content analysis for test sample of different solid fuels. Oxygen content is then calculated by subtraction of total sample weight (dry basis) from C,H,N,S and ash content. Total moisture content of the feedstock and produced bio-coal consists of surface and inherent moisture and has been determined by indirect gravimetric method by means of heating in an oven at a temperature of 105 ± 3 °C for 24 h. The higher heating values (HHV) were measured with a bomb calorimeter (C200 IKA, Germany). The condensed phase was analysed for total organic carbon (High TOC II + N, Elementar, Germany) while the gaseous phase composition was determined by ND-Infrared absorption (BINOS, Leybold-Heraeus, Germany).

3. Results and discussion

3.1. Main products from a jatropha plantation

Jatropha curcas is known to be a multi-product plant. Different plant parts and products have different actual and potential uses. Jatropha plants are usually pruned once in a year to keep them at sizes suitable for harvesting fruits (2–2.5 m height). The pruning is usually done during the season when the plants shed leaves before the ensuing flowering and fruiting season. Pruning also results in new branch growth, and this has been observed to increase flowering and fruit production in some jatropha cultivars (G. Francis, unpublished observation). Sun drying results in a reduction in weight of jatropha pruned twigs to 25% of the fresh matter as shown in Table 1.

Average dry fruit production per plant at maturity for plants generated from standardised seeds has been observed to be around 4.5 kg per plant per year at age of 5 years (accession JP1010, grown at 3 m x 3 m spacing at Jatropower AG, Baar, Switzerland's jatropha research farm near Coimbatore, India; G. Francis, unpublished data). There is not much reviewed literature on actual production data for the *Jatropha curcas* crop developed with elite standardised seeds for comparison. This is because standardised seeds are available in the market since only 3 years. However, the observed production figures are in agreement with scientific opinion expressed elsewhere. Lama et al (Lama et al., 2018), for example, found the global mean (± SE) seed yield of *Jatropha curcas* crop to be 2218 ± 148 kg $ha^{-1} y^{-1}$ in their review of published information. Wani et al. (2016) reported a yield of 2–3 tonnes of dry seed per ha for a selected genotype observed in field experiments conducted by ICRISAT in India. Screw pressing extracted 28 ± 1% oil when whole seeds obtained from trial plantation of standardised seeds were crushed and solvent extraction extracted almost all of the oil from kernel powder (average 57.5% oil the kernels) in a laboratory scale extractor using petroleum ether as solvent (G. Francis, unpublished observations).

The fruits harvested were dried and stored in a moisture-free store room until further processing. Such processing involves dehusking to obtain seeds and fruit husk. The proportion of various fractions in sun dried fruits (moisture content of 6%) is shown in Fig. 2.

The fruit husk alone contributes 38 ± 1% by weight of the dried fruit. Previous reports have shown the variation of the proportion of the different fractions of jatropha fruits from different regions (Singh et al., 2008), caused probably by the variety of jatropha and the conditions under which they grow. The measured values reported here are, however, broadly in agreement with values reported (Makkar et al., 1998).

In most present jatropha production systems, the seeds are crushed with shell in a screw press to obtain oil as was done in our trial. In this process, the two main products will be oil (approximately 28% by weight) and oil cake (72% including 7% residual oil). In large-scale plantations in future, it is expected that the seeds will be deshelled before oil extraction resulting in the separation of shell and kernel. The kernel is then subjected to pressing or solvent extraction to extract oil. In the latter case substantial quantities of seed shell (37.5% by weight of the seeds) and kernel meal will be generated as residue. The two possible jatropha seed processing systems are presented graphically in Fig. 3.

All the possible by-products and the quantities of each per ha per

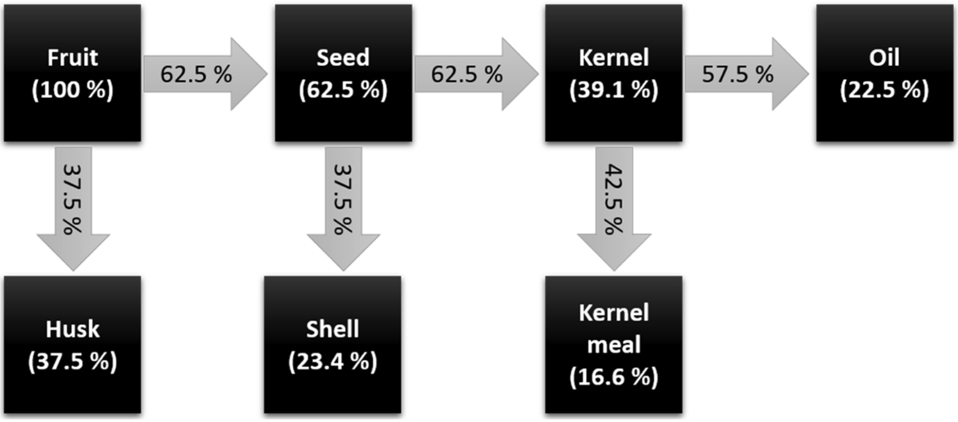

Fig. 2. Schematic diagram showing estimates of the average proportion of different fractions of Jatropha fruit.

year based on the data obtained from the trial plantation is presented in Table 1. It is assumed that dehusking of fruits and deshelling of seeds are 100% efficient, as was the case in our manual processing.

3.2. BSP processing of jatropha by-products to bio-coal

Biomass Steam Processing has been developed as an alternative to existing coalification processes such as pyrolysis and Hydro-Thermal Carbonisation (HTC) (Steinbrück et al., 2012). It has advantages compared to HTC in that it has comparatively moderate reaction parameters (atmospheric pressure, much shorter reaction time) and can convert wet and dry biomass (Steinbrück et al., 2012). The characteristics of the bio-coal produced through BSP is comparable to that produced from the other processes such as pyrolysis and HTC (Steinbrück et al., 2012).

3.2.1. BSP feedstock characterisation

A wide range of lignocellulosic biomass with various characteristics e.g. moisture content, ash content and diverse organic composition has been treated to study the BSP process and its kinetics (Boll, 2012; Heyd, 2013; Steinbrück et al., 2012, 2015). The jatropha by-products analysed are predominantly dry lignocellulosic biomass, with average ash contents of 2–9%. The seed shell and seed cake contain a relatively high content of lignin (Singh et al., 2008).

Table 2 shows ultimate analysis and other properties of different jatropha by-products used as the input feedstock.

Table 2
Ultimate analysis and other important properties of the input feedstock derived from Jatropha.

	Oil cake	Seed shell	Fruit husk	Pruned twigs
Moisture wt. %[a]	3	3	3	3
C [%][b]	46.58 ± 0.36	48.01 ± 0.28	42.49 ± 0.36	45.22 ± 0.24
H [%][b]	6.29 ± 0.01	5.82 ± 0.02	5.64 ± 0.05	5.95 ± 0.05
N [%][b]	5.66 ± 0.15	1.30 ± 0.03	0.62 ± 0.03	0.06 ± 0.02
S [%][b]	0.39 ± 0.01	0.12 ± 0.00	0.12 ± 0.02	0.08 ± 0.00
O [%][b,c]	32.59	42.47	42.40	45.04
Ash content [%][b]	8.49	2.28	8.73	3.65
Calorific value [MJ/kg][b]	18.76 ± 0.04	17.78 ± 0.06	14.91 ± 0.01	19.16 ± 0.16

[a] wet basis.
[b] dry basis.
[c] calculated by difference.

The data presented in previous reports (Kumar and Pant, 2015; Makkar et al., 1998; Raheman and Mondal, 2012; Wani et al., 2016), show the range of values for the chemical composition of the different jatropha fractions. The values obtained are generally in range except for the ash content of the fruit husk, where the samples analysed in this paper has a conspicuously low ash content of 8.7% by weight compared to the expected value of around 14%. The material was ensured to be completely free of sand and dust in our case. The mineral composition of the soil on which the jatropha was grown could also have played a role in the low ash content in the husk samples analysed.

BSP was operated to study the conversion of jatropha residues at a temperature range between 250 to 350 °C for 30 min. The obtained

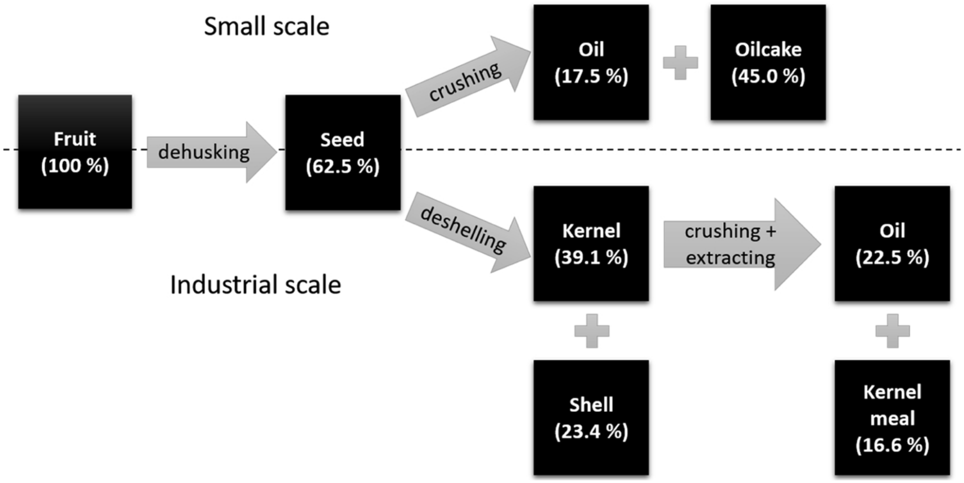

Fig. 3. Two possible seed processing systems for Jatropha oil extraction with the resulting products and estimations of the average proportions of each fraction.

Table 3

Ultimate analysis and other properties for bio-coal obtained from Jatropha residues at 350 °C and about.30 min.

Analysis	Oil cake- coal	Seed shell- coal	Fruit husk- coal	Pruned twigs- coal
Moisture wt.%[a]	~ 0	~ 0	~ 0	~ 0
C [%][b]	58.82 ± 0.48	61.64 ± 2.10	53.50 ± 0.52	60.71 ± 0.40
H [%][b]	5.12 ± 0.09	5.03 ± 0.08	4.81 ± 0.20	4.60 ± 0.04
N [%][b]	3.81 ± 0.20	0.80 ± 0.02	0.85 ± 0.02	0.49 ± 0.15
S [%][b]	0.16 ± 0.01	0.09 ± 0.00	0.10 ± 0.01	0.07 ± 0.00
O [%][b,c]	23.06	28.67	24.25	22.46
Ash content [%][b]	9.03	3.77	16.49	11.67
Calorific value [MJ/kg][b]	24.18 ± 0.08	24.79 ± 0.30	21.30 ± 0.38	24.68 ± 0.12

[a] wet basis.

[b] dry basis.

[c] calculated by difference.

solid products have a brownish to black colour and they were odour free. As the results show, the coalification is the result of different complex reactions such as decarboxylation, dehydration and oxidation, which take place in varied rates at different temperatures. These complex interactions depend on the origin of the material and the existing bonds. Table 3 presents the ultimate analysis and some other important properties of bio-coal from jatropha residues produced at 350 °C and 30 min reaction time.

Practically no ash was released through the BSP treatment and ash content of the solid bio-coal product rose approximately linearly with decreasing product yield. Thus, ash content of the solid product could be used as a constant component in the mass balance for the modelling. The nitrogen content of pruned twigs and husk residue was observed to be below 1%, that of seed shell was 1.3% and oil cake had an initial N amount of 5–6%.

For almost all of the bio-coals produced, a reduction in the nitrogen content has been observed after conversion. The process has a considerable effect on the decrease of O:C and H:C ratio. The position of typical biomass and related BSP products are shown on Van Krevelen diagram (Schumacher et al., 1960) in the Fig. 4. The product resembles in quality to the typical products of the natural pathway of the coalification curve. Based on O:C and H:C fraction in the Fig. 4, BSP coal produced at 300 and 350 °C could be similar to peat and lignite respectively.

3.2.2. *Coal yield in relation to reaction conditions*

Fig. 5 shows the obtained solid product yield of the BSP process from jatropha residues with retention time of 30 min for different reaction temperatures. Generally, the higher the temperature of the reaction, the lower the coal yield will be. Temperature increase can be directly correlated to the mass yield reduction and the organic content will decrease to almost zero at extremely high temperatures. Extending the reaction time has a smaller impact on coal yield compared to raising the temperature, and this effect will be gradually fade at higher temperature ranges.

At the lowest temperature, the experiment results in a % coal yield of between 90 and 66 for jatropha fruit husk and oil cake respectively showing that fruit husk required higher temperature to be carbonised. At 300 °C, the % coal yield has been estimated from 83 to 50 for fruit husk and pruned twigs respectively presenting the highest rate of volatilisation. At 350 °C, results show consistent % coal yields of 54, 48, 47 and 35 for seed shell, oil cake, fruit husk and pruned twigs respectively (Fig. 5).

3.2.3. *Heat content improvement of residues through conversion to bio-coal*

Fig. 6 presents the higher heating value of various jatropha fractions as well as their BSP bio-coal at different temperatures and a constant reaction time of 30 min. An improvement of calorific value of the yielded coal can be obtained at the temperature of 350 °C. The calorific value of the jatropha oil cake, husk, shell and twigs increased from 18.8, 17.8, 14.9 and 19.2 MJ/kg respectively to 24.2, 24.8, 21.3 and 24.7 MJ/kg in the respective bio-coals. This energy intensification is similar to what has been reported previously for bio-coal produced from straw and wood chips through the BSP process (Steinbrück et al., 2012).

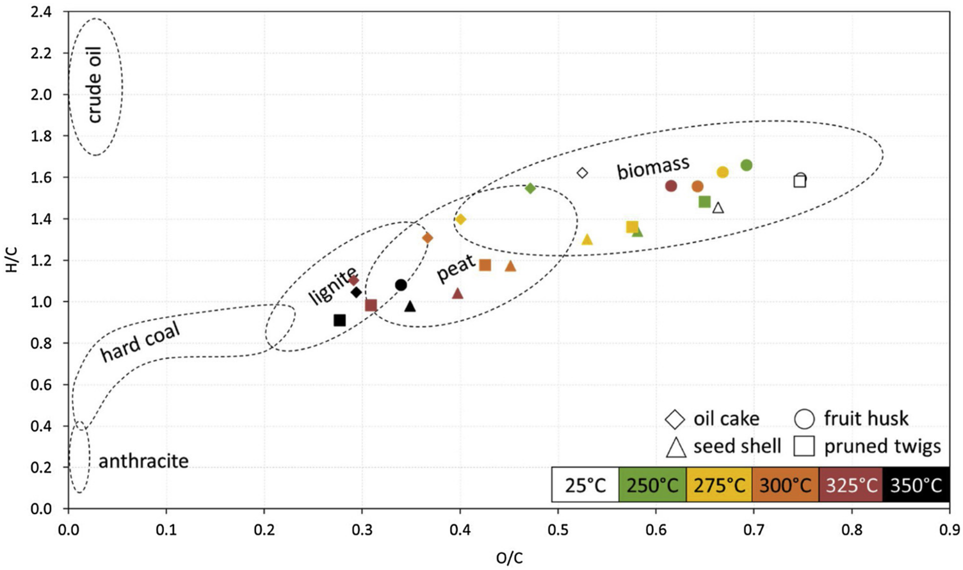

Fig. 4. Van Krevelen diagram, average ratio of O-C and H-C for typical fossil fuels and biomass composition as well as bio-coal produced through BSP.

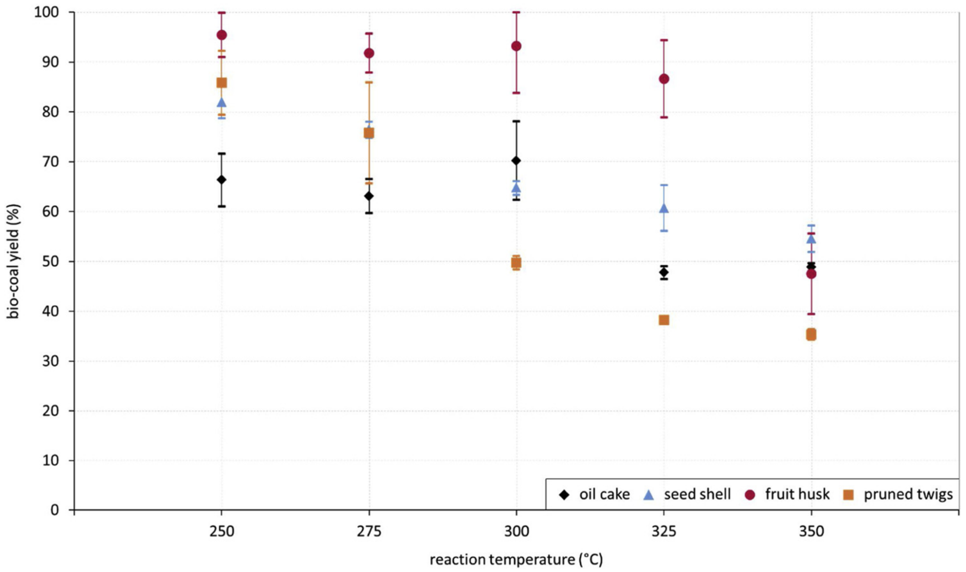

Fig. 5. Coal yield vs. temperature for constant retention time of 30 min.

Fruit husk coal with energy content of around 21 MJ.kg^{-1} is the lowest while other fractions have the calorific value in the range of 24.5–25 MJ.kg^{-1}. As the trend shows, raising the temperature has a considerable influence on calorific value and yield of the solid product, but it also depends on the organic composition of the respective feedstock. In addition to that, the effect of reaction time variation on calorific value has been observed to be the same as its effect on coal yield and it strongly depends on the composition of the samples (Boll, 2012; Heyd, 2013).

To optimise the temperature of the carbonisation, the minimum required quality of the bio-coal depending on the further application has to be fulfilled. An analysis of energy densification ratio (heating value of carbonised solid product divided by heating value of dried input feedstock) and coal yield is also required. From the results presented, temperature of 350 °C for reaction time of 30 min has been chosen as the optimum condition for obtaining high quality bio-coal from jatropha residue through the BSP process.

Table 4

Estimation of annual energy output from 5-year old Jatropha plantation per ha.

Product fraction[2]	Annual amount (kg.a^{-1})	Energy per unit (MJ. kg^{-1})	energy per year (GJ.a^{-1})
Extracted oil	778	39	30.34
Total bio-coal	2542	23.94	60.85
Twigs-coal	788	24.77	19.51
Husk-coal	793	21.87	17.34
Oil cake-coal[1]	962	24.95	24.00

[1] according to Fig. 2, small scale oil extraction applied, thus here, oil cake is the sum of seed cake and shell.

[2] average proportions calculated based on actual measurements and analysis of seeds obtained from the agronomic trial.

3.3. Total potential energy yield from bio-oil and bio-coal from by-products from a 1 ha jatropha plantation

In the Table 4, the annual energy yield of a 1 ha, 5-year old jatropha

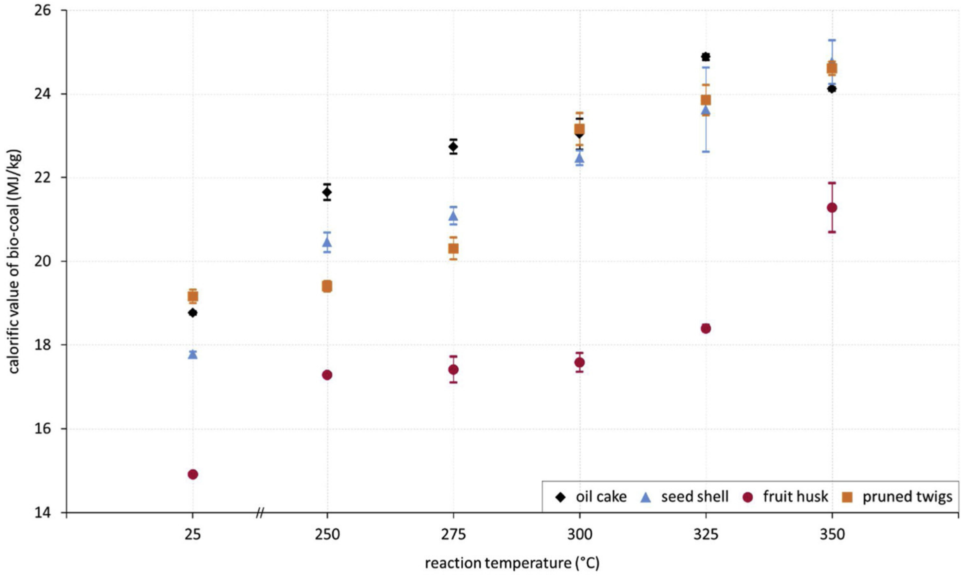

Fig. 6. Higher heating value of different Jatropha residues and bio-coal produced from them at various temperatures.

plantation is estimated. The quantitative yields of oil and biomass residues has been comparable to those reported in the literature (Wani et al., 2016). BSP enables the conversion of the raw residues to higher energy content bio-coal with measurable product yield and energy content. The annual energy gain from a mature jatropha plantation per unit cultivated area when the residues are treated with BSP is evident from Table 4. It shows that besides 778 kg.ha^{-1} extracted bio-oil with total energy content of about 30 GJ, more than 2500 kg.ha^{-1} bio-coal with total energy content of at least 60 GJ can be additionally produced.

3.4. Path to profitability in jatropha plantations

The profitable edible oil crops either have a very high oil productivity (oil palm) or have markets for oil and the by-products (soybean, rapeseed, sunflower etc.). Current jatropha plantations are all raised with the conventional toxic variety and the whole seeds are crushed to extract oil mechanically. Thus as reported earlier (Singh et al., 2008) only a range of 17–18% of the total dry fruit yields a commercially marketable product. Even the future solvent extraction model of jatropha seed processing will result in a high percentage of solid residue (husk and shell amounting to 61% by weight of the dry fruit biomass). The pruned twigs also result in a substantial biomass fraction that is currently not commercially exploited. Utilising the pruned twigs for bio-coal production will be advisable and profitable in cases where they are collected and burned outside the plantation (the usual case in most of the small scale jatropha plantations presently). The utilisation of such residues from biomass, which form a major share of the exportable biomass yield, can contribute to the jatropha crop becoming more broadly profitable rather than in niches as is presently the case (e.g. in regions where the produced oil can be sold locally at a higher price than in the international market). There are references in literature where the generation of large quantities of biomass residues from the jatropha crop are mentioned and their potential as energy sources is presented (Gonzales, 2016). In other reports, attempts to use jatropha fruit husk and seed shell as burning briquettes (Wani et al., 2016) and the oil cake as biogas feedstock (Singh et al., 2008) have been attempted. Also the chemical and thermal treatment of oil cake with the aim to produce catalysts for biodiesel production has been discussed (Kamel et al., 2018). Heat treatment of jatropha residues (e.g. the oil cake) under high temperature and pressure has also been reported resulting in the generation of bio-coal and bio-crude (Makkar et al., 1998; Singh et al., 2008). In this investigation, the solid residues arising out of plantation management, seed processing and oil extraction have been used to study the feasibility of applying BSP as a thermochemical process to convert the residues into a high-energy content fuel. The different tested residue fractions produced bio-coal with different yields and qualities (Table 4), which can be utilised individually or mixed with other co-substrates for suitable applications e.g. pelletising into bio-coal briquettes.

4. Conclusions

Jatropha curcas remains relevant as a bioenergy crop. Beside interesting characteristics of jatropha as an adaptable plant on a wide variety of soils and climatic zones including in nutrient depleted poor soils, the comparatively high amount of oil content brings it more into the focus of green alternatives for energy production. In addition to the primary product, bio-oil, jatropha cropping results in several by-products such as seed cake, fruit husk, seed shell and pruned twigs, that are currently not commercially marketed due to relatively low energy density.

BSP – a steam assisted carbonisation process for lignocellulosic biomass – enables production of a carbon-rich bio-coal with relatively high product yields. This process is a promising approach to convert non-food biomass and organic wastes into bio-coal with high-energy content. Through BSP, an energy densification of jatropha residues results in a total marketable energy yield of more than 90 GJ per year per hectare of 5-year-old jatropha plantations compared with a total yield of 30 GJ when the oil alone is marketed. BSP densifies the energy content of the residues so that the produced bio-coal will be useful and feasible for energy-related applications such domestic furnaces as well as co-firing fuel in large-scale power plants. Furthermore, it provides an advantageous feedstock for production of activated charcoal via activation process. The conversion of cropping by-products, e.g. through BSP, can result in higher quantities of marketable products leading to enhancement of the profitability of jatropha plantations. The bio-coal produced is CO_2 neutral and provide a useful input top the bio-economy.

Acknowledgments

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