HIGH YIELD AND QUALITY CHARCOAL FROM OIL PALM KERNEL SHELL WITH AN IMPROVED PILOT-SCALE CONTINUOUS CARBONISATION SYSTEM

Z NAHRUL HAYAWIN[1]*; A A ASTIMAR[1]; M F IBRAHIM[2]; A W NOORSHAMSIANA[1] and M ROPANDI[1]

ABSTRACT

The present study compared the production, quality, and yield of charcoal manufactured from oil palm kernel shell (OPKS) via an improved pilot-scale continuous carbonisation system, the pilot rotary kiln (PRK), with a batch conventional carbonisation approach, the Taki carbonisation system (TCS). Previous investigations demonstrated that the PRK was highly energy-efficient at 55% compared to 38% in TCS. Furthermore, the PRK attained a higher OPKS-charcoal yield at 30 ± 2.4% than TCS, which produced 22 ± 1.7%. The improved system was a self-sustaining carbonisation process that could continuously run for 8 hr, whereas the TCS required 72 hr to convert the same amount of OPKS into charcoal. A good quality charcoal (83.7 ± 2.0% fixed carbon, 10.2 ± 1.4% volatile matter, 6.1 ± 1.2% ash, and 33.1 ± 1.8 MJ kg^{-1} higher heating value) was also acquired via the PRK. The present study also demonstrated that the PRK approach was more financially feasible than TCS as it was projected to require lower capital cost and a higher benefit-to-cost ratio (B:C), which palm oil mill operators could achieve.

INTRODUCTION

Charcoal is a porous carbon-rich solid generated through pyrolysis with little or no oxygen (O_2) at moderate temperatures, between 350°C-700°C (Chen *et al.*, 2019). In developing countries, charcoal is primarily employed as domestic fuel, an energy source in power plants, in soil amendments, and an ingredient in chemical products (Fan *et al.*, 2022; Heberlein *et al.*, 2022; Kamali *et al.*, 2022), while activated carbon is utilised in water and air treatment. Moreover, charcoal mitigates global warming by reducing greenhouse gas (GHG) emissions (Basalirwa *et al.*, 2020; Nahrul *et al.*, 2020).

Charcoal is advantageous over coal and coke as it is easier to store, cheaper, lighter, cleaner, safer, free from sulphur and mercury, and possessed a higher heating value (Lan *et al.*, 2019; Tymoszuk *et al.*, 2019). Charcoal could be acquired from lignocellulosic material, including agricultural biomass composed of high carbon content, an essential characteristic of charcoal production (Sangsuk *et al.*, 2020). Converting agricultural biomass to charcoal also aids in reducing the accumulation of agricultural wastes, making it environmentally friendly (Awasthi *et al.*, 2020).

In Malaysia, the palm oil business is the largest agricultural industry that generates an abundant amount of oil palm biomass yearly in the form of oil palm empty fruit bunch (OPEFB), oil palm mesocarp fibre (OPMF), oil palm kernel shell (OPKS), an oil palm frond (OPF), and oil palm trunk (OPT) (Kushairi *et al.*, 2018). The OPEFB, OPF, and OPT are returned to plantations for mulching purposes. Approximately 30% of 454 Malaysian palm oil mills utilise oil palm biomass to produce biofertiliser, biogas, and wood products (Mahlia *et al.*, 2019). Presently, OPKS is directly employed as a solid fuel boiler for steam and energy generation (Vijaya *et al.*, 2008).

[1] Malaysian Palm Oil Board,
   6 Persiaran Institusi, Bandar Baru Bangi,
   43000 Kajang, Selangor, Malaysia.

[2] Department of Bioprocess Technology,
   Faculty of Biotechnology and Biomolecular Sciences,
   Universiti Putra Malaysia, 43400 Serdang,
   Selangor, Malaysia.

* Corresponding author: nahrul.hayawin@mpob.gov.my

According to Idris *et al.* (2015), transforming OPKS, OPMF, and OPEFB into charcoal and selling it as an energy resource would be 3.0 to 3.5 times more profitable, which could be included in the Malaysian renewable energy (RE) policy. Moreover, Malaysia aims to achieve between 2080 and 4000 MW of installed RE capacity by 2030 (Hamzah *et al.*, 2019). The energy content of oil palm biomass is at a minimum of 65.0% of the low-rank coal range of 17-24 MJ kg^{-1}. Consequently, oil palm biomass could be utilised as a solid fuel for boiler alone or mixed with charcoal. Moreover, oil palm biomass contains low sulphur (0.2%), preventing SOx production during combustion (Harimi *et al.*, 2005).

Producing charcoal from agricultural biomass is achievable through various carbonisation technologies. Due to their simplicity, low capital, and operational cost, traditional carbonisation methods, such as brick kilns, earth pits, and earth mounds, are still operating (Santos *et al.*, 2017); an example is the Taki carbonisation system (TCS) (Astimar *et al.*, 2012). Nonetheless, the major drawback of the traditional technologies is that they are batch systems. Furthermore, the techniques require over seven days to obtain charcoal with a low yield, while the gases produced are released directly into the atmosphere (Kammen and Lew, 2005).

A metal rotary kiln was developed to shorten the carbonisation process and produce a higher charcoal yield (Bailis *et al.*, 2013; Sangsuk *et al.*, 2018; Tavakkol *et al.*, 2021). Subsequently, the method was further improved for a continuous carbonisation system that manufactures increased charcoal yield with good HHV and low gaseous emission. Furthermore, the gases emitted during the process are treated before releasing them into the atmosphere. In the current study, OPKS-charcoal was manufactured via the pilot rotary kiln (PRK) to evaluate the performance of the new continuous carbonisation technology. The method was also compared to the traditional batch carbonisation technique, the TCS.

MATERIALS AND METHODS

Sample Preparation

The present study obtained OPKS samples from the Ulu Kanchong Palm Oil Mill, Negeri Sembilan, Malaysia. On average, the diameter of the kernel shells was approximately 15 mm. The samples were prepared according to the methodology outlined by Nahrul Hayawin *et al.* (2018). First, the OPKS was sun-dried for two weeks to allow the moisture content to be under 10%. Subsequently, the dried OPKS was measured with a thermogravimetric analyser (TGA) for proximate analysis before the carbonisation process.

Carbonisation via TCS

The TCS is an earthen kiln categorised under the traditional carbonisation system. The method utilises tropical wood residues from wood industries as a fuel. A TCS consisting of two furnace kilns that could carbonise a total of 2.24 t of OPKS per batch was employed in the present study. The furnace kilns were made from bricks laid with clay (wall thickness = 0.24 m) and 5.8 × 3 × 3.3 m in length, width, and height, respectively (*Figure 1*). Each kiln comprised a door to load the raw materials and the system was equipped with an 8 m chimney connected to a wood vinegar collecting tank (diameter = 1 m, height = 2.1 m). The whole system was located in a plant that covered an area of 240 m^2.

The TCS was operated with 1.5 t of tropical wood residues cut to 1.5 m long as fuel loaded vertically at the back of the furnace kilns. Subsequently, 1.1 t of OPKS were weighed and loaded into the drums (diameter = 0.58 m, height = 0.85 m). All loaded drums were arranged in the furnaces after their lids were closed. Tropical wood residues loaded at the back of the kilns were then ignited before closing the furnace door to block the air intake. Subsequently, the carbonisation temperatures inside the furnaces were recorded. The fire was extinguished after 72 hr and the system was allowed to cool for five days. The resulting OPKS-charcoal was collected and stored at the charcoal-making centre, while the wood vinegar from the TCS system was collected from the collecting tank, stored, and kept in 150 L plastic drums.

Carbonisation with PRK

Figure 2 illustrates the schematic diagram representation of the continuous carbonisation system, PRK, designed and built by a local engineer. The carbonisation reactor was 4 m long with outer and inner diameters of 508 and 476 mm and could withstand temperatures over 900°C. Furthermore, an alternative door was added at the end of the reactor to prevent the charcoal from being stuck. An automatic pressure valve system was also attached to the top of the reactor to prevent pressure from exceeding the limit.

The PRK could carbonise up to 2 t of raw material per day. Since the system was continuous, it could run for 24 hr without stopping once it started. The system employed diesel to ignite the burner, operating between 178 and 356 kW power and approximately 10 135 mbar pressure. A scrubber was also employed to capture the smoke and treat the gas released during the carbonisation process. The SS400/Rubber scrubber possessed a 0.25 m^3 capacity, compatible with the chemical and physical properties of the gas stream. A cyclone

separator with approximately 0.25 m³ capacity was also attached to separate particulates from the by-product. Moreover, the PRK was attached to two condenser units, each at 1.5 × 1 × 2 m (height × width × length) and 0.25 m³ capacity.

The system was initiated by igniting the burner and heating for 2 hr until the optimum temperature of 700°C was obtained. Subsequently, the burner was turned off pre-OPKS with less than 10% moisture content was fed into the screw feeder. The self-burning raw material (exothermic process) moved horizontally in the reactor for approximately an hour and turned into charcoal at the end of the process. Hourly, 80 kg OPKS was introduced until all 1.2 t were processed and the charcoal was collected by loading it in the tightly closed drum to avoid air intake. The smoke produced during the carbonisation was channelled to a scrubber, while the wood vinegar was collected at the outlet pipe placed before the chimney, stored, and kept in a closed 150 L plastic drum.

Analytical Procedures

The current study analysed the lignocellulosic compositions of the OPKS and OPKS-charcoal according to the TAPPI Test Method (T 203 om-83 and T 222 om-83). Additionally, the proximate (volatile matter, fixed carbon, and moisture and ash contents) and ultimate [carbon (C), hydrogen (H), nitrogen (N), and sulfur (S)] analyses were performed according to ASTM D7582-10 and ASTM E775-778, respectively, with thermogravimetric analyser (TGA) [(Mettler Toledo, TGA/SDTA 851, United States of America (USA)] and an elemental analyser (CHNS/O Perkin Elmer 2400, Series 2, USA).

The chemical compositions of the wood vinegar obtained in the present study were assessed with gas chromatography-mass spectrometry (GC-MS) (Shimadzu GCMS–QP2010Plus, Japan) on a TG-WAXMS capillary column (60 m × 0.25 mm × 0.25 μm). The sampling was managed at a split
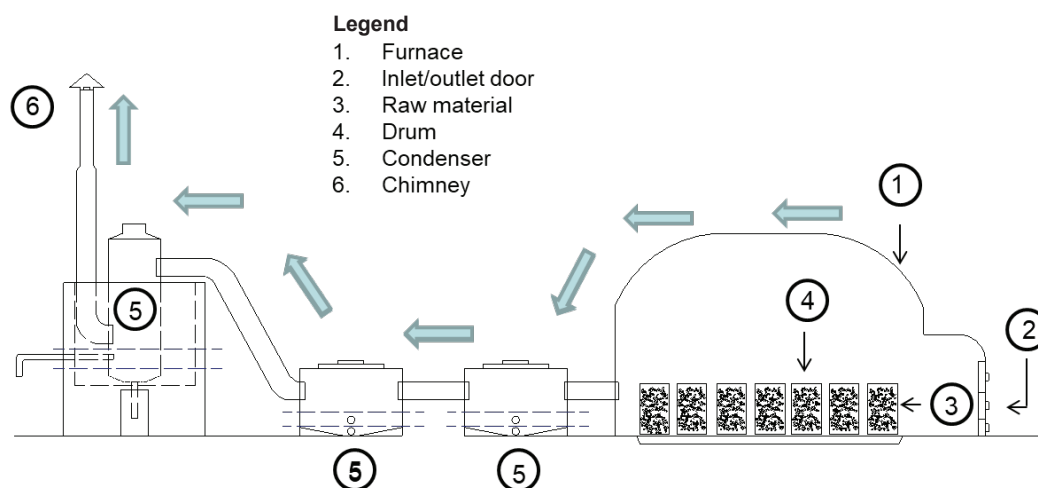

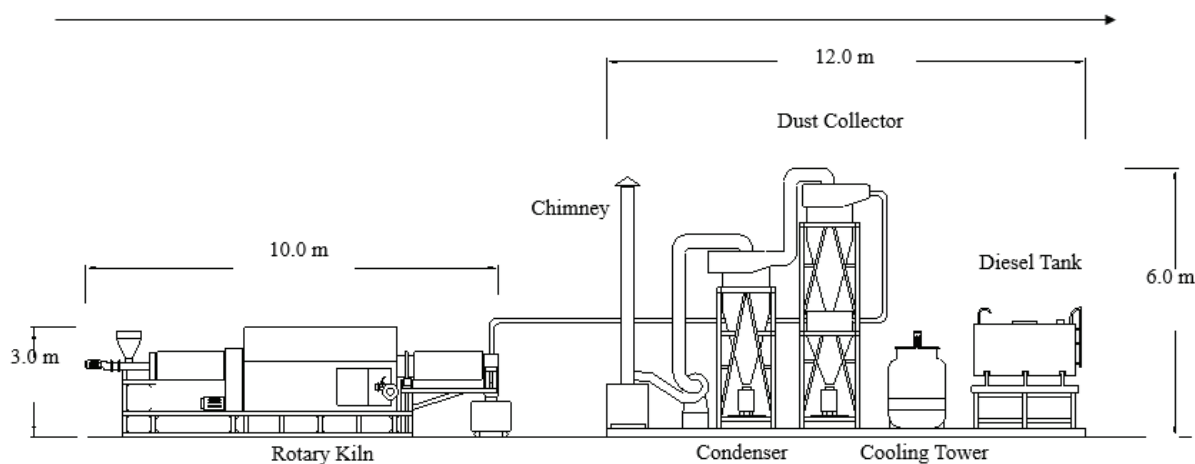*Figure 1. The schematic diagram of the TCS system.*

Figure 2. The schematic diagram of the PRK system.

rate of 80:1 with 1 μL of the wood vinegar injected into the column. The injection port temperature was 260°C, while the column temperature was maintained at 60°C for 2 min. Subsequently, the temperature was programmed to rise to 240°C at 10°C min^{-1} for 10 min. Helium was employed as the carrier gas at a flow rate of 1.2 mL min^{-1}. Mass spectrometry was performed with an electron impact (EI) source at 70 eV electron energy, 280°C ion source temperature, and a mass scanning range of 45-550 amu s^{-1}.

The composition of the gas released during the carbonisation process was quantitatively measured with a gas chromatography GC (GC Agilent Technologies 6890N) equipped with thermal conductivity (TCD) analyser and flame ionisation detector (FID). Furthermore, the higher heating value (HHV) of the charcoal obtained in the current study was analysed with a Parr 1261 bomb calorimeter (ISO 18125:2017). All assessments were repeated thrice.

Energy Balance Calculation

The input and output energy of the present study was considered for energy balance calculation (Kodera and Kaiho, 2016). First, Equation (1) was employed to calculate the input energy from the calorific contents of the raw materials. Subsequently, the calorific content of the charcoal recovered was determined with Equation (2), and the heat required to evaporate water was calculated with Equations (3), (4), and (5). Finally, Equation (6) determined the net heat loss due to convection radiation.

$$\text{Calorific content of raw material} = \text{Raw material (dry basis)} \times \text{alorific of value raw material} \quad (1)$$

$$\text{Calorific content of charcoal} = \text{Charcoal (dry basis)} \times \text{calorific value of charcoal} \quad (2)$$

$$\text{Heat required to evaporate water (liquid)} = C`p \times n \times (373\text{-Trt}) \quad (3)$$

$$\text{Heat required to evaporate water (gas)} = Cp \times n \times (Tp\text{-}373) \quad (4)$$

$$\text{Total heat required to evaporate water} = \text{Heat required to evaporate water (liquid)} + \text{heat required to evaporate water (gas)} \quad (5)$$

$$\text{Net heat loss by convection radiation} = \text{Input energy} - \text{output energy} \quad (6)$$

where C'p represents the heat capacity of water (J mol.K^{-1}), n is water in mol, Trt denotes room temperature (K), Cp is the heat capacity of steam (J mol.K^{-1}), and Tp denotes the temperature of the product (K).

RESULTS AND DISCUSSION

The Production of OPKS-biochar via the PRK and TCS Systems

Carbonisation profile. The OPKS were characterised prior to producing biochar through the PRK and TCS systems to ensure that the raw material employed in the current study has a consistent composition. Compared to other types of oil palm biomass, raw OPKS contains higher lignin and fixed carbon contents and a low ash percentage, making OPKS an excellent material for producing charcoal with higher yield and good quality (*Table 1*).

In TCS, the temperature rose slowly from 150°C to 300°C in the central region of the carbonisation chamber during the initial 5-10 hr of operation. The temperature was then increased rapidly to approximately 700°C after 12 hr before slowly decreasing towards the end of the process, which took approximately 75 hr (*Figure 3a*). Meanwhile, the PRK took 3 hr during the pre-carbonisation process to reach the highest temperature, 700°C, which was maintained throughout the process *Figure 3b*. The burner in the PRK system was automatically turned off when the temperature inside the kiln reached 700°C. The temperature was kept constant for approximately 6 hr for self-burning before it naturally dropped.

The results demonstrated that the PRK was a better carbonisation system that could increase the temperature faster and complete the carbonisation process in a shorter duration than TCS. During the carbonisation process, more volatile compounds were released due to the thermal decomposition of the OPKS. The hemicellulose component decomposed at 250°C to 300°C, followed by cellulose at an average temperature between 350°C and 400°C. At temperatures above 400°C, lignin started to degrade, similar to the report by Chen *et al.* (2016).

The Production Yield and Quality of the OPKS-charcoal

Table 2 summarises the performance comparisons of different carbonisation systems employed in producing OPKS-charcoal. The PRK system was developed with a high-quality metal to prevent heat loss to the environment, resulting in a faster carbonisation process, thus shortening the retention time. Consequently, the technique required a shorter process duration, 8 hr, than other systems, including heat distribution pipe kiln (HDP), transportable metal kin (TPI), and TCS.

The PRK system is also a continuous operation that utilises a suitable amount of raw material during the carbonisation process that continuously loads, carbonises, and collects. The approach

TABLE 1. CHARACTERISTICS COMPARISON BETWEEN THE RAW OPKS EMPLOYED IN THE CURRENT STUDY AND OTHER TYPES OF OIL PALM BIOMASS UTILISED IN CHARCOAL PRODUCTION

Properties	OPKS (present study)	OPKS	OPEFB	OPF	OPT
HHV (MJ kg^{-1})	17.9 ± 0.5	18.3	17.9	17.3	19.3
Cellulose	27.7 ± 0.1	30.1	50.0	56.0	41.0
Hemicellulose	21.6 ± 0.4	21.4	30.0	27.0	32.0
Lignin	44.0 ± 1.0	47.3	17.0	21.0	25.0
Proximate analysis					
Volatile matter	71.0 ± 0.1	77.4	83.9	72.5	79.8
Moisture content	-	-	6.8	7.4	8.34
Fixed carbon	26.3 ± 1.0	20.0	8.9	5.81	13.3
Ash	2.6 ± 0.2	2.59	7.08	14.3	6.9
Ultimate analysis					
C	60.9 ± 1.2	43.6	45.6	38.4	43.8
H	12.8 ± 0.8	4.92	6.19	5.53	6.2
N	0.66 ± 0.1	0.49	0.35	2.3	0.44
S	0.19 ± 0.1	-	ND	0.09	0.09

Source: Goh *et al.* (2012); Nahrul Hayawin *et al.* (2017); Nipattummakul *et al.* (2012); Nyakuma *et al.* (2014); Oh *et al.* (2016); Purwanto *et al.* (2018) and Trangkaprasith, (2011).
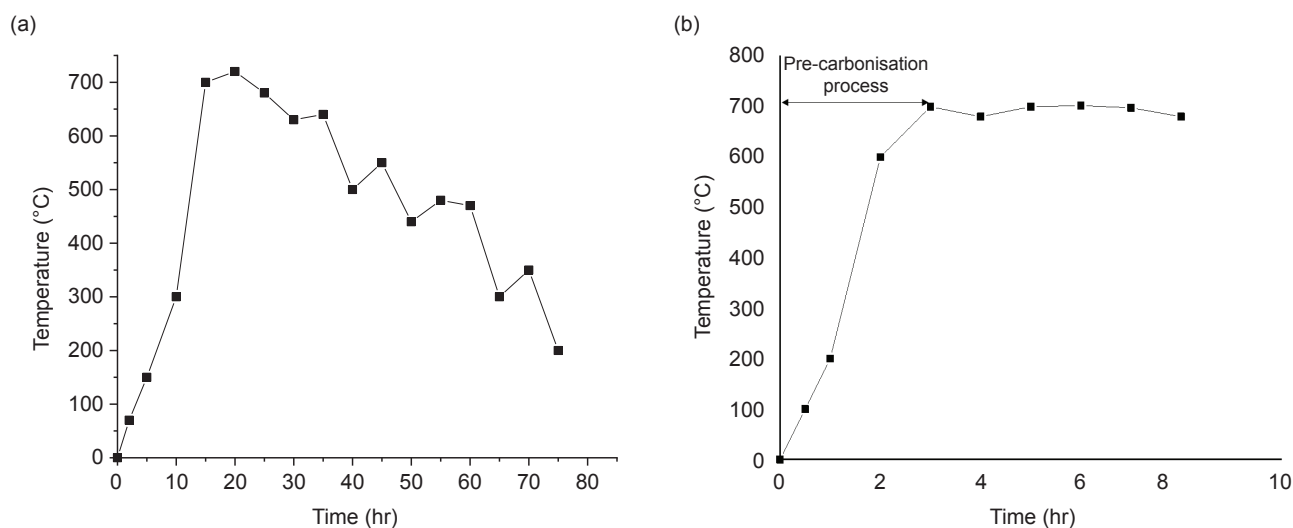

Figure 3. The temperature profile of the OPKS-charcoal production in the (a) TCS, and (b) PRK systems.

accomplishes faster carbonisation, prevents the over-burning of raw material into ash, and thus, increases the quality of OPKS-charcoal compared to TCS and other batch kiln systems. Conversely, low OPKS-charcoal yield (22 ± 1.7%) was produced with TCS due to a longer carbonisation process, burning more OPKS into ash.

A conventional earth kiln system requires a high temperature, 500°C, to reduce volatile matters and tar due to its material structures, hence decreasing the quality and yield of the charcoal obtained (Sangsuk *et al.*, 2018). In the PRK system, more liquids and tar were removed from the raw material during carbonisation at 400°C-700°C, resulting in increased fixed carbon (Arami-niya *et al.*, 2010). Moreover, exothermic decomposition started within the temperature range, which involved the breakdown and devolatilisation of the OPKS that released mixed gases, vapours, and tars, therefore contributing to higher fixed carbon content (Wang *et al.*, 2017). Consequently, the PRK produced OPKS-charcoal with high yield and fixed carbon content at 30 ± 2.4% and 83.7 ± 2.0%, respectively.

The OPKS-charcoal acquired through the PRK documented higher HHV than those obtained via TCS, kiln-HDP, and TPI kiln. The increased HHV of the PRK-produced OPKS-charcoal was due to faster heat distribution throughout the kiln, resulting in efficient heat transfer to materials in the reactor. Conversely, a thermal gradient was generated in the TCS from the hot surfaces of the char particles to its interior, leading to difficulties in caloric transport (Alslaibi *et al.*, 2013). The observations supported the findings reported by Parikh *et al.* (2005), which correlated HHV with the fixed carbon, volatile

matter, and ash content of the charcoal. Moreover, the high ash content of the OPKS-charcoal acquired through TCS also contributed to the low HHV. Overall, the OPKS-charcoal produced via the PRK approach documented higher quality and yield than batch systems (TCS, kiln HDP, and TPI kiln). The system also produced OPKS-charcoal that met the United Kingdom (UK) standard quality specifications for imported charcoal (Paddon and Harker, 1979).

Energy Efficiency

The heat in the distribution pipe in the kiln of the PRK system was rotated, resulting in perfectly carbonised materials, producing OPKS-charcoal with elevated HHV. The uniformity during the carbonisation process in the PRK approach resulted in its high efficiency (55%) compared to the TCS (38%) (*Table 3*). Furthermore, increased

mass yield and HHV supplied highly efficient energy-conversion charcoal. Charcoal efficiency is classified into four categories, (1) 8%-12% for the conventional or traditional kiln, (2) 12%-17% for improved conventional or traditional kiln, (3) 14%-20% for industrial technology, and (4) 25%-33% for new high yield technology (Energypedia, 2019), where the PRK method is classified under the fourth category.

By-products

The carbonisation of OPKS into biochar produces two main by-products, wood vinegar and gases. In the current study, the wood vinegar from the PRK method was collected during carbonisation before being analysed with GC. Nevertheless, the vinegar collected from TCS was not evaluated as it was mixed with the vinegar from the firewood employed during carbonisation. *Table 4* lists approximately

TABLE 2. COMPARISONS BETWEEN THE TCS AND PRKS-PRODUCED CHARCOAL AND THE UK SPECIFICATIONS FOR IMPORTED CHARCOAL

Item	TCS (present study)	PRK (present study)	Metal kiln-heat distribution pipe (HDP) (Sangsuk *et al.*, 2018)	Transportable metal kiln (TPI) (Paddon and Harker, 1979)	UK specification (Paddon and Harker, 1979)
Carbonisation duration (hr)	72	8	27	34	-
Moisture content of raw material (%)	9.55 ± 0.7	9.55 ± 1.0	30	38	-
HHV of raw material (MJ kg^{-1})	17.9 ± 0.9	17.9 ± 0.9	18.5	21.7	-
Moisture content of OPKS-charcoal (%)	-	-	8.5	3.5	< 5
Volatile matter of OPKS-charcoal (%, dry basis)	12.5 ± 1.0	10.2 ± 1.4	7.7	13.3	< 13
Fixed carbon of OPKS-charcoal (%, dry basis)	80.1 ± 2.0	83.7 ± 2.0	81	81.1	> 80
Ash content of the OPKS-charcoal (%, dry basis)	7.4 ± 0.1	6.1 ± 1.2	11.3	2.10	< 3
HHV of OPKS-charcoal (MJ kg^{-1}, dry basis)	30.9 ± 0.9	33.1 ± 1.8	30.4	32.5	> 30
OPKS-charcoal yield (%)	22 ± 1.7	30 ± 2.4	24	21	-
Cost per system (USD)	45 761	102 963	9 300	1 000 (Austin and Kohn, 1990)	-

TABLE 3. THE ENERGY BALANCE OF THE OPKS-CHARCOAL PRODUCED VIA THE TCS AND PRK APPROACHES

Energy	TCS	PRK
Input		
Raw material (OPKS)	160.6×10^6 kJ	$1\,032.7 \times 10^6$ kJ
Raw material firewood	33.7×10^6 kJ	-
Diesel	-	0.14×10^6 kJ
Scrubber	-	7.3×10^6 kJ
Total input	194.3×10^6 kJ	$1\,040.1 \times 10^6$ kJ
Output		
OPKS-charcoal	60.9×10^6 kJ	572.1×10^6 kJ
Wood vinegar	42.5×10^6 kJ	510.5×10^6 kJ
Total output	103.4×10^6 kJ	$1\,082.6 \times 10^6$ kJ
Heat required to evaporate water (gas)	6.64×10^5 kJ	5.40×10^5 kJ
Total heat required to evaporate water	8.25×10^5 kJ	7.01×10^5 kJ
Total output energy	8.3×10^6 kJ	17.9×10^6 kJ
Net heat loss by convection radiation/exhaust	45.9×10^6 kJ	16.2×10^6 kJ
Net-energy ratio	0.53	1.04
Energy efficiency = [(yield OPKS-charcoal × HHV OPKS-charcoal)/ (HHV OPKS)] × 100	38%	55%

33 chemical compounds detected in the OPKS-wood vinegar collected from the PRK system. The chemicals were from furan and pyran derivatives, phenol and its derivatives, organic acids, ketones, amides, and alcohols.

The highest compounds in the OPKS-wood vinegar were phenols and their derivatives, accounting for 41.9% of the total composition. The major compounds present in the group were 3-amino-1, 2-propanediol (23.0%) and phenol (18.8%), followed by organic acids (38.2%), primarily hexadecanoic acid. Other compounds (18.9%), amide (18.5%), furan and pyran derivatives (11.8%), alcohols (9.3%), and ketones (1.91%) were also detected. Phenols and furans were derived from the decomposition of lignin and hemicellulosic components in woody materials, including oil palm biomass (Mathew and Zakaria, 2015), while amide, alcohols, and ketones were produced from the decomposition of cellulose during the carbonisation process (Stefanidis *et al.*, 2014).

According to Suresh *et al.* (2019), the antifungal activities and some preservative effects of the OPKS are attributable to the phenols, ketones, and organic acids. Moreover, the organic acids and phenols in the OPKS-wood vinegar were correlated with strong bacteria inhibition (Ma *et al.*, 2013). The organic acids in wood vinegar also improved the nutritional quality of fruits due to enhanced soil nutrients, such as NH_4^+-N, NO_3^-, N, and Mg, that are essential for plant growth (Zhang *et al.*, 2020).

Consequently, carbonising OPKS produces good quality charcoal and wood vinegar for various applications.

In the current study, gaseous pollutants released during OPKS carbonisation with TCS and PRK were examined at 700°C, the temperature at which high HHV charcoal was produced (*Table 5*). Primarily, H_2, CO, and CH_4 gases were recorded at approximately 74.0% and 51.2% of the total volume in the PRK and TCS systems. According to Wu *et al.* (2019), H_2 was primarily produced from the secondary tar cracking reaction and dehydrogenation of cellulose. The CO was contributed from the carbonyl functional group, while an unstable intermediate decomposition product formed CH_4 during the OPKS carbonisation. The gases could be captured and comprehensively converted to synthesise hydrogen and natural gases, hence considered one of the most promising fossil fuel alternatives in the future (Zhang *et al.*, 2016).

The CO_2 compounds were principally derived from oxygenated organic and inorganic components in OPKS (Adam, 2009). Conventional carbonisation, such as the TCS and traditional charcoal systems, produce the highest CH_4 and CO_2. Nevertheless, the emission of CH_4 gas has more notable greenhouse effects than CO_2 as the gas was from biomass burning. Accordingly, introducing an environmentally efficient rotary kiln or PRK could significantly reduce the harmful gaseous emissions.

TABLE 4. THE COMPOUNDS IDENTIFIED IN THE OPKS-WOOD VINEGAR PRODUCED DURING THE CARBONISATION PROCESS WITH THE PRK SYSTEM

No.	Compound	Retention time (min)	Relative content (%)
	Furan and pyran derivatives		**11.8**
1	Pyridine	7.47	5.13
2	Paromomycin	14.5	1.5
3	Pyridine	14.5	2.17
4	Cystine	15.7	2.96
	Phenol and derivatives		**41.8**
5	3-Amino-1,2-propanediol	9.54	23.0
6	Phenol	20.2	18.8
	Organic acids		**38.2**
7	Acetic acid	10.3	1.56
8	Hexadecanoic acid	19.8	36.6
	Ketones *(1.91)*		**1.91**
9	Butyrolactone	14.2	1.91
	Amide *(18.57)*		**18.5**
10	Acetamide	8.18	4.46
11	Benzeneethanamine	8.37	1.25
12	N-Methoxy-1-ribofuranosy l-4-imidazolecarboxylic amide	9.18	12.8
	Alcohols		**9.30**
13	Ethanol	11.6	9.30
	Others		**18.9**
14	D-Mannoheptulose	9.36	12.3
15	d-Glycero-d-ido-heptose	13.8	2.85
16	Deoxyspergualin	14.2	3.81

TABLE 5. THE COMPOSITIONS OF THE GASEOUS PRODUCTS FROM OPKS CARBONISATION AT 700°C VIA DIFFERENT SYSTEMS

Gas (wt%)	TCS	PRK	Giudicianni et al. (2017)
H_2	5.04 ± 1.0	36.8 ± 3.4	0.3-4.8
CH_4	24.1 ± 5.0	16.7 ± 2.2	0.3-5.3
CO_2	45.7 ± 3.5	16.7 ± 2.8	74.2-87.7
CO	22.1 ± 1.9	20.4 ± 0.9	7.6-19.4
C_2	2.98 ± 0.9	5.96 ± 1.8	-
Others	-	3.24 ± 1.7	-

Comparison and Economic Analysis

The economic analysis of the TCS and PRK systems assessed in the current study is summarised in *Table 6*. The estimated fixed cost to acquire OPKS-charcoal via TCS and PRK was RM12 318 and RM35 077 respectively. The payback period for the TCS was projected at 4.46 years, which was longer than the PRK, requiring 0.26 years. The findings were due to the lower internal rate of return (IRR) of TCS, 48%, compared to PRK at 65%, contributed by a higher benefit to cost ratio (B:C) of 1.18 compared to 0.85 by the TCS.

Since the B:C of the PRK employed in the present study was >1, the net present value (NPV) was positive, and the IRR was greater than the opportunity cost of capital, the investment for the approach was more financially feasible than TCS. Furthermore, the economic attainability of PRK would be more profitable if the system is installed near palm oil millers and utilises the OPKS produced by the mills. The approach could reduce the cost of transportation for raw materials, while excess energy and steam produced internally by the mills could be redirected to operate the PRK.

CONCLUSION

Harvesting OKPS-charcoal at 700°C carbonisation temperature utilising raw materials from OPKS via the PRK, a continuous carbonisation technology, produced the highest charcoal and energy efficiency at 38% and 55%, respectively. In the current study, the OPKS-charcoal acquired through the PRK and TCS systems recorded 33.1 and 30.9 MJ kg^{-1} HHV, respectively. The OPKS-charcoal with the high yield, HHV, and low gaseous emissions was considerable to the palm oil industry as it offered value-added

TABLE 6. ECONOMICS ANALYSIS OF THE TCS AND PRK PRODUCED OPKS-CHARCOAL IN A PILOT-PLANT CAPACITY (RM1 = USD0.23)

Item	Cost involved in the TCS system	Cost involved in the PRK system
Capital cost (building, TCS system, and infrastructure)	RM300 000	RM500 000
Operating cost (per month) (A)		
Electricity	RM15	RM2 550
Water	RM15	RM20
Transportation	RM600	RM600
Labour	RM6 000	RM3 600
Raw material, OPKS	RM2 688	RM17 280
Firewood/Diesel*	RM3 000	RM11 027*
Total production cost (A)	RM12 318	RM35 077
Average charcoal and vinegar sale (per month) (B)		
Charcoal price (RM3 kg^{-1})	RM5 913.60 Charcoal produced was 1 971.20 kg month^{-1} = RM3 × 1 971.20 kg	RM51 840 Charcoal produced was 17 280 kg month^{-1} = RM3 × 17 280 kg
Price of wood vinegar (RM10 L^{-1})	RM12 000 Wood vinegar produced was 1 200 L month^{-1} = RM10 × 1 200 L	RM144 000 Wood vinegar produced was 14 400 L month^{-1} = RM10 × 14 400 L
Total sales per month (B)	RM17 913.60	RM195 840.00
Net profit per month (B − A)	RM5 595.60 ≈ USD1 274.91	RM160 763 ≈ USD36 628.63
Payback period = per year	4.46 years	0.26 years

products and a zero-waste operation. Furthermore, manufacturing OPKS-charcoal with the continuous PRK approach could generate higher profit than conventional carbonisation technologies, therefore suitable for utilisation in commercial settings.

REFERENCES

Adam, J (2009). Improved and more environmentally friendly charcoal production system using a low-cost retort-kiln (Eco-charcoal). *Renew. Energy, 34(8)*: 1923-1925.

Alslaibi, T; Abustan, I; Ahmad, M and Foul, A (2013). A review: Production of activated carbon from agricultural by-products via conventional and microwave heating. *J. Chem. Technol. Biotechnol., 88(7)*: 1183-1190.

Arami-niya, A; Mohd, W; Wan, A and Mjalli, F (2010). Using granular activated carbon prepared from oil palm shell by ZnCl 2 and physical activation for methane adsorption. *J. Anal. Appl. Pyrolysis, 89(2)*: 197-203.

Astimar, A; Ropandi, M; Norfaizah, J; Nahrul Hayawin, Z and Zawawi, I (2012). The production of oil palm-based activated charcoal and pyroligneous acid (wood vinegar). *MPOB Information Series, TT No. 515, (June)*: 1-2.

Austin, J E and Kohn, T O (1990). *Strategic Management in Developing Countries: Case Studies.* Free Press, USA. 691 pp.

Awasthi, M K; Duan, Y; Awasthi, S K; Liu, T and Zhang, Z (2020). Influence of bamboo biochar on mitigating greenhouse gas emissions and nitrogen loss during poultry manure composting. *Bioresour. Technol., 303(February)*: 122952.

Bailis, R; Rujanavech, C; Dwivedi, P; Oliveira, A De; Chang, H; Carneiro, R and Miranda, D (2013). Energy for sustainable development innovation in charcoal production: A comparative life-cycle assessment of two kiln technologies in Brazil. *Energy Sustain. Dev., 17(2)*: 189-200.

Basalirwa, D; Sudo, S; Wacal, C; Akae, F; Oo, A Z; Koyama, S; Sasagawa, D; Yamamoto, S; Masunaga, T and Nishihara, E (2020). Assessment of crop residue and palm shell biochar incorporation on greenhouse gas emissions during the fallow and crop growing seasons of broccoli (*Brassica oleracea* var. *italica*). *Soil Tillage Res., 196(October 2019)*: 104435.

Chen, D; Chen, X; Sun, J; Zheng, Z and Fu, K (2016). Pyrolysis polygeneration of pine nut shell: Quality of pyrolysis products and study on the preparation of activated carbon from biochar. *Bioresour. Technol., 216*: 629-636.

Chen, W H; Wang, C W; Ong, H C; Show, P L and Hsieh, T H (2019). Torrefaction, pyrolysis and two-stage thermodegradation of hemicellulose, cellulose and lignin. *Fuel, 258*: 116168.

Energypedia (2019). Charcoal production. GIZ HERA cooking energy compedium. https://energypedia.info/wiki/Charcoal_Production, assessed on 6 January 2021.

Fan, X; Wang, X; Cai, Y; Xie, H; Han, S and Hao, C (2022). Functionalized cotton charcoal/chitosan biomass-based hydrogel for capturing Pb^{2+}, Cu^{2+} and MB. *J. Hazard. Mater., 423*: 127191.

Goh, C S; Tan, H T and Lee, K T (2012). Pretreatment of oil palm frond using hot compressed water: An evaluation of compositional changes and pulp digestibility using severity factors. *Bioresour. Technol., 110*: 662-669.

Hamzah, N; Tokimatsu, K and Yoshikawa, K (2019). Solid fuel from oil palm biomass residues and municipal solid waste by hydrothermal treatment for electrical power generation in Malaysia: A review. *Sustainability, 11:* 1060.

Harimi, M; Megat Ahmad, M; Sapuan, S and Idris, A (2005). Numerical analysis of emission component from incineration of palm oil wastes. *Biomass and Bioenergy, 28*: 339-345.

Heberlein, S; Chan, W P; Veksha, A; Giannis, A; Hupa, L and Lisak, G (2022). High temperature slagging gasification of municipal solid waste with biomass charcoal as a greener auxiliary fuel. *J. Hazard. Mater., 423*: 127057.

Idris, J; Shirai, Y; Andou, Y; Mohd Ali, A; Othman, M; Ibrahim, I and Hassan, M (2015). Self-sustained carbonisation of oil palm biomass produced an acceptable heating value charcoal with low gaseous emission. *J. Clean. Prod., 89*: 257-261.

Kamali, M; Sweygers, N; Al-Salem, S; Appels, L; Aminabhavi, T M and Dewil, R (2022). Biochar for soil applications-sustainability aspects, challenges and future prospects. *Chem. Eng. J., 428*: 131189.

Kammen, D M and Lew, D J (2005). Review of technologies for the production and use of charcoal. *Renewable and Appropriate Energy Laboratory Report*, 1-19.

Kodera, Y and Kaiho, M (2016). Model calculation of heat balance of wood pyrolysis. *J. Jpn. Inst. Energy*, *95(10)*: 881-889.

Kushairi, A; Loh, S K; Azman, I; Hishamuddin, E; Ong-Abdullah, M; Izuddin, Z B M N; Razmah, G; Sundram, S and Parveez, G K A (2018). Oil palm economic performance in Malaysia and R&D progress in 2018. *J. Oil Palm Res.*, *30(2)*: 163-195.

Lan, W; Chen, G; Zhu, X; Wang, X; Wang, X and Xu, B (2019). Research on the characteristics of biomass gasification in a fluidized bed. *J. Energy Inst.*, *92*: 613-620.

Ma, C; Song, K; Yu, J; Yang, L; Zhao, C; Wang, W; Zu, G and Zu, Y (2013). Pyrolysis process and antioxidant activity of pyroligneous acid from *Rosmarinus officinalis* leaves. *J. Anal. Appl. Pyrolysis*, *104*: 38-47.

Mahlia, T M I; Ismail, N; Hossain, N; Silitonga, A S and Shamsuddin, A H (2019). Palm oil and its wastes as bioenergy sources: A comprehensive review. *Environ. Sci. Pollut. Res.*, *26(15):* 1-18.

Mathew, S and Zakaria, Z A (2015). Pyroligneous acid-the smoky acidic liquid from plant biomass. *Appl. Microbiol. Biotechnol.*, *99(2)*: 611-622.

Nahrul Hayawin, Z; Astimar, A A; Idris, J; Mamat, R; Hassan, M A; Bahrin, E K and Suraini Abd-Aziz (2017). Microwave-assisted pre-carbonisation of palm kernel shell produced charcoal with high heating value and low gaseous emission. *J. Clean. Prod.*, *142*: 2945-2949.

Nahrul Hayawin, Z; Astimar, A A; Idris, J; Nor Faizah, J; Ropandi, M; Mohamad Faizal, I; Hassan, M A and Abd Aziz, S (2018). Reduction of POME final discharge residual using activated bioadsorbent from oil palm kernel shell. *J. Clean. Prod.*, *182*: 830-837.

Nahrul Hayawin, Z; Ibrahim, M F; Norfaizah, J; Ropandi, M; Astimar, A A; Noorshamsiana, A W and Abd Aziz, S (2020). Palm oil mill final discharge treatment by a continuous adsorption system using oil palm kernel shell activated carbon produced from two-in-one carbonisation activation system reactor. *J. Water Process Eng.*, 101262.

Nipattummakul, N; Ahmed, I I; Kerdsuwan, S and Gupta, A K (2012). Steam gasification of oil palm trunk waste for clean syngas production. *Appl. Energy, 92:* 778-782.

Nyakuma, B B; Johari, A; Ahmad, A and Abdullah, T A T (2014). Comparative analysis of the calorific fuel properties of empty fruit bunch fiber and briquette. *Energy Procedia, 52*: 466-473.

Oh, S J; Choi, G G and Kim, J S (2016). Characteristics of bio-oil from the pyrolysis of palm kernel shell in a newly developed two-stage pyrolyzer. *Energy, 113*: 108-115.

Paddon, A R and Harker, A P (1979). The production of charcoal in a portable metal kiln. *Tropical Products Institute, 12*: 17.

Parikh, J; Channiwala, S A and Ghosal, G K (2005). A correlation for calculating HHV from proximate analysis of solid fuels. *Fuel*, *84(5)*: 487-494.

Purwanto, H; Zakiyuddin, A M; Rozhan, A N; Mohamad, A S and Salleh, H M (2018). Effect of charcoal derived from oil palm empty fruit bunch on the sinter characteristics of low grade iron ore. *J. Clean. Prod.*, *200*: 954-959.

Sangsuk, S; Suebsiri, S and Puakhom, P (2018). The metal kiln with heat distribution pipes for high quality charcoal and wood vinegar production. *Energy Sustain. Dev.*, *47*: 149-157.

Santos, S de F de O M; Piekarski, C M; Ugaya, C M L; Donato, D B; Braghini, A; de Francisco, A C and Carvalho, A M M L (2017). Life cycle analysis of charcoal production in masonry kilns with and without carbonisation process generated gas combustion. *Sustainability*, *9(9)*: 1-20.

Stefanidis, S D; Kalogiannis, K G; Iliopoulou, E F; Michailof, C M; Pilavachi, P A and Lappas, A A (2014). A study of lignocellulosic biomass pyrolysis via the pyrolysis of cellulose, hemicellulose and lignin. *J. Anal. Appl. Pyrolysis*, *105*: 143-150.

Suresh, G; Pakdel, H; Rouissi, T; Brar, S K; Fliss, I and Roy, C (2019). *In vitro* evaluation of antimicrobial efficacy of pyroligneous acid from softwood mixture. *Biotechnology Research and Innovation*, *3(1)*: 47-53.

Tavakkol, S; Zirwes, T; Denev, J A; Jamshidi, F; Weber, N; Bockhorn, H and Trimis, D (2021). An Eulerian-Lagrangian method for wet biomass carbonisation in rotary kiln reactors. *Renew. Sust. Energ. Rev.*, *139*: 110582.

Trangkaprasith, K (2011). Heating value enhancement of fuel pellets from frond of oil palm. *Int. Conf. Biol. Environ. Chem. IPCBEE Vol.1. IACSIT Press. Singapore*, *1*: 302-306.

Tymoszuk, M; Mroczek, K; Kalisz, S and Kubiczek, H (2019). An investigation of biomass grindability. *Energy*, *183*: 116-126.

Vijaya, S; Ma, A N; Choo, Y M and Nik Meriam, N S (2008). Life cycle inventory of the production of crude palm oil - A gate to gate case study of 12 palm oil mills. *J. Oil Palm Res.*, *20(2)*: 484-494.

Wang, Q; Han, K; Gao, J; Li, H and Lu, C (2017). The pyrolysis of biomass briquettes: Effect of pyrolysis temperature and phosphorus additives on the quality and combustion of bio-char briquettes. *Fuel*, *199*: 488-496.

Wu, Z; Li, Y; Xu, D and Meng, H (2019). Co-pyrolysis of lignocellulosic biomass with low-quality coal: Optimal design and synergistic effect from gaseous products distribution. *Fuel*, *236*: 43-54.

Zhang, S; Chen, Z; Cai, Q and Ding, D (2016). The integrated process for hydrogen production from biomass: Study on the catalytic conversion behavior of pyrolytic vapor in gase solid simultaneous gasification process. *Int. J. Hydrog. Energy*, *41(16)*: 6653-6661.

Zhang, Y; Wang, X; Liu, B; Liu, Q; Zheng, H; You, X; Sun, K; Luo, X and Li, F (2020). Comparative study of individual and co-application of biochar and wood vinegar on blueberry fruit yield and nutritional quality. *Chemosphere*, *246*: 125699.