ORIGINAL ARTICLE

Conversion of oil palm waste into value-added products through pyrolysis: a sensitivity and techno-economic investigation

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Abstract
In this study, an empirical model for the pyrolysis of major oil palm wastes (OPW) such as palm kernel shell (PKS), empty fruit bunches (EFB), and oil palm frond (OPF), and their blends is developed. Moreover, the techno-economic feasibility of the wastes is investigated to determine the type of waste that would be suitable for the commercialization of different types of products. According to the model results, the bio-oil dominates the pyrolysis process' product output, accounting for 59.21, 50.51, 56.60, and 55.65% of PKS, EFB, OPF, and their blend, respectively. Whereas biochar yield is 23.21, 23.1, 22.95, and 23.08%, gas yield is 17.57, 26.38, 20.44, and 21.27%. The findings demonstrate that the feedstocks under consideration are mostly suitable for producing bio-oil. According to the economic analysis, PKS-based pyrolysis has the highest capital expenses (CAPEX), while EFB-based pyrolysis has the lowest CAPEX of all tested feedstocks. Furthermore, PKS has the highest operating expenses (OPEX) due to its relatively higher market price as well as higher moisture content, which necessitates more energy input during the drying stage. Among the feedstocks, OPF has delivered the highest profit of USD 17 M/year, with a 22% return on investment (ROI). In terms of investment capital payback period, all OPW feedstocks demonstrated a reasonable period of 4–6 years. Bio-oil is the most valuable pyrolysis product, with the highest market value when compared to biochar and syngas. The established prediction model can be utilized as a solid reference for biomass pyrolysis modelling studies. Furthermore, the predicted values are reasonable enough to be used in industrial process design.

Keywords Pyrolysis · Predictive model · Oil palm waste · Biochar · Bio-oil · Syngas

Abbreviations

OPW	Oil palm waste
PKS	Palm kernel shell
EFB	Empty fruit bunch
OPF	Oil palm frond
MF	Mesocarp fibre
PF	Palm fruit
OPT	Oil palm trunk
USD	United States dollars
HHV	Higher heating value
LHV	Lower heating value
TGA	Thermogravimetric analysis
CAPEX	Capital expenses
OPEX	Operational expenses
ROI	Return on investment
MSP	Minimum selling price
CEPCI	Chemical Engineering Plant Cost Index
daf.	Dry and ash-free basis

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1 Introduction

Despite a paradigm shift towards renewable energy around the world, there is still a high dependence on fossil fuels for energy recovery from organic wastes. Heavy reliance on fossil fuels has contributed to a range of problems, such as greenhouse gas emissions, rising temperatures, disturbing weather patterns, and imbalances in the energy sector [1, 2]. In the wake of all the issues described above, most nations in the world have developed strategies to find alternative and sustainable energy sources to address increasing energy demand and curb pollution [3]. This shift to renewable energy sources would not only assist to slow down climate

change but also stimulate the world economy [4]. Among the renewable energy sources, biomass has been gaining world attention in the last few decades because of its plentiful availability (of about 200–700 EJ/year), carbon neutrality, low sulfur levels, and low acid levels [5]. Indeed, biomass has considerable promise as a source of renewable energy, with enormous potential in the production of biofuels for heat, power, and transportation. It should be mentioned that biomass is a 100% renewable energy resource since CO_2 emitted during its transformation (decomposition) does not increase atmospheric carbon dioxide because it is organic in nature [6].

Oil palm is one of the world's most important sources of edible oil. Malaysia is the world's second-largest exporter of palm oil, accounting for 33% of global palm oil demand [7]. Oil palm plants are farmed on roughly 9.6 million hectares of land in Malaysia, creating an extravagant quantity of waste of around 95.3 million tons [8, 9]. Oil palm waste (OPW) constitutes different waste generated from palm oil processing and oil palm plant cultivation. The waste from palm mill majorly comprises palm oil mill effluent (POME) (60%), empty fruit bunches (EFB) (23%), mesocarp fibre (MF) (21%), and palm kernel shell (PKS) (5%) [10, 11]. The second source of OPW is obtained from palm oil fields where oil palm fronds (OPF) and oil palm trunk (OPT) are generated. Despite OPWs' ubiquitous availability, it is underutilized, with most of it ending up in landfills or being used sparingly as soil conditioners (fertilizers). OPW has a typical heating value of 16–20 MJ/kg; hence, they can be used to produce energy and other valuable chemicals [12,

13]. In this work, OPWs such as EFB, PKS, OPF, and a blend of all the three feedstocks are only considered as these wastes are generated in large quantities and also an appropriate use of these wastes remains a concern for palm oil millers and municipal governments. The palm tree parts that are considered in this study are illustrated in Fig. 1.

Energy can be recovered from biomass via both biological and thermochemical methods, where the latter is crucial for converting the lignocellulosic biomass into all three phases of fuels (solid, liquid, and gas) [14]. When it comes to thermochemical conversion applications, pyrolysis has been found to be one of the most effective methods for producing bio-oil, syngas, and biochar [15]. Until a few decades ago, the primary purpose of pyrolysis was to produce a liquid (bio-oil) for use as fuel. This is because bio-oils generated utilizing pyrolysis technology have superior features such as reduced viscosity, lower melting point, and greater cetane values when compared to transesterification [16]. However, now there is a growing interest in producing biochar by biomass pyrolysis [17]. The pyrolysis mechanism of conversion of the aforementioned OPW is investigated in this study.

Depending on the desired prediction, researchers have developed various models of varying complexity so far. Four main model types are employed, which include (1) empiric models, (2) kinetic models, (3) chemical equilibrium-based models, and (4) mechanistic models [18]. Despite the availability of the above models, researchers often use empiric models to forecast the distribution of pyrolysis products. In empirical models, a set reported experimental investigations and data are mathematically

Fig. 1 Illustration of palm tree parts considered in this study
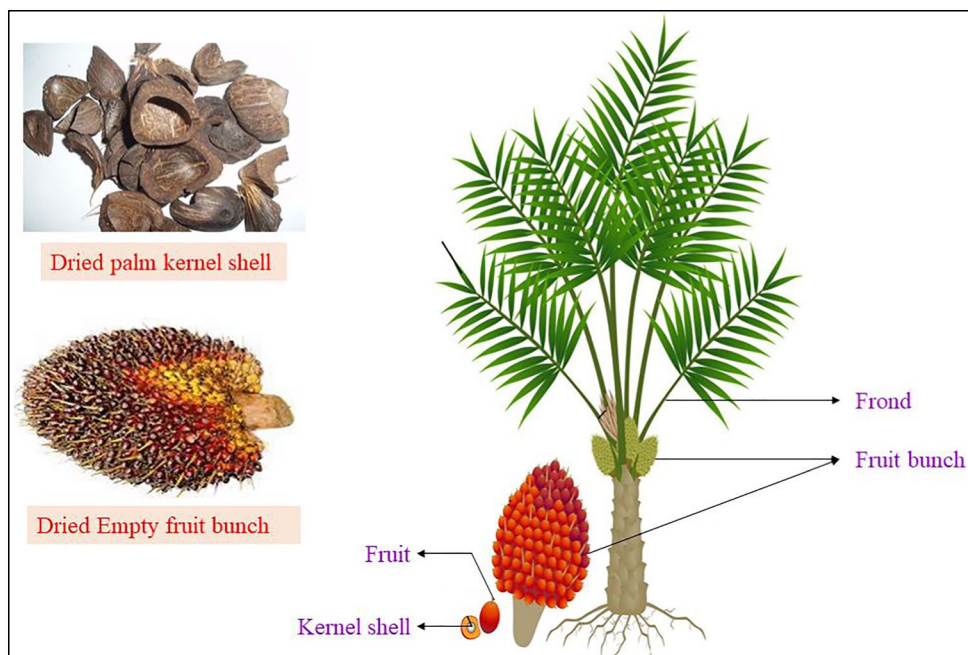
optimized to develop a general model, which explains and offers empirical results [19]. The empirical model has been used in this investigation because it accurately predicts the properties of pyrolysis products [20]. The reactions involved in the pyrolysis process provide the basis for the model. During the simulation phase, pyrolysis regulating parameters like heating rate and temperature are considered. To carry out the mass and energy balances, the current model uses empirical equations, and empirical correlations to depict the overall patterns of product distribution. A technical and economical evaluation of biofuels production from OPW is needed to determine commercial aspects. In this study, the economic evaluation of OPW pyrolysis has been weighed against one and another. The technical assessment provides a thorough evaluation of the process yield, product characteristics, and operating conditions. Wherein the economic study evaluates the process feasibility and provides insights on its capital expenses, operational expenses, payback period, investment return, and annual profit.

In the search to forecast the pyrolysis process, researchers have developed several empiric models. Sharma et al. [21] developed an empirical model to calculate biochar output and flue gas composition of slow pyrolysis of wood. The researchers used and solved set of various equations with zero degrees of freedom using experimental data for the ratio CO to CO_2, CO/CO_2, H_2 to CO_2, and total hydrocarbons to CO_2 by considering the works reported elsewhere [22]. However, the model did not account for temperature parameters in the prediction of char yield. Neves et al. [23] developed an empirical model to characterize the patterns of product distribution using heat and mass balances and empirical correlations. Similarly, Song [24] used the empirical relationships obtained by Neves et al. [23] to apply kinetic parameters to a gasifier reactor. In the current study, the kinetics model of pyrolysis proposed by Song [24] is further improved to forecast yield of pyrolysis

products (biochar, flue gas, and tar). Table 1 compares the details of the previous studies with the current work.

As shown in the table, the majority of the models are based only on the characteristics of feedstock materials, with just a few models based on feedstock attributes and pyrolysis operation parameters. The current study is one of the few that considers both feedstock qualities and pyrolysis conditions. It should also be emphasized that economic analysis based on prediction models is uncommon, and this study is unique in that it focuses on both technical and economic assessment.

The aim of this study is to assess the performance of empirical models for predicting biochar, bio-oil, and syngas. Empirical models were developed based on the proximate and ultimate analyses results of the feedstock samples and also on the pyrolysis operating conditions. The another objective of this investigation is to evaluate the techno-economic analysis of pyrolysis of OPW for the production of bio-oil, biochar, and syngas by considering initial capital investment, operational costs of production, and power consumption by considering the reported data in literature. To the best of the author's knowledge, no published information regarding a prediction model dealing with sensitivity and techno-economic assessments of this type is available. The products of pyrolysis process can be used for soil improvement, carbon sequestration, wastewater treatment, and also for generating energy and power. The techno-economic assessment of OPW will be helpful for the commercializing of biofuel products obtained from pyrolysis process.

2 Material and methods

The feedstock used for this investigation are three types of OPW such as EFB, PKS, and OPF. The EFB and PKS wastes were taken from Kilang Sawit Felcra Nasarudin Sdn. Bhd, Perak, Malaysia, while OPF waste was collected from a palm

Table 1 presents details of some previous pyrolysis studies and novelty of the current study

Model development based on					Predicts		Economic evaluation	Reference
Proximate analysis	Ultimate analysis	Biochemical analysis	Particle size	Operating conditions	Product yield	Products composition		
☐	☐	✓	☐	☐	✓	✓	☐	[21]
✓	✓	☐	✓	☐	✓	✓	☐	[25]
☐	☐	✓	☐	☐	☐	✓	☐	[26]
✓	✓	☐	☐	☐	✓	✓	☐	[23]
☐	☐	✓	☐	✓	✓	✓	☐	[27]
✓	☐	☐	☐	☐	☐	✓	☐	[28]
✓	✓	☐	☐	✓	✓	✓	☐	[29]
☐	✓	☐	☐	☐	✓	✓	☐	[30]
✓	✓	☐	☐	✓	✓	✓	✓	Current study

oil mill in Malaysia. The received OPW were kept in sunlight for 4–5 days to reduce their moisture content. The dried wastes were then grounded and sieved to the desired size using a jaw crusher and sieve shaker. A blend sample was prepared by taking equal proportions of the EFB, PKS, and OPF wastes.

All the prepared samples were stored in air-tight containers for subsequent characterization studies. The proximate analysis for all three types of OPW was done through a Pyris-1 thermogravimetric analyzer (PerkinElmer, USA). The moisture present in the feedstocks was evaluated using ASTM E1131-08. The volatile matter was determined using EN-15148 while the ash content was determined employing ASTM E1775-95. The fixed carbon was calculated subtracting the sum of the compositions of moisture, volatile matter, and ash from 100%. The elemental composition of feedstocks such as C, H, N, O, Cl, and S was calculated using a CHNS 932 analyzer (LECO, USA) by considering the ASTM D5373. The heat content of feedstocks was determined using IKA C5000 bomb calorimeter and higher heating values (HHV) was calculated by adopting ASTM E711-87 [31]. The compositional analysis of the samples was carried out following the procedure adopted by Chan et al. [13].

2.1 Model development and description

An empirical process simulation model was configured for the pyrolysis of OPW as presented in a simplified process flow diagram in Fig. 2. The following assumptions were adopted during the development of the prediction model [23].

(i)   The OPW samples are pyrolysed in an isothermal reactor operating under a nitrogen environment.

(ii)   The drying of samples occurs at the start of the reaction, and the samples are pyrolyzed and converted into water, biochar, bio-oil, volatile gases (CO_2, CO, CH_4, and H_2), and ash.

(iii)   These products are produced in the first stage of pyrolysis, as specified in Eqs. 1–3 [32].

(iv)   The bio-oil is further cracked into volatiles in the second step, which occurs as the temperature rises.

Depending on the biomass composition, the generated gas products split into different gaseous substances during this phase.

$$\text{Total liquid yield} = Y_{\text{bio-oil},F} + Y_{H_2O,F} + \text{Moisture content of samples} \tag{1}$$

$$\text{Total volatile gas yield} = Y_{H_2,F} + Y_{CO,F} + Y_{CH_4,F} + Y_{CO_2,F} \tag{2}$$

$$\text{Total char yield} = 0.106 + 2.43 \times \exp(-0.66 \times T \times 10^{-2}) \tag{3}$$

The composition of carbon, hydrogen, and oxygen in biochar is calculated using the following Eqs. 4–5 [32]:

$$\text{Carbon content} = 0.93 - 0.92 * \exp(-0.42 * T * 10^{-2}) \tag{4}$$

$$\text{Hydrogen content} = (-0.41 \times 10^{-2}) + (0.10 \times \exp(-0.24 \times T \times 10^{-2})) \tag{5}$$

$$\text{Oxygen content} = 0.07 + 0.85 \times \exp(-0.48 * T \times 10^{-2}) \tag{6}$$

The empirical model was initially developed by Neves et al. [23] based on replicated experiments using more than 60 biomass of various attributes, which were conducted using multiple sets of reactors, at a wide range of operating conditions (i.e., temperature of 200–1000 °C). The obtained data were then structured and analyzed to understand the pyrolytic behavior. The data are structured based on pyrolysis products (bio-oil, pyrogas, biochar, and water), as well as the products characteristics (elemental compositions and
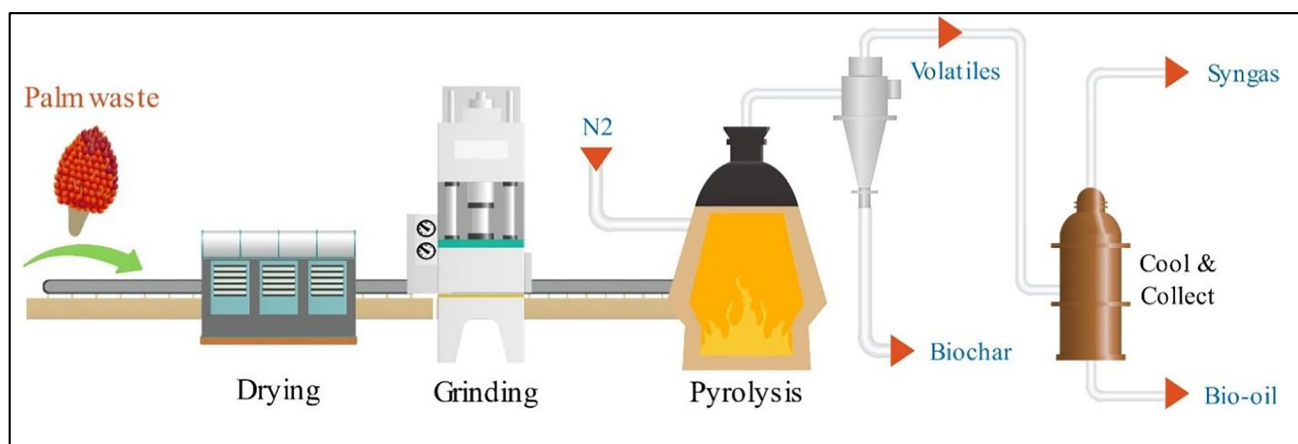

Fig. 2 A simplified process flow diagram of the oil palm waste pyrolysis

Table 2 Equations decsribing the economic parameters

Equations

$$\text{Capital expenses (CAPEX)} = \sum \text{Purchased equipment} + \text{Equipment setting} + \text{Piping} + \text{Civil} + \text{Steel} + \text{Instrumentation} + \text{Electrical} + \text{Insulation} + \text{Paint} + \text{Contract fees} + \text{General and administrative overheads} + \text{Contingencies} \tag{7}$$

$$\text{Working capital} = \frac{5\% \text{ of CAPEX}}{\text{lifetime}} \tag{8}$$

$$\text{Operating expenses (OPEX)} = \sum \text{Feedstocks} + \text{Operating charges} + \text{Labor charges} + \text{maintenance cost} + \text{Plant overhead} + \text{General and admistrative overheads} \tag{9}$$

$$\text{Subtotal operating expenses} = \sum \text{Operating charges} + \text{Labor charges} + \text{maintenance cost} + \text{Plant overhead} \tag{10}$$

$$\text{Labor charges} = (\text{Operators per shift} \times \text{Operator charges}) + (\text{supervisors per shift} \times \text{Supervisor charges}) \tag{11}$$

$$\text{Operating charges} = \frac{25\% \text{ of labor charges}}{\text{Period}} \tag{12}$$

$$\text{Plant overhead} = \frac{50\% \text{ of labor charges and maintenance}}{\text{Period}} \tag{13}$$

$$\text{General and administrative cost} = \frac{8\% \text{ of subtotal operating cost}}{\text{Period}} \tag{14}$$

$$\text{Return on investment (ROI)} (\%) = \frac{\text{Net profit}}{\text{CAPEX}} \tag{15}$$

$$\text{Payback period (years)} = \frac{\text{CAPEX}}{\text{Cashflow}} \tag{16}$$

$$\text{Minimum selling price (MSP)} \left(\frac{\text{USD}}{\text{kg}} \right) = \frac{\text{CAPEX} + \sum_1^{\text{lifespan}} (\text{Opex}(1+\text{DiscountRate})^{-\text{lifespan}})}{\sum_1^{\text{lifespan}} (\text{fuelyield}(1+\text{DiscountRate})^{-\text{lifespan}})} \tag{17}$$

$$\text{Cost}_{\text{design}} = \text{Cost}_{\text{base}} \cdot \left(\frac{\text{Capacity}_{\text{design}}}{\text{Capacity}_{\text{base}}} \right)^{\text{scaling factor}} \cdot \text{Installing factor} \tag{18}$$

$$\text{Cost}_{\text{design,USD}_{2019}} = \text{Cost}_{\text{design,USD}_t} \cdot \left(\frac{\text{CEPCI}_{2019}}{\text{CEPCI}_t} \right) \text{ where CEPCI refers to Chemical Engineering Plant Cost Index} \tag{19}$$

Table 3 Assumptions for the techno-economic analysis

	Values	Units
Parameters		
Location of the proposed plant	Qatar	
Analysis base year	2019	
Plant lifespan	25	years
Discount rate	20	%
Plant capacity	20	tonne/h
Annual operating hours	8000	h/y
Prices assumed		
PKS feedstock	50	USD/tonne
EFB feedstock	35	USD/tonne
OPF feedstock	30	USD/tonne
Blend feedstock	38	USD/tonne
N_2 gas	0.15	USD/kg
Water	0.22	USD/m^3
Electricity	0.07	USD/kwh
Syngas	0.056	USD/kg
Bio-oil	0.4	USD/kg
Biochar	0.2	USD/kg
Natural gas	2.545	USD/MMBtu
Ash disposal	16.3	USD/tonne
Wastewater discharge	0.27	USD/tonne
Operating conditions		
Operating temperature	500	°C
Drying efficiency	90	%
Nitrogen flow rate	5	liter/min (per tonne of feedstock)
Reaction time	30	min

energy contents), through which empirical relationships for the stoichiometry of biomass pyrolysis were then derived.

The energy requirement of the system is estimated based on Cheng et al. model [33], while the energy content of products is calculated based on Dulong's formula [34].

2.2 Techno-economic assessment

Cost estimation is a difficult task, and data should preferably be collected from demonstration plants, though process modeling and literature information can also be useful [35]. Capital expenses (CAPEX) include plant costs (infrastructure including piping and instrumentation) off-site costs (boilers and power generation units, offices), and engineering costs as estimated in Eqs. 7 and 8; and operational costs or expenditures (OPEX), which are further subdivided into fixed and variable costs [35]. Salaries, license fees, taxes, marketing costs, and so on are examples of fixed costs, whereas variable costs are those directly related to production volume, such as feedstock, packaging, and waste

management, as evaluated in Eqs. 9–14 [35]. The return on investment (ROI) (Eq. 15) is the relative gain or loss over a specified time period expressed as a percentage of the investment's initial cost. ROI is considered a vital business performance indicator to evaluate its profitability as a function of expenditure over a timespan. It is one of the important parameter that encourages investors to invest in a project. The payback period (Eq. 16) represents the timespan through which the cost of an investment is recovered, or the length of time required for an investor to reach a breakeven point. The term minimum selling price (MSP) (Eq. 17) refers to the price at which a particular type of good or service is usually sold. It is influenced by the product's type and life cycle. As plant prodution capacity is a critical parameter which have a major impact on the total economics and scaling up of the plant on MSP, ROI, and payback is investigated in this study [36]. The equations that are employed in this study to estimate the economic parameters are presented in Table 2.

The economic feasibility of the OPW pyrolysis is conducted for a plant feed capacity of 20 tonne/h and the assumptions made for the economic asessment are presented in Table 3. The key pyrolysis equipment costs and labor requirements are taken from some earlier technical reports [37, 38]. All prices are scaled up and inflated to the base year of analysis (2019) using the Chemical Engineering Plant Cost Index (CEPCI) (Eqs. 18 and 19) [39]. The CEPCI index is useful for accounting for changes in equipment and goods values over time and linking their values to the performance of the global economy [40]. The year 2019 is selected as the base year of analysis to avoid the uncertainities created by COVID19.

Table 4 The results of the proximate, ultimate, and heating value analyses of the oil palm waste

Components	Feedstock samples			
	PKS	EFB	OPF	Blend
Proximate analysis*				
Moisture (%)	9.70	5.30	5.30	6.77
Volatile matter (%)	72.76	72.13	71.00	72.01
Fixed carbon^d (%)	13.03	19.52	16.80	16.40
Ash (%)	4.52	3.05	6.90	4.82
Ultimate analysis**				
Carbon (%)	48.88	45.15	48.58	47.51
Hydrogen (%)	5.71	4.90	5.30	5.30
Nitrogen (%)	1.01	0.78	0.64	0.81
Oxygen^d (%)	44.39	49.17	45.49	46.38
Chlorine (%)	0.00	0.00	0.00	0.00
Sulfur (%)	0.00	0.00	0.00	0.00
Heating value analysis				
Higher heating value (HHV) (MJ/kg)	18.82	20.20	18.11	19.04

*Air-dried basis, **dry and ash-free basis; d, calculated by difference

Fig. 3 Comparison of proximate analyses of the chosen samples with other works. **a** PKS. **b** EFB. **c** OPF
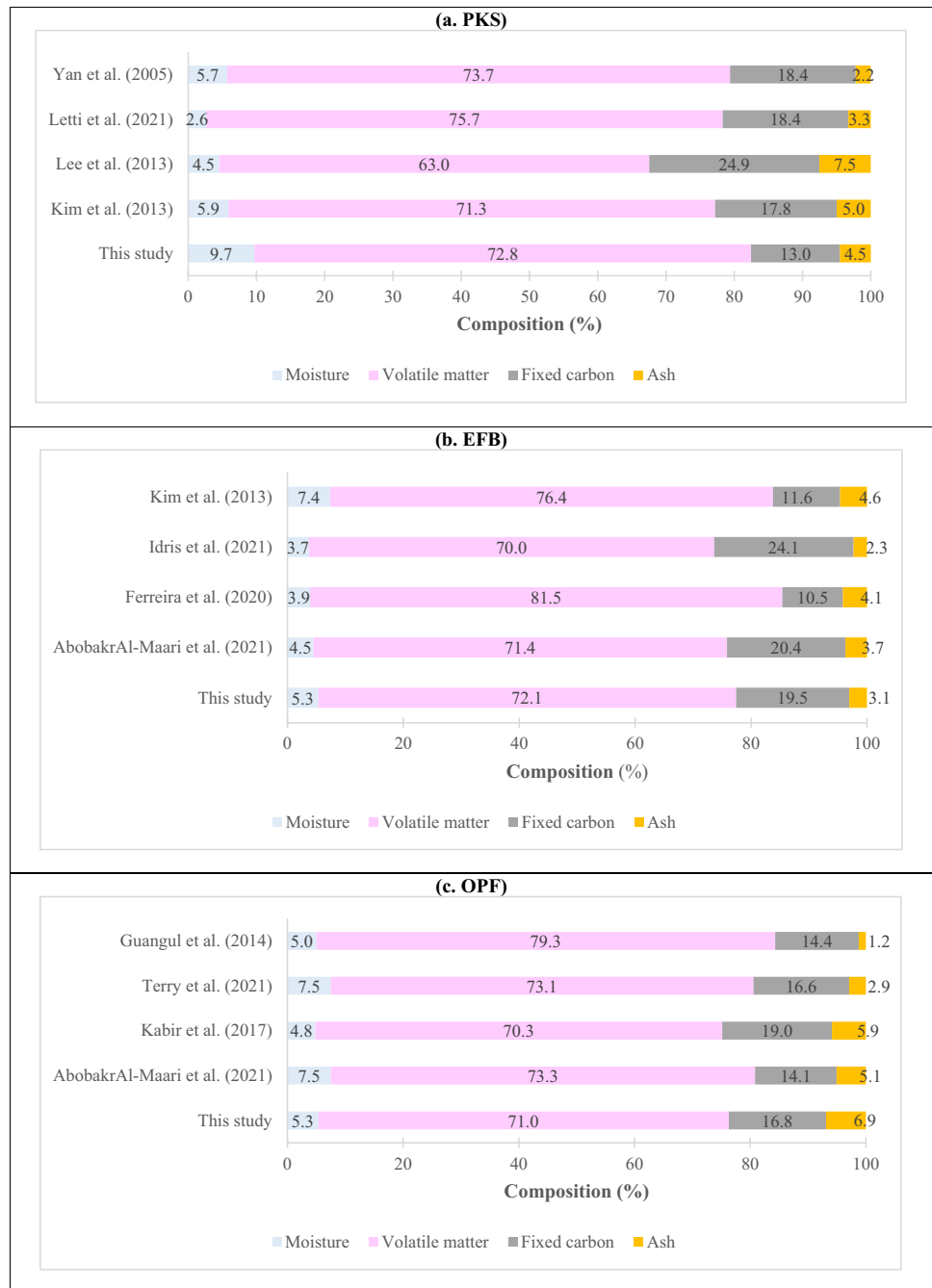
3 Results and discussion

The findings of the feedstock attributes, technical, and economical analyses have been discussed in this section.

3.1 Characteristics analysis

Below is an illustration of the results of the proximate, ultimate, heating value, and feedstock compositional assessments.

3.1.1 Proximate, ultimate, and heating value analyses

The results of the proximate, ultimate, and heating value analyses of the OPW such as PKS, EFB, OPF, and blends are presented in Table 4.

Proximate analysis indicates that the moisture content of all types of wastes is less than 10%. These feedstock samples noticeably meet the requirements for pyrolysis, which requires feedstocks with moisture content below 15% [41]. The high volatile content is noticed more than

Fig. 4 Comparison of ultimate analyses of the chosen samples with other literature. **a** PKS. **b** EFB. **c** OPF
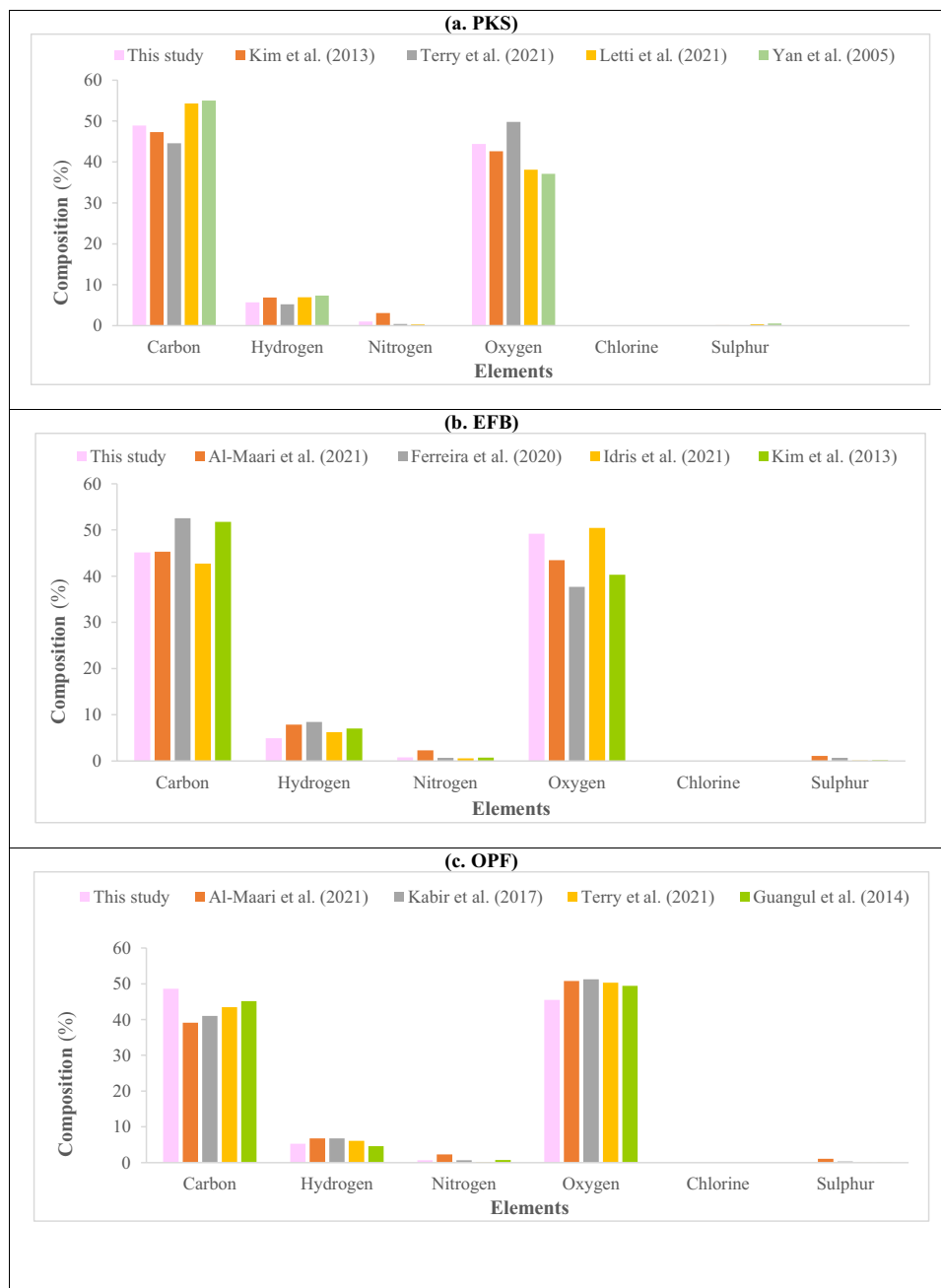
(> 70%) for all wastes. It is generally considered that biomass fuels with high volatile matter and low ash content are favorable for pyrolysis and gasification [42, 43]. A high amount of volatile matter indicates low ignition temperatures. Fuel calorific value primarily depends on its fixed carbon and volatile matter contents. All these samples have considerable fixed carbon content (13–20%), indicating that all of them could have moderate heating values. The ash content of the samples is less than 7%, indicating that they may have good heating properties. An illustration of a comparison of proximate

analyses of the chosen samples with other works can be seen in Fig. 3 [35, 44–52]. All of the works show a minor difference in the proximate analysis results of the feedstock samples. This is due to the fact that the biomass composition is influenced by some external variables such as sunshine, soil nutrients, rainfall, and available water quality [53].

The elemental analysis of the samples reveals that all of them have higher compositions of oxygen and hydrogen (OH, 50–54%) than carbon (45–49%). C-O and O–H bonds, in general, have less energy than carbon–carbon bonds [42].
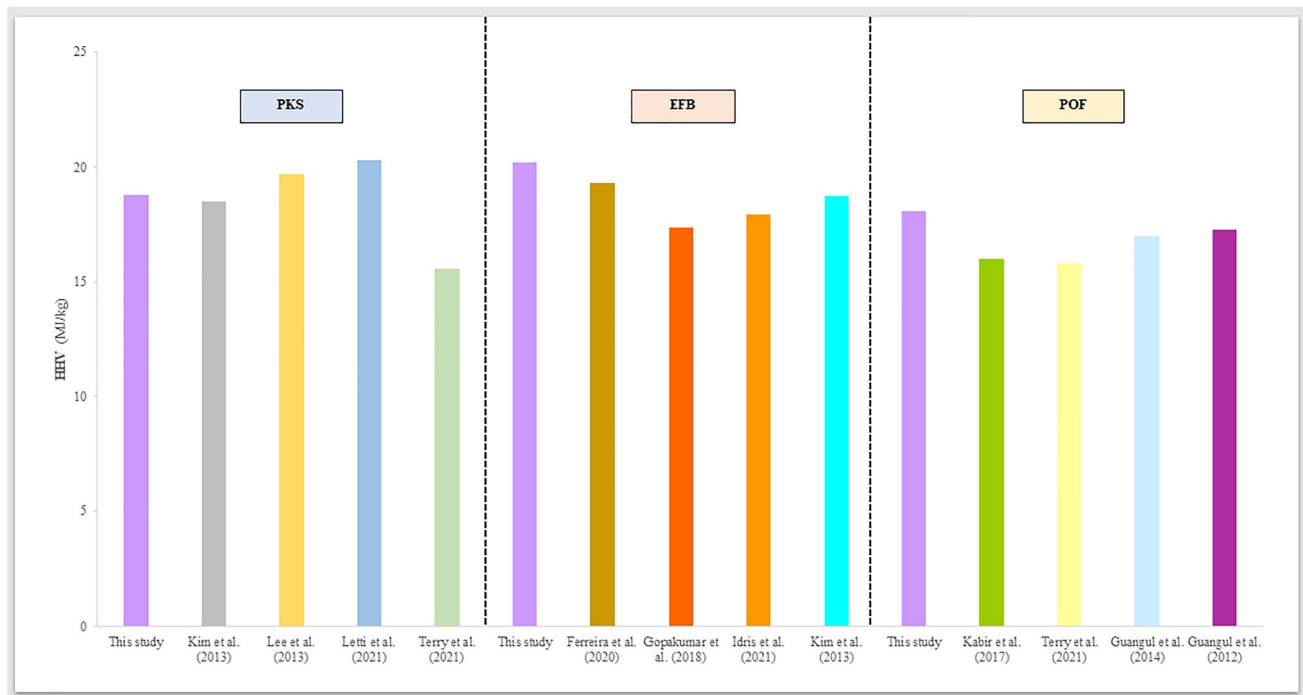
Fig. 5 Comparison of heating values of the chosen samples with other works

Biomass that contains more carbon than oxygen and hydrogen have a higher energy density [42]. Due to the lower levels of nitrogen in the samples (≤ 1), NO$_x$ emissions from these sources are unlikely to cause significant environmental harm. The absence of sulfur and chlorine also means that pyrolysis emissions from these samples will have little impact on the environment.

In Fig. 4, an example of comparison of ultimate analyses of the chosen samples with other studies is shown [35, 44–52]. In all of the works, there is a little difference in the ultimate analytical results of the feedstock samples. This might be owing to variances in biomass quality, which is impacted by factors like weather conditions and landscape quality.

Heating value is an important indicator of biomass' energy content, where it is correlated to biomass' mass fraction of organic components (i.e., carbon, hydrogen). Biomass with high net energy content is preferred for pyrolysis process, as it may generate superior energy products. The heating values of all samples were nearly identical (18–20 MJ/kg). The samples' moderate heating values imply that the pyrolysis products from these samples will also have moderate heating values. Figure 5 illustrates a comparison of the heating values of the selected samples to the heating values of other works [35, 44–48, 50–52, 54, 55]. The variation in heating values between the samples might be attributed to differences in the nature and qualities of the samples.

3.1.2 Compositional analyses

The outcome of the compositional analysis of the OPW is presented in Table 5. As can be seen from the table, the EFB and OPF have high cellulose and hemicellulose (holocellulose) contents [56], while PKS has high lignin content. Due to their high holocellulose content, EFB and OPF are expected to produce a higher gaseous and liquid product upon pyrolysis. PKS, on the other hand, is expected to produce a higher yield of biochar due to its high lignin content. In Fig. 6, a comparison of the compositional analysis of the sample works with that of other works is presented [35, 45–47, 51, 52, 57, 58]. The differences in compositional values may be related to differences in the characteristics of the samples.

3.2 Technical analysis

This section discusses the impact of feedstock types on pyrolysis product yields and syngas component composition. The section also discusses the effect of operating

Table 5 Compositional analysis results of the oil palm waste

OPW type	Composition of components (%)			
	Hemicellulose	Cellulose	Lignin	Extractives
PKS	22.8	23.8	34.6	18.8
EFB	27.5	28.2	17.9	26.4
OPF	31.1	28.4	22.8	17.7

Fig. 6 Comparison of compositional analysis outcome of the chosen samples with other studies. **a** PKS. **b** EFB. **c** OPF
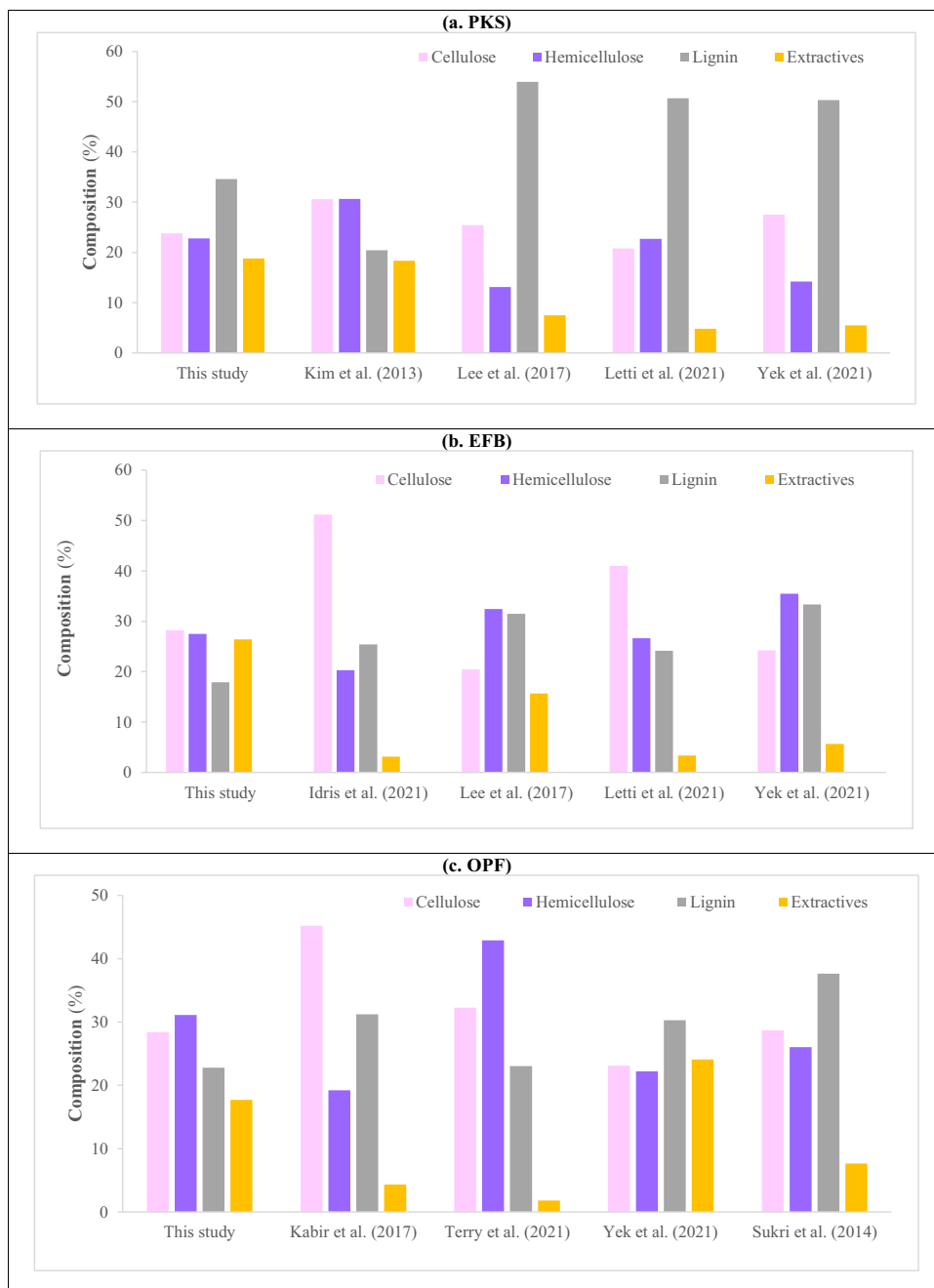
temperature on pyrolysis product yields, elemental composition, and heating value of bio-oil. It also covers how operating temperature affects the elemental composition and heating value of biochar, as well as the elemental composition and heating value of syngas.

3.2.1 Effect of feedstock types on the yields of pyrolysis products

The effect of feedstock types (various OPWs) on pyrolysis product yields is presented in Fig. 7. Among the products,

the bio-oil yield is the highest for all feedstock types. This can be explained by the exothermic degradation reaction of OPW at temperatures ranging from 300 to 500 °C, which improves feedstock devolatilization and thus increases bio-oil yield. The bio-oil yield for PKS, EFB, OPF, and blend feedstock is estimated to be 59.21, 50.51, 56.60, and 55.65% respectively. These high bio-oil yields can be due to moderate content of cellulose in these feedstocks. A biochar yield of 23.21, 23.10, 22.95, and 23.08% is estimated for PKS, EFB, OPF, and blend feedstock, respectively while the syngas yields for PKS, EFB, OPF, and blended feedstocks

Fig. 7 Effect of feedstock types on the yields of products
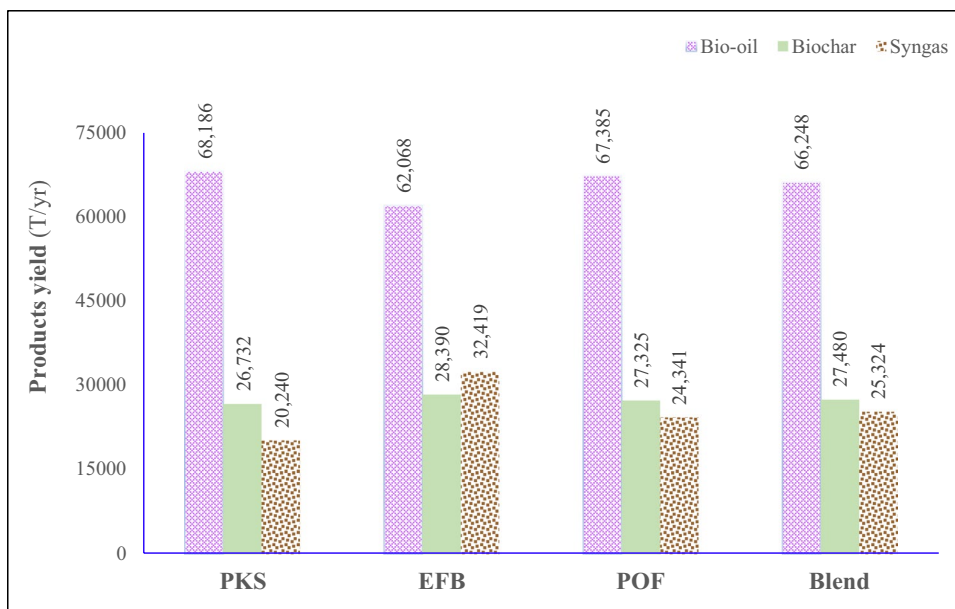
are estimated to be 17.57, 26.38, 20.44, and 21.27% respectively. The biochar yield is higher than the syngas yield for PKS, OPF, and blend feedstock. PKS and OPF have a high and moderate level of lignin, which may have contributed to their high biochar yield. In the case of EFB, the syngas yield exceeds the biochar yield, which could be attributed to the high hemicellulose and extractives content. The aforementioned findings infer that the feedstocks under consideration are mostly suitable for producing bio-oil.

Kim et al. [46] conducted a similar study to investigate the effect of feedstock types on pyrolysis product yields [46].

The researchers used PKS and EFB as pyrolysis feedstocks and conducted the experiments in a fluidized bed at 478 °C. For PKS, the yields of bio-oil, biochar, and syngas were 51.96, 23.20, and 24.80% respectively. Product yields for EFB were observed to be 53.97% (bio-oil), 28.90% (biochar), and 17.10% (syngas), respectively. Kabir et al. [51] utilized palm frond as a pyrolysis feedstock and carried out experiments in a fixed-bed reactor maintained at 500 °C [51]. Bio-oil, biochar, and syngas yields were found to be respectively 45.00, 28.00, and 27.00%. Similar to the current

Fig. 8 Effect of feedstock types on the composition of syngas components
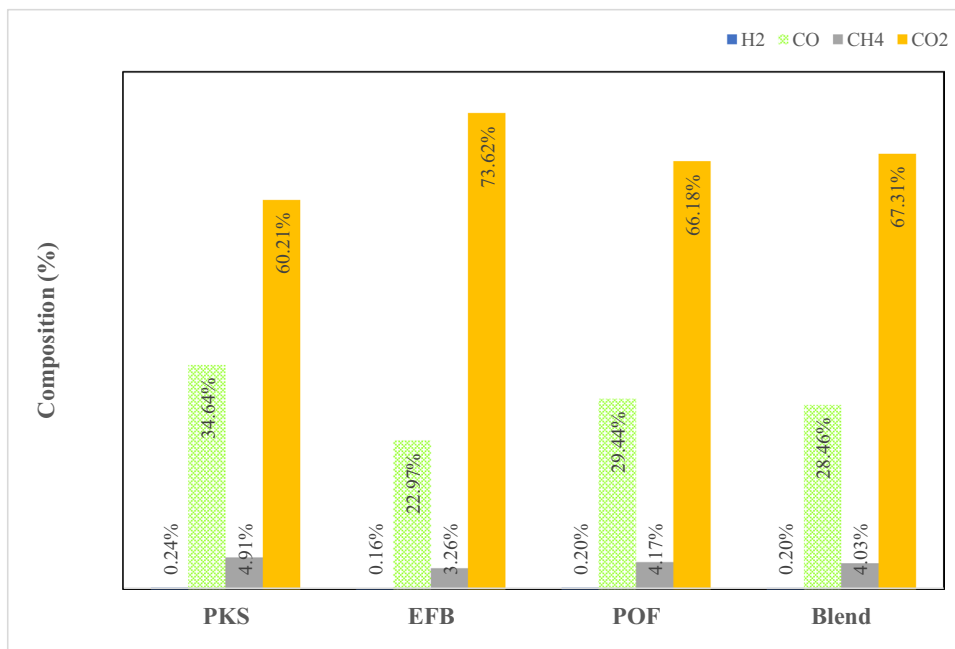
Fig. 9 Effect of operating temperature on pyrolysis products distribution of chosen samples. **a** PKS. **b** EFB. **c** OPF. **d** Equal blend
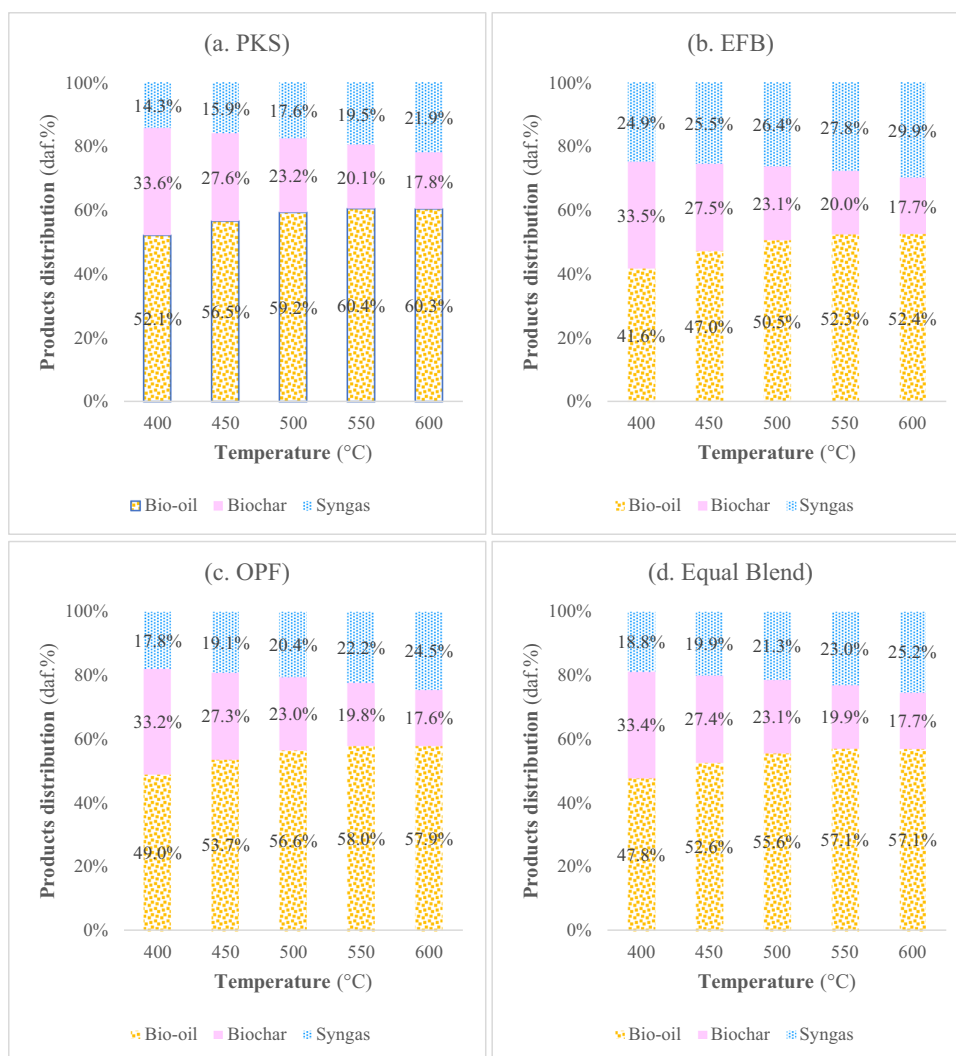
study, the yield of bio-oil was found to be greater than the yields of biochar and syngas.

3.2.2 Effect of feedstock types on the composition of syngas components

The impact of OPW types on the syngas composition is presented in Fig. 8. It can be noted that in all feedstocks, the composition of CO_2 was the highest followed by the compositions of CO, CH_4, and H_2. It can also be observed that the compositions of CH_4 and CO are higher in PKS than in OPF and EFB.

Similar to the current study, Yang et al. [59] examined the influence of PKS biomass on the syngas composition at 500 °C [59]. The compositions of syngas components were of the following order—CO_2 (54.01%), CO (36.77%), H_2 (3.56%), CH_4 (2.84%). However, in the current study, the composition of CH_4 is higher than the H_2 composition. In another study, Ferreira et al. [48] investigated the effect of

EFB feedstock on the syngas composition at 628 °C [48]. The composition of CO_2, CH_4, and H_2 was found to be 69.70, 19.90, and 10.40% respectively while composition of CO was estimated to be 0%.

3.2.3 Effect of operating temperature on the yields of pyrolysis products

The effect of temperature on the yields of bio-oil, biochar, and syngas is depicted in Fig. 9. It can be seen from the figure that increase in temperature increased the yield of bio-oil and syngas in all the feedstocks. However, the increase in temperature effected a decrease in the biochar yield. The increase in temperature enhances the breakdown of C-H and C=O bonds, releasing more volatiles in condensable and non-condensable forms, which boosts bio-oil and syngas yields accordingly, at the expense of biochar yield.

Similar to the present work, Yang et al. [59] examined the effect of temperature on the yields of bio-oil, biochar,

Fig. 10 Effect of operating temperature on the elemental composition and heating value of bio-oil produced using OPW. **a** PKS. **b** EFB. **c** OPF. **d** Equal blend
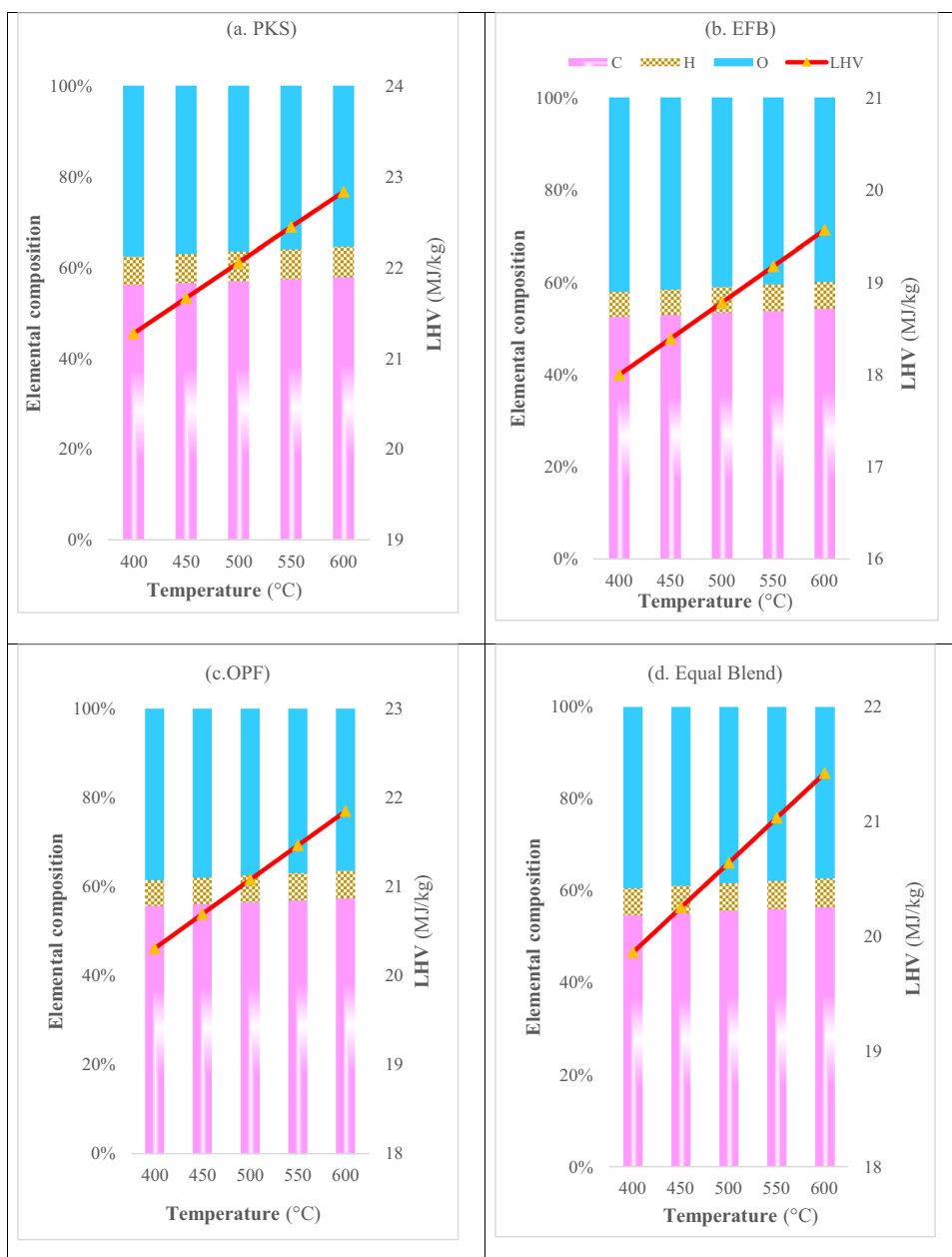

and syngas in PKS biomass [59]. With the increase in temperature from 500 to 900 °C, a decreasing trend in the bio-oil (from 29.99 to 20.09%) and biochar (from 29.04 to 10.18%) yields and an increasing trend in the syngas yields (from 36.59 to 64.47%) was observed. Meanwhile, Terry et al. [52] focused solely on the impact of operating temperature on bio-oil yield in PKS, EFB, and OPF feedstocks [52]. According to the researchers, all feedstocks showed a mixed trend. An increasing trend was observed as the temperature was increased from 350 to 450 °C. However, increasing the temperature from 450 to 550 °C resulted in a decreasing trend. The increase in bio-oil yields at higher temperatures (400 °C) is due to the promotion of

secondary reactions of primary volatiles (acids, alcohols, etc.) into incondensable gases (CH_4, CO, and CO_2) with the additional energy input.

3.2.4 Effect of operating temperature on the elemental composition and heating value of bio-oil

The effect of operating temperature on the elemental composition of bio-oil for all the selected feedstocks is presented in Fig. 10. It can be noted that increasing pyrolysis temperature from 400 to 600 °C, effected an increase in the carbon content of bio-oils (52.00–58.00%) in all the samples. In fact, the carbon content of bio-oils is maximum (54.00–58.00%)
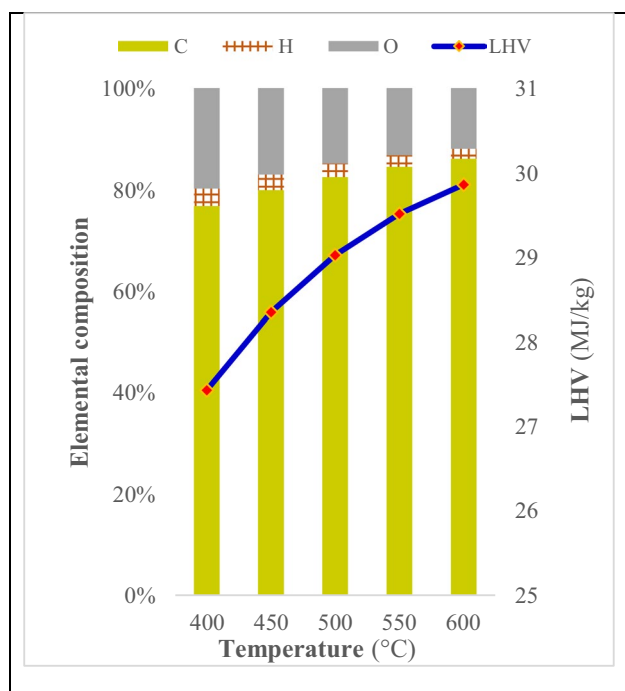
Fig. 11 Effect of operating temperature on the elemental composition and heating value of biochar for all OPW

at the highest pyrolysis temperature (500 °C). Meanwhile, increase in temperature produced a slight increase in the hydrogen content (5.40–6.70%); however, it prompted a decrease in the oxygen content (35.00–42.00%) of the bio-oils.

The elemental composition of bio-oil estimated in this study is compared to the elemental composition of bio-oil reported in other studies. Ghorbannezhad et al. [60] produced bio-oil by pyrolyzing PKS at 500 °C [60]. The elemental analysis of the bio-oil yielded the following results: carbon accounted for 58.30%, hydrogen for 8.50%, oxygen for 33.00%, and sulfur for 0.10%. Terry et al. reported on another study that demonstrated EFB pyrolysis at 500 °C [52]. The obtained bio-oil had the following elemental composition: carbon 64.61%, hydrogen 7.38%, and oxygen 25.84%. Kabir et al. [51] performed PF pyrolysis at 550 °C. The elemental composition of the obtained bio-oil is as follows: carbon 60.81%, hydrogen 8.24%, nitrogen 2.03%, oxygen 28.54%, and sulfur 0.38%.

The figure depicts the effect of operating temperature on the heating value of bio-oil for all of the feedstocks considered. With the increase in temperature (400–600 °C), an increase in heating values of bio-oil can be observed in all the feedstocks. As a matter of fact, the highest bio-oil heating value is noted at the highest pyrolysis temperature (600 °C). The estimated heating value ranges of bio-oil are as follows: 21.27–22.83 MJ/kg for

PKS, 17.99–19.56 MJ/kg for EFB, 20.30–21.84 MJ/kg for PF, and 19.86–24.42 MJ/kg for blend. These values are compared to bio-oil heating values reported elsewhere. The calorific values of PKS, EFB, and PF bio-oil have been reported to be 26.50 MJ/kg [60], 24.90 MJ/kg [46], and 23.00 MJ/kg [51] respectively.

3.2.5 Effect of operating temperature on the elemental composition and heating value of biochar

Based on the adapted model (Eqs. 4–6), the composition of biochar is evaluated as a function of operating temperature alone, regardless of the feedstock composition. Therefore, the impact of operating temperature on the pyrolysis of different OPW is illustrated in Fig. 11. The increase in operating temperature triggers further devolatilization of volatile components including oxygen and hydrogen through the cleavage of C-H and C = O bonds. While the feedstock's carbon content is partly devolatilized with lesser extent than the volatile matter, resulting in higher quality of biochar. At higher operating temperatures, the yield of biochar decreases while its carbon content is boosted, and therefore, its heating value is enhanced.

3.2.6 Effect of operating temperature on the elemental composition and heating value of syngas

The effect of operating temperature on the syngas components of all feedstocks is illustrated in Fig. 12. It is worthy to note that increasing the pyrolysis temperature from 400 to 600 °C contributed to a minor increase in H_2 composition, an increase in CO composition, a slight increase in CH_4 composition, and a decrease in CO_2 composition. At the highest pyrolysis temperature (600 °C), the composition of H_2, CO, and CH_4 is the highest, whereas the composition of CO_2 is the lowest. Yang et al. [59] investigated the effect of temperature on the syngas composition of PKS in a manner similar to the current study [59]. The composition of H_2 (3.56–33.49%) and CH_4 (2.84–11.92%) increased significantly when the pyrolysis temperature was increased from 400 to 600 °C. However, temperature increase caused a mixed response (first a decrease, then an increase) in CO and CO_2 composition. The composition of H_2, CO, and CH_4 was maximum at the highest temperature (900 °C), as in the current study. The figure also describes the effect of operating temperature on syngas heating value for all feedstocks considered. An increase in heating values of syngas can be observed in all feedstocks as temperature (400–600 °C) rises. Indeed, the highest syngas heating value was observed at the highest pyrolysis temperature (600 °C). Syngas heating values are estimated to be 5.68–7.22 MJ/kg for PKS,

Fig. 12 Effect of operating temperature on the elemental composition and heating value of syngas for all oil palm wastes (**a**, **b**, **c**, **d**)
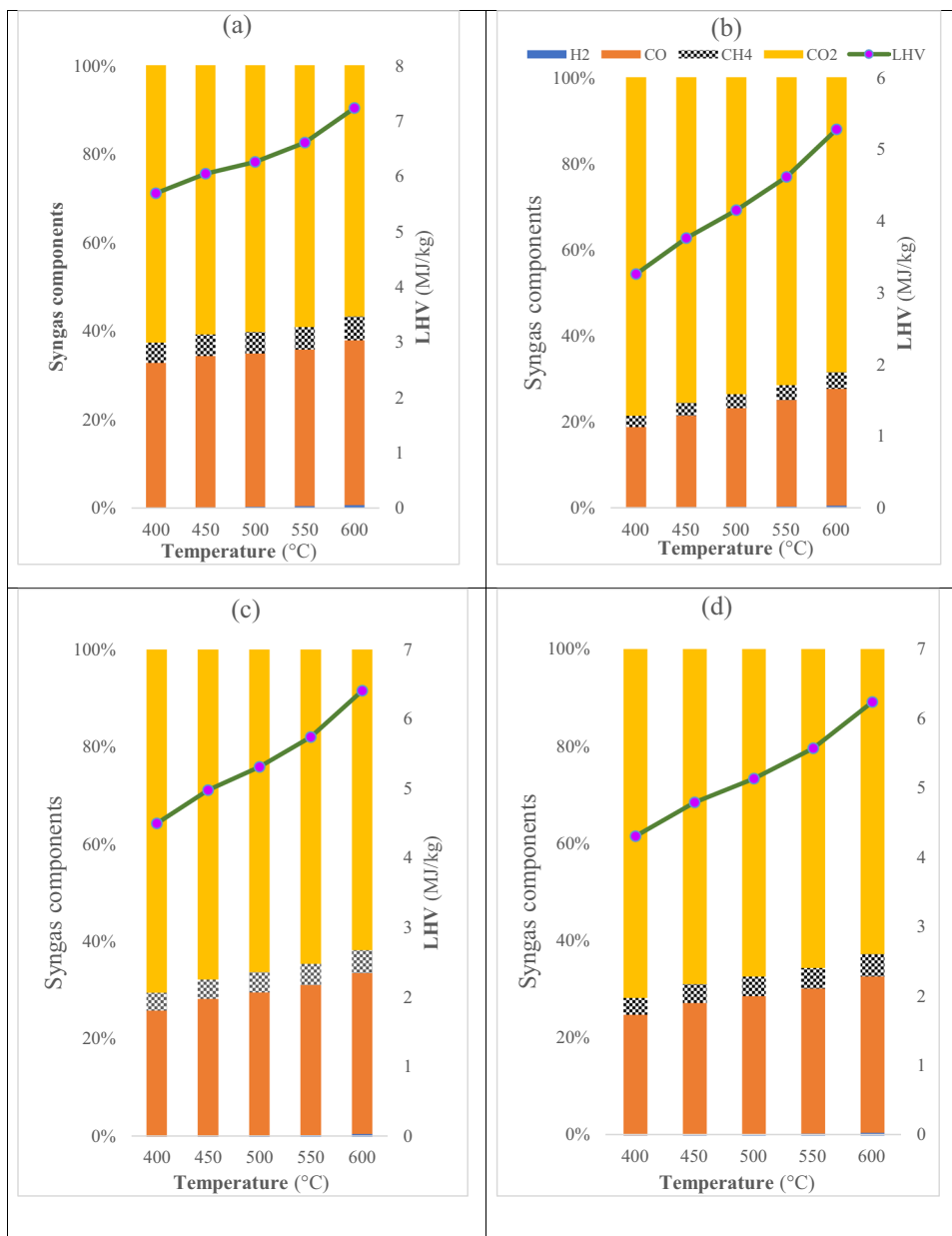
3.25–5.27 MJ/kg for EFB, 4.50–6.40 MJ/kg for PF, and 4.30–6.23 MJ/kg for blend.

3.3 Economic evaluation

The influence of feedstock types on economic factors, payback duration, yearly sales, and MSP is discussed in this section.

3.3.1 Effect of feedstock types on economic parameters

A summary of the key economic parameters of the pyrolysis plant is presented in Fig. 13. The CAPEX (project investment cost) is estimated to be USD 75–80 M. PKS-based pyrolysis is associated to the highest CAPEX, while EFB pyrolysis exhibited the lowest CAPEX among all tested feedstocks. The variation in CAPEX is mainly related to the bio-oil yield variation based on the different OPW feedstocks, where higher bio-oil yields require larger filtering subunits, and therefore higher costs. Purchased equipment occupied the largest portion of CAPEX at approximately 35%, followed by site development and construction expenses at 9% each. Whereas the OPEX is evaluated to be USD 17–20 M/year. The key component of OPEX is the feedstock price at around 41% of total OPEX, followed by raw materials treatment and utilities at 21 and 19%, respectively. As such, highest OPEX is associated to

Fig. 13 Effect of feedstock types on economic parameters
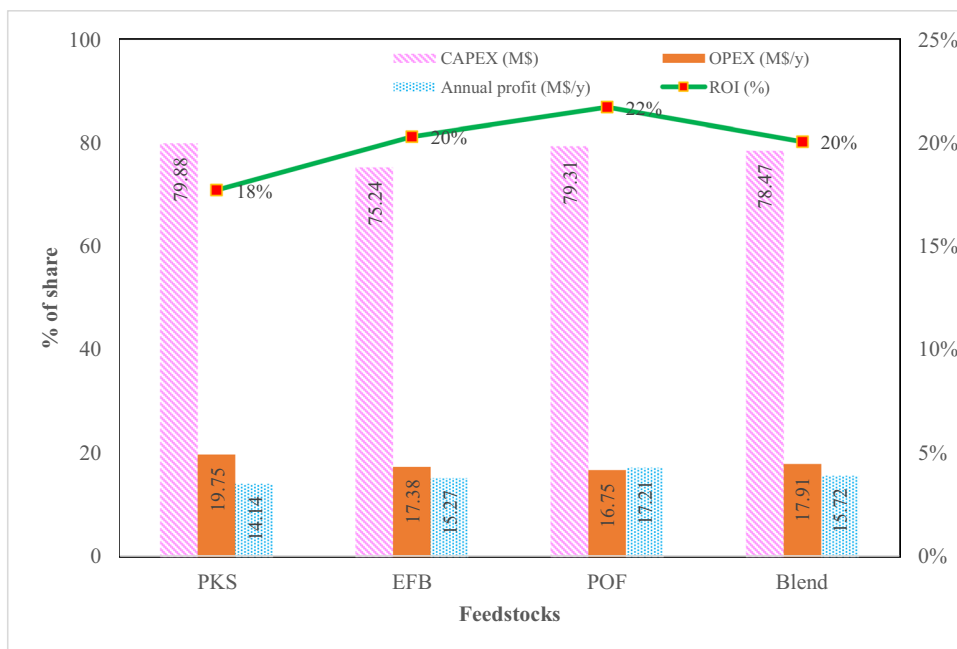

PKS due to its relatively higher market price, as well as higher moisture content, which requires more energy input at the drying stage. As for the ROI for the different OPWs-based pyrolysis, it is interlinked to the annual profit. The highest profit is found to be USD 17 M/year when OPF is introduced as feedstock, resulting in 22% ROI. The high profit is also associated with the lower market price of OPF as compared to the other OPWs. Likewise, PKS achieved the lowest annual profit which is USD 17 M/year at an ROI of 18%.

3.3.2 Effect of feedstock types on payback period

The effect of feedstock types on payback period is illustrated in Fig. 14. As far as the payback period of investment capital is concerned, all OPW feedstocks exhibited a reasonable period between 4 and 6 years. The best performing feedstock is found to be OPF again, while an average of 5-year payback period is achieved when an equal blend of the three OPW categories is utilized in the process. Since feedstock

Fig. 14 Effect of feedstock types on payback period
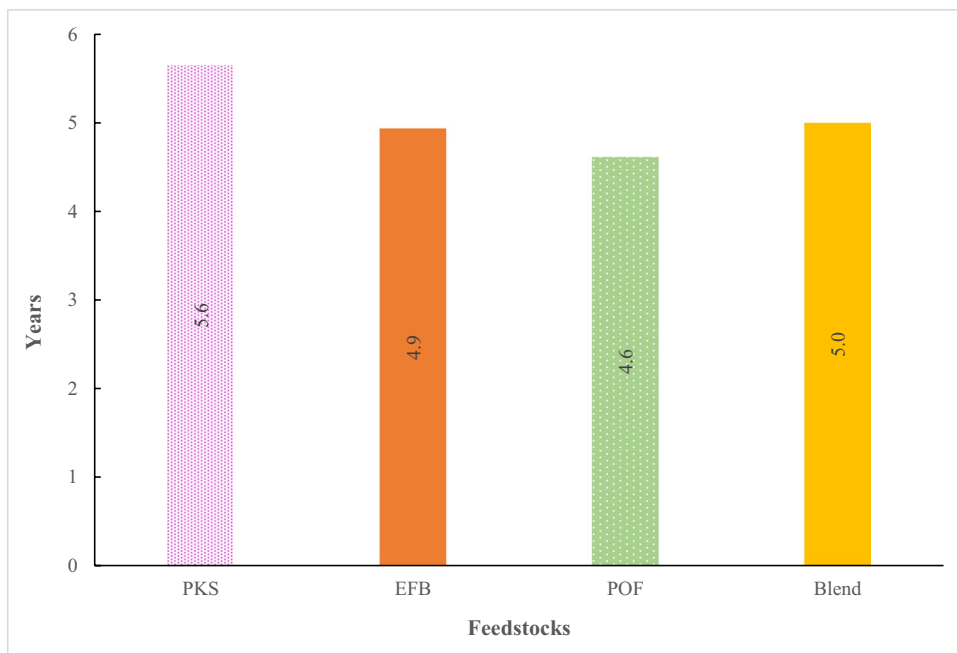
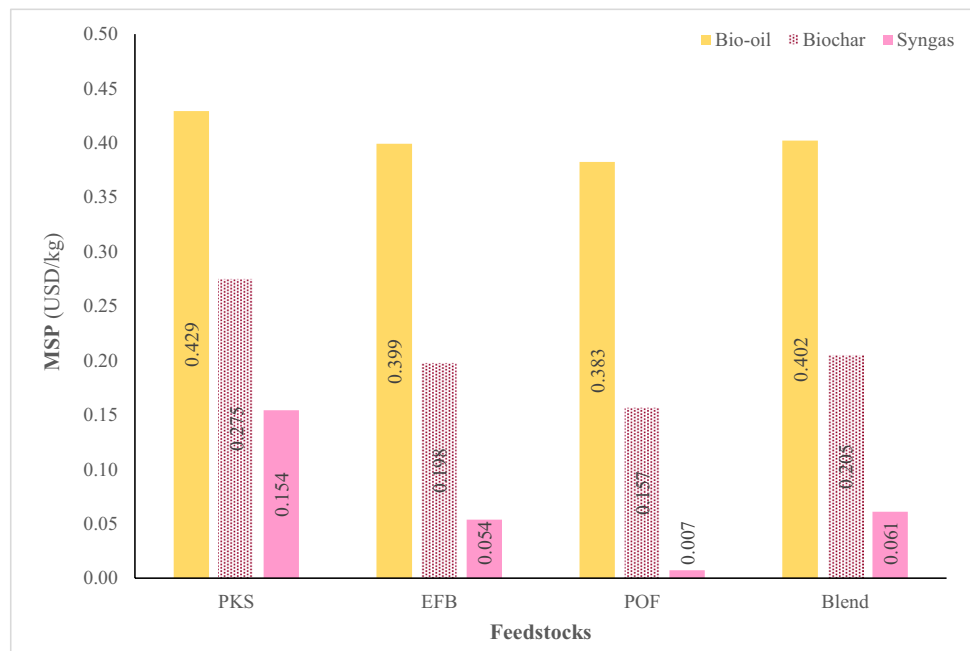**Fig. 15** Effect of feedstock types on annual sales
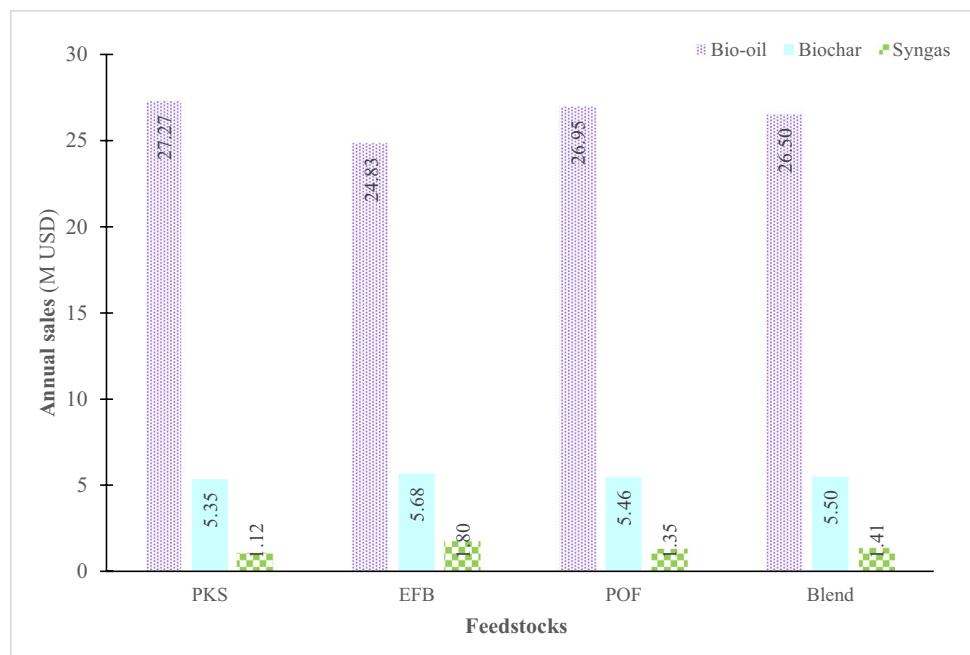
price is a key component of OPEX, it is considered the most sensitive parameter in achieving a favorable payback period.

3.3.3 Effect of feedstock types on annual sales

The influence of feedstock types on annual sales is illustrated in Fig. 15. Bio-oil is the most valuable product of the pyrolysis with highest market value as compared to biochar and syngas. As such, bio-oil yield is the most sensitive parameter for the determination of favorable annual sales. Therefore, PKS- and OPF-based pyrolysis exhibited the highest annual sales is around USD 34 M for each, with bio-oil occupying 79–80% of total sales. Likewise, EFB is associated to the lowest annual sales, at around USD 32 M/year, with bio-oil occupying 76% of total sales.

Fig. 16 Effect of feedstock types on minimum selling price

3.3.4 Effect of feedstock types on MSP

The MSP is considered one of the most important economic parameters in determining the extent of process' economic feasibility [39]. Where MSP takes into consideration of the product yield, CAPEX, OPEX, sales, and discount rate. The most favorable MSPs of the different pyrolysis products are achieved when OPF is utilized as feedstock, where all three products (bio-oil, biochar, and syngas) achieved an MSP below their corresponding market price. The effect of feedstock types on MSP is illustrated in Fig. 16. In the former scenario, bio-oil's MSP is 4% below its market price, while biochar's MSP is 17% below the market value. In addition, EFB achieved MSPs that are extremely close to the market values of the products, being slightly below the threshold. Nevertheless, PKS-based pyrolysis resulted in slightly high MSPs, with bio-oil and biochar's prices being 7 and 27% above the market value, respectively. The blend of OPWs resulted in moderate MSPs that are slightly higher than the market price; however, the blending ratio could be adjusted towards higher percentages of OPF and EFB to achieve better MSPs.

4 Conclusions and prospects

In this study, an empirical model is instituted for the pyrolysis process for the various oil palm wastes (OPW) such as palm kernel shell (PKS), empty fruit bunches (EFB), oil palm frond (OPF), and their blend. Characterization of all wastes depicted that the volatile matter is above 70% and fixed carbon in the range of (13–20%) suitable for the pyrolysis process. The elemental analysis of the samples reveals that all of them have higher compositions of oxygen and hydrogen (OH 50–54%) than carbon (45–49%). In addition, all the wastes have higher value of higher heating values in the range of (18–19 MJ/kg), which instigate the suitability for energy production. The product yield of the pyrolysis process is dominated by the bio-oil, which contributed 59.21, 50.51, 56.60, and 55.65% for PKS, EFB, OPF, and their blend respectively. Whereas the bio char yield was 23.21, 23.1, 22.95, and 23.08% and gas yield was 17.57, 26.38, 20.44, and 21.27% respectively. PKS showed a higher yield of for bio-oil and biochar, whereas a higher gas yield of 26.38% was noticed for EFB. With respect to the syngas composition (all feedstocks), CO and CO_2 are the major components contributing to more than 90% of syngas. The temperature has a significant impact on pyrolysis products. PKS produced the highest bio-oil yield (40% at 600 °C). Maximum biochar yields of 21, 22, and 25% were observed for PKS, EFB, and OPF at 400 °C. The increase in lower heating value from 18 to 22 MJ/kg of bio-oil obtained from all wastes is noticed with the temperature increase from 400

to 600 °C. The economic evaluation indicated the capital expenses (CAPEX) was in the range of USD 75–80 M, and operation expenses (OPEX) was between USD 17 and 20 M/year. PKS showed the highest CAPEX USD 79.88 M, whereas the EFB demonstrated a lower CAPEX of USD 75.24 M. OPF produced the largest profit of USD 17 M/year, with a 22% return on investment (ROI), among the feedstocks. All OPW feedstocks indicated a reasonable payback period of 4–6 years in terms of investment capital. When compared to biochar and syngas, bio-oil is the most valuable pyrolysis product, with the highest market value.

For biomass pyrolysis modeling investigations, the existing prediction model can be used as a solid reference. The model has been proven to be suitable for forecasting slow pyrolysis processes for lignocellulosic biomass feedstock and may be used to calculate pyrolysis products in the absence of experimental data. In addition, the predicted values are accurate enough to be employed in the design of industrial processes. Although the model predicts the yield and composition of pyrolysis products well, it has a significant constraint in predicting the stoichiometry of the pyrolysis process since it requires limited input variables such as proximate and ultimate feedstock material analysis and pyrolysis temperature. The influence of operational factors other than temperature is unaccounted for in this model, which is a significant disadvantage.

Exergy-based evaluations should be used in the future to design large-scale oil palm waste pyrolysis facilities and optimize their performance characteristics. In future studies, advanced exergy-based approaches should be used to improve the quality and dependability of the results. Future research should concentrate on the development of new methods to integrate the exergetic, environmental, and economical components of bioenergy systems. Future research should also focus on identifying the realistic potential for enhancement of bioenergy systems utilizing the advanced exergo-environmental technique.

Declarations

Conflict of interest The authors declare no competing interests.

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