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Carbon capture through solar-driven CO₂ gasification of oil palm empty fruit bunch to produce syngas and biochar

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ABSTRACT

Oil palm empty fruit bunch (OPEFB) is an abundant organic waste in Malaysia that is often disposed of through field burning. A previous study has shown that solar-driven steam gasification of OPEFB can produce hydrogenrich syngas with an energy upgrade factor of 1.2 and a carbon conversion efficiency of 95.1 %. Beyond its potential as a biofuel, OPEFB can also act as a carbon sink, capturing photosynthetically stored carbon. This study explores the potential of amplifying OPEFB's negative carbon emissions through solar-driven gasification, using CO₂ as the gasifying agent. In this work, a Central Composite Design (CCD) approach was employed to assess the influence of temperature (1100–1300 °C) and CO₂/OPEFB molar ratio (1.6–3.0) on H₂/CO molar ratio and energy upgrade factor, with a constant OPEFB flow rate of 1.8 g/min. The results demonstrated that at an energy upgrade factor of 1.4, 94.9 % of the total carbon was converted into syngas with a H₂/CO molar ratio of 0.3. The maximum observed net carbon capture yield of 0.4 g C/g OPEFB was achieved at 1300 °C and a CO₂/OPEFB molar ratio of 3.0. The remaining carbon (94.4–95.7 wt %) was converted into biochar with low heavy metal content, which has potential as a soil enhancer.

1. Introduction

The production of crude palm oil (CPO) from oil palm fresh fruit bunch (OPFFB) generates various types of solid and liquid residues [1–3]. Notably, oil palm empty fruit bunch (OPEFB), mesocarp fibre (MF), and palm kernel shell (PKS) are the solid residues, whereas palm oil mill effluent (POME) is the liquid residue [1]. Disposal of these types of economically undervalued residues is not environmentally favourable [4]. Therefore, it is important to convert harmful oil palm residues into value-added products.

OPEFB is the most abundant solid residue in Malaysia's palm oil industry, with an estimated 21.8 million tonnes generated in 2020 [5–7]. When utilized for energy production, OPEFB can mitigate approximately 218.6 kg CO₂-equivalent per ton, potentially reducing annual greenhouse gas emissions of 4.8 million metric tonnes in Malaysia [8]. Generally, OPFFB residues are incinerated to generate

steam for CPO production, which contributes to the energy demands of palm oil mills [1]. However, the incineration of OPEFB is problematic due to its lignocellulosic structure and the high moisture content of about 60 wt % [9]. The field-burned OPEFB further produces white smoke, which is harmful to the environment [10]. Moreover, OPEFB is left in dump sides, forming anaerobic conditions that cause emissions of greenhouse gases (GHG), i.e., CH₄ and CO₂ [2]. Therefore, adequate treatment and utilisation of OPEFB are urgently needed to reduce the environmental burden. Some amounts of OPEFB are used as a biofertiliser in palm oil plantations and for mushroom cultivation [9]; however, this practice is not sufficient to utilise the large amounts of produced OPEFB [1].

Carbon sequestration or capture, along with energy recovery, offers a more sustainable alternative to field burning [2]. Gasification plants, focusing on bioenergy production with carbon capture, have gained attention as a key component of global mitigation strategies [4,11–14].

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Utilising OPEFB as feedstock in these plants could minimise landfill use and generate value-added products. In addition, converting OPEFB into syngas and biochar via solar-driven gasification could be an energetically more attractive solution [2]. Malaysia's abundant solar energy potential of 4–6 kWh/(m^2 .day) and 4–8 daily hours of sunshine [2,15], make it conducive for solar-driven gasification.

Even though it is still at an early stage of development, CO_2 gasification emerges as a promising alternative to the conventional process of syngas production from natural gas [16]. In this regard, solar-driven gasification using CO_2 as the gasifying agent is one of the promising negative emission technologies (NETs) and carbon capture methods [16]. Solar-driven CO_2 gasification utilises highly concentrated solar power to locally generate temperatures above $1000 \,^{\circ}C$ [17]. Under these conditions, OPEFB reacts with CO_2 to generate CO-rich syngas, as expressed in Equation (1). The method to develop the molecular formula of OPEFB was reported in a previous study [2].

$$C_{7.4}H_{12.1}O_{5.1}$$
 + 2.3 CO₂ → 9.7 CO + 6.05 H₂ ΔH°_{1} = + 2765.8 kJ / mol (1)

Syngas (CO and H₂), the main product of solar-driven CO₂ gasification of OPEFB, is an important precursor and intermediate gas for the synthesis of various commodity chemicals. For instance, CO is used in the manufacturing of acrylic acid, formic acid, dimethyl carbonate, propionic acid, acetic anhydride, acetic acid, and formamides, which possess multiple industrial downstream applications [16]. CO produced from bio-waste can also be used as fuel for solid oxide fuel cells (SOFCs) to generate electricity at high efficiency [18]. In addition, CO is simultaneously produced with H₂, forming syngas, which is an energy-rich gaseous fuel mixture. Syngas serves as a carbon and energy source for various industrial processes, such as the Fischer-Tropsch (FT) process, ammonia production, methanol production, dimethyl ether production, power and heat generation, and a substitute for natural gas [16]. Different applications require specific H₂/CO molar ratios in syngas. To expand the application potential of CO-rich syngas, it is necessary to mix it with H₂ to achieve the desired molar ratio for a variety of downstream applications [16]. For instance, the synthesis of methanol, dimethyl ether, and formaldehyde requires a H₂/CO molar ratio of 2, ethanol requires a H₂/CO molar ratio of \leq 1, FT fuels require H₂/CO molar ratio of \geq 2, and power generation requires a H₂/CO molar ratio of \geq 50 [19].

Carbon sequestration through biochar is an attractive option among negative emission technologies (NETs) with relatively high technical readiness, good carbon abatement potential, and moderate costs [20]. Biochar from gasification is a carbon-rich material with potential applications in soil amendment and carbon sequestration, acting as a stable carbon sink which contributes to negative carbon emissions [20–22]. Additionally, advancements in biochar modification methods open up diverse applications beyond soil amendment [23]. These developments highlight the potential of utilising solar-driven CO_2 gasification of OPEFB to produce biochar.

Previous studies have explored conventional CO₂ gasification of various residues to produce CO-rich syngas, including wood biomass [24,25], plastics [26], and coal [27]. However, there is limited research on solar-driven CO₂ gasification [17,28-30]. Bellouard et al. [30] found that solar-driven CO2 gasification of wood biomass achieved a H2/CO molar ratio of 0.4-0.7 and a carbon conversion rate of 97.1 wt %, for a temperature range of 1100–1400 $^\circ C$ and CO2 flowrate range of 0.2–0.6 NL/min. These findings illustrate the efficient process of solar-driven CO₂ gasification to produce CO-rich syngas from biomass. Moreover, Chew et al. [4] investigated the CO₂ gasification of torrefied oil palm biomass but found that torrefaction negatively affected energy yield and limited the range of attainable H₂/CO molar ratios, which subsequently hindered the possible downstream applications. Furthermore, Chan et al. [16] extensively investigated the recent progress of CO2 gasification of various types of feedstocks and its promising potential to produce CO-rich syngas. However, thus far, solar-driven CO2 gasification of raw OPEFB to produce CO-rich syngas and biochar was never reported before. Therefore, the main objectives of the present study are: a) to assess the multifactor parametric effects of operating temperature and $CO_2/OPEFB$ molar ratio on the response variables, i.e., H_2/CO molar ratio and energy upgrade factor, using CO_2 as the gasifying agent, b) to determine the optimum operating conditions within the range of the operating variables, and c) to characterise the produced biochar and propose its potential application. In this study, central composite design (CCD) method was applied. CCD has proven to be a useful statistical technique for optimising multifactor parameters in the gasification of various types of biomasses [2,31,32]. CCD provides a comprehensive analysis of the independent and interaction effects of operating variables, offering a deeper understanding compared to conventional analysis methods [2].

This study contributes to the development of NETs by harnessing the abundance of solar thermal energy, CO₂, and OPEFB to generate valueadded syngas and biochar. The findings of this study could be a steppingstone towards decarbonisation efforts within the palm oil industry. It is also in line with the global commitment towards achieving the UN Sustainable Development Goals (SDGs) 7, 12, and 13, as well as the 2015 Paris Agreement on Climate Control [20].

The reduction of GHG emissions through NETs can generate carbon credits—tradable certificates that represent the avoidance of one metric ton of CO_2 emissions [33]. As global demand increases and regulatory frameworks strengthen, the value of carbon credits is projected to rise significantly, potentially reaching \$238 per ton by 2050 [34]. These credits can be traded in carbon markets, providing financial incentives for industries to adopt cleaner technologies [35]. Additionally, the future cost of Concentrated Solar Power (CSP) is expected to decline due to advancements in power blocks, receivers, thermal storage, and solar fields [36]. According to NREL projections, CSP Levelised Cost of Energy (LCOE) could drop substantially, improving economic viability, from \$88.7/MWh in 2025 to an estimated \$43.4 - \$59.5/MWh by 2050 [36].

2. Materials and methods

2.1. Biomass feedstock

OPEFB was obtained from a palm oil mill in Malaysia. Prior to shipment, OPEFB fibres were washed, dried, shredded, grinded, and then stored at room temperature until use. More details are available in a previous work [2].

The proximate analysis, i.e., moisture content, total and volatile solids, and ash contents of OPEFB was performed according to the standard method reported by APHA [37]. The ultimate analysis, i.e., carbon, hydrogen, nitrogen, and sulfur contents of OPEFB was performed via CHNS elemental analysis (Flash 2000, Thermo Scientific, USA). The oxygen content (wt. %) was calculated by the difference, i.e., 100 - (C + H + N + S). The lower heating value (LHV) of OPEFB was taken from the literature [38]. Table 1 summarises OPEFB characteristics and comparison with the literature.

2.2. Experimental setup

The complete experimental system is illustrated in Fig. 1. Its main components consist of a sun-tracking heliostat, solar concentrating parabola dish, conical spouted bed solar reactor connected with a biomass feeding hopper, a filtering unit, and a gas analysis system. More details on the solar reactor concept, design, and experimental protocol have been previously reported [30,40,41].

The experimental setup, located at CNRS-PROMES solar laboratory in Odeillo, France, uses a 2-m parabolic concentrator to reflect and concentrate solar radiation. A sun-tracking heliostat, located 30 m beneath the setup trap door, reflects the solar radiation vertically to the concentrator. The motorised trapdoor partially closes or opens to regulate the reflected incident solar power and thus the reactor temperature. The reactor, positioned under the concentrator, receives the

Table 1

Oil palm empty fruit bunch (OPEFB) characteristics.

OPEFB characterisation	Composition (wt. %)		
	This study	Farid et al. [39]	Chang et al. [10]
Moisture content	11.3 ± 0.1	$\textbf{7.9} \pm \textbf{0.4}$	2.4–14.3
Proximate analysis (% ^a)			
Volatile matter	$\textbf{87.7} \pm \textbf{0.1}$	71.0 ± 0.7	70.0-83.9
Fixed carbon	1.0 ± 0.1	14.6 ± 0.7	9.0-18.3
Ash	1.0	$\textbf{6.4} \pm \textbf{0.5}$	1.3-13.7
Ultimate analysis (%ª)			
С	$\textbf{48.4} \pm \textbf{0.1}$	44.9 ± 0.6	43.8-54.8
Н	6.7 ± 0.1	6.6 ± 0.1	4.4–7.4
Ν	0.6 ± 0.1	0.9 ± 0.1	0.3-1.2
S	0.1	-	0.04-1.1
O ^b	44.2 ± 0.4	47.6 ± 0.1	38.3-47.8
Lower Heating Value (MJ/kg)	16.1 ^c	16.9 ± 0.4	16.8–19.2

^a Weight percent on a dry basis.

^b By difference (100-(C + H + N + S)).

^c Value taken from literature [38].

concentrated solar flux through a 2-cm aperture. The flux density at the focal point can go up to 10 MW/m^2 with direct normal irradiation (DNI) of 1 kW/m², following a Gaussian distribution.

Gasification reactions occurred in the reactor's cone-like cavity, which was insulated at the bottom and sides. The gasification of OPEFB is a multifaceted thermochemical process involving several stages: drying, devolatilization (pyrolysis), heterogeneous char reactions, and homogeneous gas-phase reactions [42,43]. When OPEFB particles enter the high-temperature cavity, they rapidly heat up, leading to moisture evaporation [44]. As the temperature continues to rise, devolatilization takes place, during which volatile compounds decompose and are released from the biomass [44]. OPEFB gasification using CO2 as the gasifying agent primarily involves heterogeneous and homogeneous reactions that drive the conversion of solid carbon into syngas. The key reaction could likely be the Boudouard reaction (C + $CO_2 \Rightarrow 2CO$), which is endothermic and enhances CO production at high temperatures [42–44]. Additionally, biochar gasification (C + CO₂ \rightarrow CO) plays a crucial role in carbon conversion, while secondary reactions such as the reverse water-gas shift (CO₂ + H₂ \Rightarrow CO + H₂O) influence the H₂/CO ratio [42]. The reaction kinetics are largely controlled by temperature, biochar reactivity, and the availability of CO₂ at the reaction sites, with higher temperatures favouring increased conversion rates and syngas vields [43]. Further details on the reaction kinetics and simulation of biomass gasification are reported in the literature [42-44].

Biomass was injected into the cavity through a motorised feeding

hopper connected via a screw feeding mechanism. Temperature was measured using a B-type thermocouple and verified with a solar-blind optical pyrometer operating at 4.8–5.2 μ m (Impac, LumaSense Technologies, Inc., USA). Pressure of the reactor was atmospheric in all the experiments.

A gas flow was injected into the reactor cavity consisting of Ar carrier gas, at a constant flowrate of 2.5 NL/min, and the gasifying agent (CO₂). The carrier gas was introduced to create an anaerobic atmosphere, and transport biomass particles to the top of the cavity for better solar power absorption [30]. It also ensures proper mixing of the biomass with CO₂ [30].

The syngas products were cooled in a gas bubbler and filtered to remove the carried ashes, char, and tars before entering the gas analyser. Syngas composition was measured via a syngas analyser (X-Stream XEGP, Emerson, USA, precision ± 1 % of full scale) which utilises Non-Dispersive Infrared (NDIR) and Thermal Conductivity Detection (TCD) technologies for the measurement of main gases in syngas. The concentrations of CO, CO₂, CH₄, and C_nH_m were measured using NDIR cells, while H₂ concentration was measured using a thermal conductivity detector. Moreover, the produced syngas composition was periodically measured using a gas chromatograph (GC, Varian CP4900, Agilent, USA) for further verification of the results [30] which uses chromatographic techniques to separate and quantify components in complex mixtures like syngas. The GC was equipped with two columns (MolSieve 5A PLOT and PoraPLOT U for light hydrocarbons) and the carrier gas was argon. More details of the analysis methods are available in the literature [40,45]. Gas flowrates were controlled via mass flow controllers (MFC, Brooks Instruments model 5850 S). After each experiment, the outlet components were weighted for mass balance. The mass and energy balances of the experiments are discussed in the Supplementary Material (sections 2 and 3, respectively).

2.3. Experimental design

CCD, a response surface methodology, was used in this study to optimize the operating conditions for the solar-driven gasification of OPEFB [46–48]. More details on the design of circumscribed CCD can be found in the literature [49]. An array of designed experiments was generated using Statistica Software (StatSoft v. 8.0). The generalized equation for CCD with two factors, based on the quadratic Taylor series polynomial approximation, is presented in Equation (2).

$$Y_{i} = \beta_{0} + \sum_{j=1}^{k} \beta_{j} \mathbf{x}_{ij} + \sum_{j=1}^{k} \beta_{j} \mathbf{x}_{ij}^{2} + \sum_{j=1}^{k-1} \sum_{j>j}^{k} \beta'_{jj} \mathbf{x}_{ij} \mathbf{x}'_{ij} + \varepsilon_{i}$$
(2)



Fig. 1. Schematic diagram of the experimental setup.

The experimental design included temperature and CO₂/OPEFB molar ratio as the operating variables, with a constant OPEFB flowrate of 1.8 g/min which is reported to be suitable for such experiments [50]. The operating variables were coded at three levels: -1 (low), 0 (medium), and +1 (high). To obtain a rotatable CCD model, the extreme levels of the star design ($-\alpha$, $+\alpha$) were added to the model whereby $|\alpha|$ is equal to 1.41 [51]. The selected values and levels of the temperature and CO₂/OPEFB molar ratio were determined based on prior studies on the solar gasification of OPEFB and wood biomass [2,41,50]. For two factors, a CCD requires 9 experiments. In this study, the central-level experiment was conducted in duplicate. Since the results of the duplicate were consistent, only one replicate is presented and discussed. Table 2 provides further details on the investigated levels of the independent operating variables.

2.3.1. Selection of response variables

To assess the produced syngas quality for possible applications, H_2/CO molar ratio is the suitable response variable [31]. Other gases like CO_2 , CH_4 , and C_2H_y are generated as by-products in smaller quantities. The energy upgrade factor is the other response variable used to assess the efficiency of solar-driven gasification by measuring the storage of solar energy in the syngas products. Syngas yield was also investigated to identify the quantity of syngas produced for each operating condition.

 $\rm H_2/CO$ molar ratio, $\rm H_2/CH_4$ molar ratio, and energy upgrade factor were calculated from the molar syngas yields, the LHV of OPEFB and syngas, and the solar energy input. Additionally, carbon conversion efficiency was determined based on the carbon content in OPEFB and syngas components, providing insight into how effectively carbon was utilized in the gasification process. Carbon consumption rate was also analysed to quantify the rate at which carbon was converted into gaseous products under varying conditions. Furthermore, the net carbon capture yield was evaluated to assess the overall effectiveness of the process in capturing and retaining carbon within useful syngas components. Further explanations of the methods of data processing and evaluation are reported in an earlier study [2] and provided in the Supplementary Material (section 1).

A total number of 9 experiments were performed under the designed operating conditions. Table 2 shows the CCD experimental design consisting of the selected operating variables versus response variables.

2.3.2. Statistical analysis

Principal component analysis (PCA) was conducted using RStudio software (version 1.1.456) to assess the correlation between the operating and response variables [52,53]. Standardization of variable values was performed to reduce dataset dimensionality. Each eigenvector in a PCA biplot serves as a single operating or response variable. Eigenvectors pointing in identical directions are positively correlated, whereas eigenvectors with opposite directions are inversely correlated. Perpendicular eigenvectors indicate an independent correlation. The weight of a variable eigenvector, determined by its length, indicates the relative importance of each principal component.

Two principal components (PC1 and PC2) were selected as they captured over 95 % of the data variability for the H_2/CO molar ratio and energy upgrade factor. PC1 and PC2 in our dataset correspond to the primary directions of variation within the data. PC1 accounts for the largest variance, while PC2 represents the next highest variance, orthogonal to PC1.

The obtained results were visualised and statistically analysed using Design-Expert Software (version 13) and RStudio Software (version 1.1.456). Significant interactions were identified through PCA and ANOVA to quantify the impact of each operating variable on the selected response variables.

2.4. Biochar characterisation

Biochar samples were collected for analysis from two locations: (i) the solar reactor alumina tube at the exit of the conical cavity and (ii) the gas filtering unit, after each solar-driven gasification experiment. A comparison was made between biochar produced from solar-driven gasification using steam (as presented in our previous work [2]) and CO_2 as the gasifying agents. The elemental composition of the biochar, including carbon, hydrogen, and nitrogen content, was determined using an elemental analyser (Flash 2000 Elemental Analyser, Thermo-Fisher, USA). The surface area, pore volume, and pore size of the biochar samples were measured using a surface analyser (Gemini VII 2390p, Micromeritics Instrument Co., USA) with N₂ at 77 K. Prior to analysis, the samples were heated at 60 °C for 24 h to remove adsorbed gases. The specific surface area was determined using the Brunauer-Emmett-Teller (BET) method, while the pore size distribution was obtained through Barret-Joyner-Halenda (BJH) adsorption analysis.

The metal composition was analysed using inductively coupled plasma - optical emission spectrometry (ICP-OES) (Optima 5300DV, PerkinElmer Co., USA). Biochar and positive control samples (raw OPEFB with particle size < 1 mm) were subjected to pretreatment using the microwave digestion method (Multiwave PRO, Anton Paar GmbH, Austria). Approximately 25 mg of each sample was destructed in a solution consisting of 4.5 mL of 30 % HCl, 1.5 mL of 65 % HNO₃, and 0.2 mL of 40 % HF. Then, solutions containing the biochar samples were further digested with an extra 6 mL of 65 % HNO₃. Biochar samples, which proved to be more recalcitrant to destruction; were further mixed with 2 mL of 30 % H₂O₂. The destruction time in the microwave was 60 min at maximum power and temperature (13 kW and 210 °C, respectively). After the destruction, all samples were diluted with Milli-Q water to 50 mL.

The metals analysed included phosphorus (P), potassium (K), sodium (Na), magnesium (Mg), manganese (Mn), calcium (Ca), iron (Fe),

Table 2

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Central Composite Design (CCD) experimental matrix and results of solar-driven CO_2 gasification of OPEFB (at OPEFB flowrate = 1.8 g/min).
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Run	1 Operating Variables			CCD response variables		Carbon capture results		Related results			
	Temp. (°C)	CO ₂ /OPEFB molar ratio	CO ₂ flowrate ^a (NmL/min)	H ₂ /CO molar ratio	Energy upgrade factor	Carbon conversion (wt. %)	Net carbon consumption rate (g/min)	Net carbon capture yield (gC/gOPEFB)	H ₂ /CH ₄ molar ratio	Syngas yield (mmol/g OPEFB)	η _{solar-} to-fuel (%)
1	1059 (-1.41)	2.3 (0)	506.0	0.4	1.2	57.0	0.3	0.2	3.6	59.0	10.2
2	1100 (-1)	1.6 (-1)	352.0	0.4	1.0	65.3	0.3	0.2	4.7	54.3	7.3
3	1100 (-1)	3.0 (+1)	662.2	0.4	1.3	77.1	0.3	0.2	4.5	69.8	11.7
4	1200 (0)	1.3 (-1.41)	286.0	0.5	1.2	84.1	0.5	0.3	8.7	68.1	13.9
5	1200 (0)	3.3 (+1.41)	726.0	0.3	1.3	68.0	0.6	0.3	6.5	69.7	14.4
6	1200 (0)	2.3 (0)	506.0	0.4	1.3	85.4	0.6	0.3	6.5	71.6	12.9
7	1300 (+1)	1.6 (-1)	352.0	0.4	1.3	86.1	0.6	0.3	10.2	73.4	12.6
8	1300 (+1)	3.0 (+1)	662.2	0.3	1.4	94.9	0.7	0.4	9.9	79.5	13.7
9	1341 (+1.41)	2.3 (0)	506.0	0.4	1.4	87.7	0.7	0.4	12.1	77.4	8.8

^a CO₂ flowrate (g/min) is calculated from multiplying CO₂/OPEFB molar ratio with OPEFB flowrate.

cadmium (Cd), chromium (Cr), copper (Cu), nickel (Ni), lead (Pb), and zinc (Zn). All values were reported as the average of three determinations per sample and expressed on a dry matter basis. This analysis aimed to demonstrate the potential application of biochar as a biofertiliser [54,55]. The particle structure and surface topography of raw OPEFB and biochar were examined using scanning electron microscopy (SEM) (XL30ESEM, Philips, NL).

3. Results and discussion

3.1. Global performance analysis

Syngas components produced from solar-driven CO_2 gasification of OPEFB proportionally increased with increasing temperature and CO_2 / OPEFB molar ratio. OPEFB flowrate was kept constant at 1.8 g/min. At the applied flowrate, the solar reactor showed effective experimental performance as indicated by stable syngas production and syngas composition, and no pyrolytic smoke was observed through visual observation of the reactor window. Thus, it was assumed that the OPEFB feed flowrate was suitable for the kinetic rate of the gasification process. This finding comes in agreement with reported literature [50].

Fig. 2 illustrates the syngas yields at various operating conditions. In Fig. 2, CO₂ yield was excluded from the total syngas yield from an energy perspective because it is the most oxidised form of carbon. However, for syngas volumetric composition, black box analysis was used to differentiate the proportion of CO₂ generated from the solar-driven gasification of OPEFB and the unreacted CO₂ injected into the reactor. In this regard, it was observed that the CO₂ consumption rate was positively proportional to the operating temperature. For instance, carbon dioxide was consumed and converted at a rate of up to 0.3, 0.6, and 0.7 g/min at 1100 °C, 1200 °C, and 1300 °C, respectively. This observation comes in agreement with reported literature values [50]. Net carbon capture yield followed a similar trend reaching a maximum of 0.4 gC/gOPEFB at 1300 °C and a CO₂/OPEFB molar ratio of 3.0.

At 1300 °C, total syngas yield reached 77.4 mmol/g _{OPEFB} with a composition of 28.0 % and 57.3 % v/v for H₂ and CO, respectively. The generated syngas yield was 89.5 % of the theoretical value of 86.5 mmol/g _{OPEFB}, with a stoichiometric composition of 38.4 % and 61.6 % for H₂ and CO, respectively, using Equation (1). The syngas yield obtained in our present study was higher than that of a reported study reaching 61.0 mmol/g _{biomass} from the solar-driven gasification of wood

biomass at 1300 °C [45]. Results obtained at 1300 °C showed that the H_2 fraction was lower and the CO fraction higher than the results of Bellouard et al. [45], who found 31 % v/v for H_2 and 42 % v/v for CO. This observation indicates that in our present work, more efficient gasification of OPEFB and conversion of CO₂ feed took place. This finding is supported by the calculated carbon conversion efficiency of 94.9 %, which was also higher than the 82.4 % of the cited work [45]. These results could identify that the type and structure of the biomass have an impact of the gasification process efficiency and CO₂ conversion.

At 1200 °C, the syngas yield reached a maximum of 71.6 mmol/g $_{OPEFB}$, with a composition of 22.6 % and 54.4 % v/v for H₂ and CO, respectively. The syngas yield achieved 82.8 % of the theoretical value, according to Equation (1). At 1200 °C, the obtained syngas showed a lower H₂ fraction and a higher CO fraction than the results of Bellouard et al. [40] who reported 24.0 % and 44.0 % v/v for H₂ and CO, respectively. A carbon conversion efficiency of 85.4 % was achieved, which was comparable to the 87.7 % in the cited work [40] in which wood was gasified at 1200 °C using CO₂ as the gasifying agent.

At 1100 °C, the highest syngas yield was 69.8 mmol/g _{OPEFB}, consisting of 14.4 % and 37.2 % v/v for H₂ and CO, respectively. The achieved syngas yield represented 80.7 % of the theoretical value. The generated syngas showed slightly lower concentrations of H₂ and CO than Bellouard et al. [40], who found 16.0 % and 44.0 % v/v for H₂ and CO, respectively. A carbon conversion efficiency of 77.1 % was achieved, which was higher than the 70.4 % in the cited study [40].

Results clearly demonstrated that an efficient syngas yield could be generated from the solar-driven gasification of OPEFB using CO₂ as the gasifying agent. Experiment #8 showed the highest syngas yield and carbon conversion efficiency of 79.4 mmol/g _{OPEFB} and 94.9 %, respectively. This experiment also achieved a H₂/CO molar ratio of 0.3. Based on stoichiometric values, a H₂/CO molar ratio of 0.6 was expected. The lower experimental H₂/CO molar ratio indicated that extra CO was obtained from the gasifying agent (CO₂) by the Boudouard reaction [40].

The experimental $\eta_{solar-to-fuel}$ achieved a range of 7.3–14.4 % in this study. The effect of changing the operating variables was statistically not significant (p > 0.05) on $\eta_{solar-to-fuel}$. However, it showed a slightly proportional increase with X₂ (CO₂/OPEFB molar ratio). To illustrate, at 1100 °C, increasing X₂ from 1.6 to 3.0 increased $\eta_{solar-to-fuel}$ from 7.3 to 11.7 %. Furthermore, at 1200 °C, increasing X₂ from 1.3 to 3.3 increased $\eta_{solar-to-fuel}$ from 13.9 to 14.4 %. Similarly, at 1300 °C, increasing X₂ from



Fig. 2. Syngas yield and product composition for solar-driven gasification of OPEFB under 2 varying operating conditions: temperature (1100–1300 °C) and CO₂/ OPEFB molar ratio (1.6–3.0) at constant OPEFB flowrate (1.8 g/min).

1.6 to 3.0 increased $\eta_{solar-to-fuel}$ from 12.6 to 13.7 %. Temperatures above 1300 °C reduced $\eta_{solar \ to \ fuel}$ due to the increase in heat losses (radiative and conductive) [2], which explained why a $\eta_{solar \ to \ fuel}$ of 8.8 % at 1341 °C was obtained.

The $\eta_{solar\ to\ fuel}$ value using CO₂ as the gasifying agent was lower compared to when steam was used, which could be due to the slower reaction kinetics [56], resulting in higher reaction duration, in turn increasing solar energy consumption and heat losses. For instance, the highest $\eta_{solar\ to\ fuel}$ using solar-driven steam gasification of OPEFB was 19.6 % [2] compared to 14.4 % in our present study. These findings are supported by similar observations in literature in which carbonaceous materials were gasified [56]. According to Numazawa et al. [56], the frequency factor, i.e., the reaction kinetics, of steam gasification of metallurgical coke was approximately 10 times higher than that of CO₂ gasification.

3.2. Analysis of the operating and response variables

The influence on the response variables (H₂/CO molar ratio and η_{solar} to fuel) resulting from changing the operating variables was experimentally investigated and statistically analysed by CCD. Principle component analysis (PCA) was also used to identify the statistical significance of the effect of each operating variable on the response variables. PCA was performed by considering the scaled values of the operating variables.

3.2.1. Influence on H_2/CO molar ratio

Fig. 3A shows that CO₂/OPEFB molar ratio (X_2) had a strong inverse correlation with H₂/CO molar ratio (Y_1), whereas temperature (X_1) showed a nearly independent effect on Y_1 , indicated by their nearly perpendicular correlation. These observations are further supported by ANOVA analysis reporting a p-value of 0.0326 which indicates its statistical significance. Moreover, ANOVA analysis of the parameters showed p-values of 0.4013 and 0.0135 for X_1 and X_2 , respectively, indicating that only X_2 is statistically significant. Further details on ANOVA results are available in the Supplementary Material (section 4.1, Table A.2). To validate the results of PCA and ANOVA analyses, the effects of changing process variables (X_1 and X_2) on Y_1 were experimentally conducted and statistically investigated by CCD. As shown in Fig. 3B, at constant X_2 , Y_1 did not change significantly which is in line with the findings of PCA and ANOVA analyses. To illustrate, at a constant X_2 of 2.5, changing X_1 between 1000 and 1400 °C resulted in a constant Y_1 at 0.4. On the other hand, at a constant X_1 of 1200 °C, changing X_2 between 1.3 and 3.3 resulted in significant changes of Y_1 between 0.3 and 0.5. Further analysis of the interaction effects between the temperature and CO₂/OPEFB molar ratio, and their impact on the H₂/CO molar ratio, can be found in the Supplementary Material (section 5, Figure A.3(A)).

Injecting CO₂ at a higher flowrate resulted in enhancing the produced CO quantity, thus decreasing Y₁, which was expected from its theoretical gasification reaction (Equation (1)). The experimentally obtained values of Y₁ were between 0.3 and 0.5. As observed in Fig. 3B, there was no optimum condition achieved in this study for the H₂/CO molar ratio, which could be due to the maximum allowable process conditions, i.e., temperature \leq 1400 °C, and CO₂ flowrate \leq 700 NmL/ min. Hence, the optimal conditions of the H₂/CO molar ratio, represented by a CCD plateau curve, are likely to occur at higher operating conditions that surpass the upper limit of the solar gasification reactor. Consequently, establishing a quadratic correlation was not possible.

The minimum H_2 /CO molar ratio of 0.3 was experimentally reached. It should be noted that widening the resulting H_2 /CO molar ratios could diversify CO applications, such as in fuel cells [57], catalyst production, electronics, semiconductor applications, and the manufacture of metal carbonyls [58].

Optimisation of Y_1 depended on the desired outcome; if more CO is needed, then X_2 between 2 and 3.5 and temperature between 1100 and 1400 °C could be chosen as optimised conditions to attain a Y_1 of 0.3–0.35. In addition, it was evidenced that the gasifying agent played a crucial role in the syngas composition, which was also reported in the literature [59]. Therefore, choosing a suitable gasifying agent is essential to control and optimize the desired product.

3.2.2. Carbon sequestration potential of OPEFB solar-driven syngas

From a carbon sequestration perspective, it is interesting to analyse the composition gap between the OPEFB solar-driven syngas and the gas requirements of selected carbon-based materials. Examples include advanced carbon materials synthesis through chemical vapour deposition (CVD) and other carbon-based chemicals through the FT process. Advanced carbon materials are considered to be the backbone of engineering and scientific innovation due to their outstanding chemical,



Fig. 3. (A): PCA of scaled operating variables (X_1, X_2) vs. scaled H₂/CO molar ratio (Y_1) , (B) 3D response surface plot analysing the effects of operating variables (X_1, X_2) on H₂/CO molar ratio (Y_1) at constant OPEFB flowrate of 1.8 g/min $(X_1 = \text{temperature}, X_2 = \text{CO}_2/\text{OPEFB}$ molar ratio).

physical, and electrical properties, which would result in long-term carbon sequestration potential [60]. The synthesis of FT chemicals from OPEFB solar-driven syngas can represent a process with long-term carbon sequestration potential [61]. The products of FT synthesis can include long-lived chemicals, waxes, or even construction materials [62]. Even when FT products are used as fuels, the carbon released can be part of a circular carbon economy if the CO₂ is captured and reused, contributing to reducing the reliance on fossil fuels and lowering the overall carbon footprint [62].

Solar-driven gasification of OPEFB using either steam [2] or CO_2 as the gasifying agents could potentially produce large amounts of syngas with varying H₂/CO molar ratios ranging from 0.3 in the present study, to 1.6 in the previous work [2]. Table 3 compares the target carbon sequestration methods, experimentally achieved OPEFB solar-driven syngas composition, and the upgrade gap analysis.

The economic viability of carbon sequestration and carbon-based material synthesis depends on the evolving carbon markets [34]. The projected rising values of carbon credit could support OPEFB-derived syngas in sustainable industries. Additionally, the advancements in CSP infrastructure and the projected drop in its LCOE [36] could lower energy costs, improving the scalability of solar-driven gasification and its role in carbon sequestration. Further details on the scalability prospects of the solar reactor are provided in Supplementary Material (Section 7).

3.2.3. Influence on energy upgrade factor

The influence on the energy upgrade factor due to changing operating variables was experimentally assessed and statistically evaluated, as shown in Fig. 4(A and B). Further details on ANOVA results are available in the Supplementary Material (section 4.2, Table A.3). Most experiments showed an energy upgrade factor higher than 1.0, demonstrating that the calorific value of the generated syngas was higher than the original feedstock [2]. The directions of the PCA eigenvectors in Fig. 4A illustrated that temperature (X₁) and CO₂/OPEFB molar ratio (X₂) were positively correlated with the energy upgrade factor (Y₂). It is understandable that increasing temperature and CO₂/OPEFB molar ratio added more heat and carbon sources into the reactor, which contributed to the calorific value of the syngas output, thus enhancing the energy upgrade factor [50].

Fig. 4B illustrates the 3D response surface of the energy upgrade factor as a function of temperature and $CO_2/OPEFB$ molar ratio at a constant OPEFB flowrate of 1.8 g/min. A linear relationship was observed between the operating variables and the energy upgrade factor. Further investigation of the interaction effects between the

temperature and $CO_2/OPEFB$ molar ratio, and their impact on the energy upgrade factor, can be found in the Supplementary Material (section 5, Figure A.3(B)).

The highest energy upgrade factor of 1.4 was achieved at 1300 °C and a CO₂/OPEFB molar ratio of 3.0 (experiment #8), indicating that approximately 40 % of the generated calorific value originated from the storage of solar energy in the form of syngas [2]. The lowest energy upgrade factor of 1.0 was obtained at 1100 °C and a CO₂/OPEFB molar ratio of 1.6 (experiment #2). This low value could be due to the insufficient amount of heat source and/or CO₂ injected into the reactor cavity, thus resulting in low syngas yield. However, results still illustrated that the feedstock calorific value was fully recovered.

The observed trends indicated that the energy upgrade factor is directly proportional to the investigated operating variables. These findings agreed with the reported literature [50]. Moreover, the energy upgrade factor of syngas generated in this study was approximately 2-fold higher than those obtained from conventional autothermal gasification of OPEFB of 0.7 [66,67]. This improvement is likely due to the advantages of solar energy providing higher, more consistent temperatures (1100–1300 °C), promoting efficient carbon conversion and syngas production [2]. This leads to an enhanced yield of high-energy syngas components like CO and H₂. Unlike conventional autothermal gasification, which relies on biomass combustion for heat supply and can suffer from heat losses and incomplete reactions, solar-driven gasification allows for better temperature control and reaction kinetics, resulting in higher-quality syngas [2]. It is worth noting that 25–35 wt % of biomass is used for heating in conventional gasification [68].

As observed in Fig. 4B, no optimum condition was achieved in this study for the energy upgrade factor, which could be due to the maximum allowable processing conditions (temperature $\leq\!\!1400\,^\circ\text{C}$, and CO_2 flowrate $\leq\!\!700\,\text{NmL/min}$). Therefore, the optimal conditions of the energy upgrade factor, illustrated by the CCD plateau curve, likely occur at higher operating conditions exceeding the upper limit of the solar gasification reactor. As a result, a quadratic function could not be formulated.

Although a maximum energy upgrade factor of 1.4 was experimentally reached, CCD predicts that it could exceed 1.5 at temperatures above 1400 °C and a CO₂/OPEFB molar ratio higher than 3.0. It is worth noting that the theoretical energy upgrade factor of Equation (1) is 1.43. Therefore, the CCD predicted values higher than 1.43 may be attributed to gasification reactions with the 11.3 % humidity in OPEFB (Table 1). Additionally, excess CO₂ can react with carbon to form 2CO (Boudouard reaction), and with H₂ to form CO and H₂O (reverse water gas shift reaction) [40]. However, it was not possible to validate the CCD model

Table 3

Comparison of target carbon sequestration methods (potential product, synthesis technology, and gas requirements) with experimentally achieved OPEFB solar-driven syngas composition (using steam [2] and CO₂) and upgrade gap analysis.

	•			-		
Target carbon sequestration methods				Experimentally achieved OPEFB solar syngas composition and upgrade gap analysis		
Potential products	Ref.	Synthesis technology	Gas composition requirement	OPEFB solar-driven syngas composition	Upgrade gap analysis ^a	
Graphene/ graphite	[60]	CVD	$\mathrm{H_2/CH_4}=49$	$H_2/CH_4 = 24.8$ (experiment #15 [2])	1) 100 % CO removal, 2) 98 % $\rm H_2$ addition or 49 % $\rm CH_4$ removal, and 3) $\rm C_n H_m$ trace pollutant removal	
Carbon nanotubes	[63]	CVD	${\rm H_2/CH_4} = 4.5$	$H_2/CH_4 = 4.6$ (experiment #2 [2])	1) 100 % CO removal, 2) 2.2 % $\rm H_2$ removal or 2.2 % $\rm CH_4$ addition, and 3) $\rm C_n H_m$ trace pollutant removal	
Synthetic diamond	[64]	CVD	$H_2/CH_4 = 49$	$H_2/CH_4 = 24.8$ (experiment #15 [2])	1) 100 $\%$ CO removal, 2) 98 $\%$ H_2 addition or 49 $\%$ CH_4 removal, and 3) $C_n H_m$ trace pollutant removal	
Methanol	[<mark>19</mark>]	FT	$H_2/CO = 2$	$H_2/CO = 0.5$ (experiment #4 (this study))	1) 100 % CH ₄ removal, 2) 300 % H ₂ addition or 75 % CO removal, and 3) $C_n H_m$ trace pollutant removal	
Dimethyl ether	[19]	FT	$H_2/CO = 2$	$H_2/CO = 0.5$ (experiment #4 (this study))	1) 100 % CH ₄ removal, 2) 300 % H ₂ addition or 75 % CO removal, and 3) $C_n H_m$ trace pollutant removal	
Formaldehyde	[19]	FT	$H_2/CO = 2$	$H_2/CO = 0.5$ (experiment #4 (this study))	1) 100 % CH ₄ removal, 2) 300 % H ₂ addition or 75 % CO removal, and 3) C_nH_m trace pollutant removal	
FT fuels	[19, 65]	FT	$\rm H_2/CO \geq 2$	$H_2/CO = 0.5$ (experiment #4 (this study))	1) 100 % CH ₄ removal, 2) \geq 300 % H ₂ addition or \geq 75 % CO removal, 3) C _n H _m trace pollutant removal	
Ethanol	[19]	FT	$\rm H_2/CO \leq 1$	$H_2/CO = 0.3-0.5$ (all experiments of this study)	1) C _n H _m trace pollutant removal	

^a All percentages are expressed in mol. %.



Fig. 4. (A): PCA of scaled operating variables (X_1, X_2) vs. scaled energy upgrade factor (Y_2) , (B) 3D response surface plot analysing the effects of the operating variables (X_1, X_2) on energy upgrade factor (Y_2) at constant OPEFB flowrate of 1.8 g/min $(X_1 = \text{temperature}, X_2 = \text{CO}_2/\text{OPEFB}$ molar ratio).

predicted value as the operating conditions were beyond the operational limits of the used solar reactor.

3.3. Analysis of the generated biochar

Biochar is produced as a by-product of the solar-driven gasification of OPEFB, although in small amounts. However, due to the large annual quantities of generated OPEFB of approximately 21.8 million tonnes generated per year [5–7], biochar-generated mass will become a residue of interest that requires proper treatment and/or direct utilisation methods. It is worth noting that biochar generation represents a long-term method of carbon sequestration [69]. Therefore, biochar produced from the solar-driven gasification, using steam [2] and CO_2 (this study), was characterised and a prospective application was proposed.

During gasification, the carbon content in biochar increases. The generated biochar from solar-driven gasification of OPEFB using steam and CO_2 as the gasifying agents generated a carbon content of up to 94.4 [2] and 95.7 dry wt. % (present research), respectively. Further details and data discussions are reported in the Supplementary Material (section 6).

The surface area (S_{BET}) of biochar characterises its reactivity and combustion behaviour [54]. Biochar produced at 1100 °C showed the lowest S_{BET} due to its high ash content and poor amorphous structure [70]. The surface area and pore volume increased with the operating temperature reaching 53.4 m²/g and 0.15 cm³/g for solar-driven steam gasification and 60.9 m²/g and 0.19 cm³/g for solar-driven CO₂ gasification at 1300 °C. The small surface areas indicated that the generated biochar had low adsorptive capacities, likely due to the high operating temperatures used during solar-driven gasification. Therefore, further activation processes are needed to utilise the produced biochar as activated carbon with high adsorptive capacity. Biochar can have a low specific surface area at lower temperatures [71,72]. For example, biochar from de-alcoholised grape marc via entrained flow technology at 1200 °C had an S_{BET} of 60 and 35 m²/g with air and steam as gasifying agents, respectively [71].

Metal content analysis was performed to determine the feasibility of using biochar as a nutrient source in soil applications. Most of the main elements (P, K, Na, Mg, Mn, Ca, Fe, S) are important plant nutrients in agriculture [73]. The content of P, K, Na, and S in biochar was proportional to the operating temperature (1100-1300 °C). At 1300 °C, results showed that the P, K, and Na content in biochar reaching 1.1, 5.9, and 0.2 wt %, respectively, were 10-20-fold higher than in raw OPEFB. Moreover, the S content in biochar at 1300 °C of 0.2 wt % was around 2-fold higher than in raw OPEFB. However, the amount of remaining elements (Mg, Mn, Ca, and Fe) decreased in the biochar compared to the raw feedstock. This quantity decrease indicates that they were solubilised during the process of solar-driven gasification, which was visually observed as melted metals deposited as ash on the alumina particles at the bottom of the solar reactor cavity. Nonetheless, the concentrations of this group of elements were still in the acceptable range for soil fertilisers [73], which also agreed with other studies on the use of biochar pyrolysed at a temperature of 700 °C [55,74]. The most abundant metals in the biochar samples were P, K, Fe, and S, which are essential soil micronutrients for plants and human health [74].

Heavy metals such as Cd, Cr, Cu, Ni, and Pb were found to be extremely low or negligible in raw OPEFB and the biochar. At 1300 °C, Zn content of 0.2 wt % in the biochar was found to be 17-40-fold higher than in raw OPEFB using steam [2] and CO₂ (present study). Except for Pb, Cd, and Cr, the analysed heavy metals were considered micronutrients for plants [73]. Cd was below the detection limit (<0.01 wt %) in raw OPEFB and the biochar, whereas Cr was found in a very small amount, i.e., 0.01 wt %, in raw OPEFB, but less than the detection limit in all biochar samples. Even though essential and non-essential elements can be potentially harmful elements once they are found in high concentrations [73], the concentration ranges found in the biochar of our present study is comparable with other biochar characterisation analyses [73,74]. However, threshold concentrations for heavy metals are not determined yet and are required for biochar certification [73].

SEM analysis was used to study the morphological features of raw OPEFB and biochar at two magnifications, i.e., 125x and 500x (Figure A.5 in the Supplementary Material). A predominance of small pore sizes was shown in all samples. Both raw OPEFB and the produced biochar presented a compact structure. The fibrous texture shown in raw OPEFB was lost in the biochar, likely due to the applied high-temperature range of 1100–1300 °C during the solar-driven gasification. The loss of fibrous texture in the biochar is in line with the findings of S_{BET} analysis.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.energy.2025.135805.

Data availability

Data will be made available on request.

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Considering the biomass origin and high content of the main elements (P, K, Na, Mg, Mn, Ca, Fe, S), which are beneficial for soils and plants [74], and low levels of heavy metals (Cd, Cr, Cu, Ni, Pb), biochar is most suitable for use as a biofertiliser. However, if the intention is to use them as an adsorbent, a biochar activation process is recommended, as suggested in other studies using activating agents such as K₂CO₃ [54, 75].

4. Conclusion

Carbon capture through solar-driven gasification of OPEFB was achieved by utilising CO₂ as the gasifying agent to generate syngas. This process reached a net carbon consumption rate of 0.7 g/min and a carbon conversion efficiency of 94.9 %. The highest net carbon capture yield of 0.4 g C/g OPEFB was achieved at the highest temperature of 1300 °C and a CO₂/OPEFB molar ratio of 3.0. An effective syngas yield of 77.4 mmol/g _{OPEFB} was achieved, representing 89.5 % of the maximum theoretical yield. The constant OPEFB flowrate of 1.8 g/min achieved stable and efficient experimental performance. The increase in temperature (1100–1300 °C) and CO₂/OPEFB molar ratio (1.6–3.0) at the OPEFB flowrate of 1.8 g/min showed a linear relationship with both H₂/CO molar ratio and energy upgrade factor. By using central composite design (CCD), the CO₂/OPEFB molar ratio, process temperature, and gasifying agent can be optimised, which is important for determining the H₂/CO molar ratio in the produced syngas.

A temperature of 1300 °C and CO₂/OPEFB molar ratio of 3.0 were found to be the optimum conditions, in this study, to achieve the lowest H₂/CO molar ratio of 0.3 (corresponding to H₂ and CO yields of 19.2 mmol/g OPEFB, and 58.5 mmol/g OPEFB, respectively) and the highest energy upgrade factor of 1.4. The favourable energy upgrade factor of 1.4 indicates that 40 % of the generated calorific value was efficiently stored from solar energy in the form of syngas. However, CCD predicted that energy upgrade factors exceeding 1.5 may be reached at temperatures above 1400 °C and a CO₂/OPEFB molar ratio higher than 3.0. However, these operating conditions are beyond the operational limits of the used solar reactor.

The produced biochar was characterised by a high carbon content of 94.4–95.7 wt %. The surface area and pore volume of the biochar reached 60.9 m^2/g and 0.19 cm^3/g , respectively, whereas the pore diameter ranged between 11.4 and 14.1 nm. Elemental composition analysis showed a high content of the main elements (P, K, Na, Mg, Mn, Ca, Fe, S) of interest for soil conditioning and fertilisation purposes. Heavy metal concentrations (Cd, Cr, Cu, Ni, Pb) were found to be extremely low or negligible.

The solar-driven gasification of OPEFB could help reduce around 4.8 million metric tons of GHG emissions per year in Malaysia. This process is largely independent of grid electricity and does not rely on critical raw materials required for PV or wind energy systems, positioning it as a viable and sustainable energy production technology. In the broader context, the solar-driven gasification of OPEFB has the potential to play a key role in the global energy transition by providing an eco-friendly solution for both carbon management and energy generation.

CRediT authorship contribution statement

Saqr A.A. Al-Muraisy: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. Srirat Chuayboon: Writing – review & editing, Validation, Resources, Investigation. Lais Americo Soares: Software, Methodology. J.G. Buijnsters: Writing – review & editing, Validation, Conceptualization. Shahrul bin Ismail: Supervision, Resources. Stéphane Abanades: Writing – review & editing, Validation, Resources, Investigation, Funding acquisition, Data curation. Jules B. van Lier: Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition. Ralph E.F. Lindeboom: Writing – review & editing, Supervision, Resources, Project

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