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Conical spouted bed combustor to obtain clean energy from avocado waste

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The advantages of spouted bed technology for waste treatment are linked to the high excess of renewable biomass waste generated by the large worldwide consumption of avocado. Therefore, the applicability of avocado waste as fuel in a novel conical spouted bed combustor was investigated. The solid cyclic movement in this reactor innovatively promotes better mass and heat transfer, as well as better energy exploitation of the waste. Local heat transfer coefficients were experimentally determined in the beds of avocado waste in the combustor to assess their heat transfer and determine their value as biofuels. The combustion of the avocado beds in the spouted bed regime was performed at 300–600 °C in a conical reactor at the minimum spouting velocity. The exhaust gas evolution was monitored over time, and the emission ratios were calculated. The combustion efficiencies of avocado seeds, skin, and their binary mixtures, determined from flue gas concentrations, were compared, and the effects of temperature and bed composition on combustion efficiency were analyzed.

1. Introduction

With the rising energy demand and depletion of fossil fuels, which contribute to greenhouse gas (GHG) emissions and global warming, the European Union established in Directive EU 2018/2001 the major priority of providing clean energy by replacing fossil fuels with renewable energy [1]. Decarbonization aligns with these goals at the international level, led by the European Union. The European Commission adopted a series of legislative proposals in July 2021 in the 2030 Climate Target Plan, with the ambitious goal of becoming climate-neutral by 2050 and an intermediate target of a net reduction in greenhouse gas emissions within the range of 50 to 55% (compared to 1990). The European Union has set a target of producing 65% of electrical energy from renewable energy sources by 2030 and 80% by 2050 [2]. Renewable energy production relies on low costs and high energy efficiency, which requires technological advancement. Fuels derived from renewable sources can contribute to decarbonization and mitigate climate change as they participate in the closed cycle of biogenic carbon, in which carbon dioxide released during their combustion is the same as that captured during their growth. According to the recently approved Spanish law regarding waste and polluted soils for a circular economy [3], the useful life of waste is extended instead of being landfilled.

Biomass, with a share of about 60%, constitutes the most important alternative source of renewable energy in the EU [4]. Thermal processes for obtaining energy by biomass conversion include combustion, pyrolysis, and gasification [5].

Avocado is a positively trending edible fruit whose global consumption has increased notably over the last few years, with an estimated global production of over 8 million tons in 2020 and a harvested area of almost 825 thousand ha in 2020 [6]. It is known as green gold because of its high nourishing and antioxidant properties. Avocado consists of proteins, lipids, carbohydrates, fiber, low-saturated fats (mainly oleic acid, 71 wt%), vitamins (A, B6, B12, C, E, and K1) [7], and minerals such as calcium, iron, zinc, magnesium, sodium, phosphorus, potassium, and folic acid. Avocado consumption generates a large amount of waste. The avocado tree, *Persea americana Mill., 1768*, originally from Central America, is classified in the *Lauraceae* family and is cultivated in subtropical and Mediterranean regions. Mexico is the world's largest producer of avocados, with almost 2.4 million tons in 2020 [6]. The growing demand of the European Union's countries is met by avocados harvested in the south of Spain and in the Canary Islands, with a production of over 99,000 tons in 2020 [6]. This fruit is a berry with an oval or spherical shape, rough skin ranging from dark green to purple, and contains a fleshy light-green pulp and a single large hard seed. Although there are hundreds of varieties of commercial avocado plants, there are three main botanical varieties: Mexican (*Persea americana* var. *drymifolia*), Antillean (*Persea americana* var. *Americana*), and Guatemalan (*Persea americana* var. *guatemalensis*). Hass is one of the most cultivated varieties worldwide because of its excellent pulp quality. The industrial manufacturing and food consumption of avocado generates a large amount of waste (skin and the seed or stone), mainly in

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Nomenclature

D_b, D_c, D_i, D_o	diameter of the top diameter of the stagnant bed, upper diameter of the cone, of the dryer bottom, and of the gas inlet, respectively (m)
$\overline{d_S}$	Sauter mean diameter (m)
h	local heat transfer coefficient (W/m^2 °C)
H_{cylin}, H_{cone}, H_o	height of the cylindrical section, of the conical section and of the stagnant bed, respectively (m)
M	bed mass (kg)
q	power input of the cartridge heater (W)
r	radial coordinate (m)
r/R	dimensionless radial position
t	time (s)
T	temperature (°C)
T_b, T_s	bed and surface temperature, respectively (°C)
u, u_{ms}	velocity of the gas referred and minimum spouting velocity of the gas referred to D_i, respectively (m s^{-1})
X	moisture content (dry basis) (kg/kg)
$\overline{X_H}$, $(\overline{X_H})_u$	weight fraction of particles of the greater diameter or density in the whole bed and in the upper volume half of the bed, respectively.
x_{steel}, x_{ins}	thickness of the reactor wall and of the insulation (m)
z	longitudinal coordinate (m)

Greek letters

γ	angle of the contactor (deg)
η	combustion efficiency

Abbreviations

CI	combustibility index
FC	fixed carbon
HC	hydrocarbons HC
HHV	higher heating value
LHV	lower heating value
VM	volatile matter

guacamole production, which only employs the pulp. The avocado fruit is small to medium in size (140–400 g), of which the skin comprises up to 15 wt% [8], and the stone comprises up to 26 wt% [9]. Even though avocado wastes can be used as animal feed [10], alternatives to composting [11] or disposal in landfills are required. Novel potential applications of avocado waste include bioplastic production [12], pollutant adsorbents [13], and biorefinery applications [14]. Hass avocado is composed mainly of hemicellulose, cellulose, and lignin, with percentages around 44, 11 and 13% for seeds [15], and 11.5–25.3, 12.1–27.6, and 4.4–35.3% for skin, respectively [16].

As avocado seed and skin wastes have high calorific values, they are suitable candidates for energy recovery. Nevertheless, since research is not currently focused on energy valorization, there is scarce literature regarding the thermal valorization of avocado waste. Domínguez et al. [9] analyzed the potential use of avocado seeds as a fuel by the combustion/reforming of avocado seeds in a porous media reactor and by torrefaction and pyrolysis in a rotary furnace. In addition, the energy properties of avocado seeds were evaluated to determine the feasibility of their biomass as a solid biofuel for domestic and industrial heating applications [17]. The chemical composition of avocado skin and seed, as well as their phenolic content and antioxidant activity, were determined, aiming to fully valorizate these avocado wastes to obtain multiple bioproducts [16]. García-Vargas et al. [8] reviewed valorization strategies to obtain bioenergy, biofuels, and other commercial goods from avocado waste in a single or integrated process within a biorefinery background, as well as by green technologies such as microwaves, ultrasound, and supercritical fluids. The good thermal behavior of the avocado waste was confirmed by thermogravimetric analysis (TGA) [15]. Finally, the thermochemical conversion of avocado seed waste was conducted in a rotary reactor by torrefaction and carbonization [18].

Despite the potential application of avocado wastes for energetic purposes, these wastes present some disadvantages from an industrial standpoint, such as high moisture and ash contents [16]. Ashes remaining after combustion have an adverse effect on the combustor, equipment, and combustion process because they absorb some of the heat generated and interfere with the contact between the fuel and oxidant. Additionally, avocado wastes may be dioxin and furan precursors.

Spouted bed technology has been successfully performed for thermal treatment of biomass wastes by drying: in conventional spouted beds of fruits [19] and in conical spouted beds of sludge wastes [20–22], of biomass [23–26]; by combustion: of torrefied rice husk and other agricultural residues in spout-fluid beds [27] of rice straw in spouted beds, in conical spouted beds of cork [28], of vineyard pruning wastes [24]–[29], of fruit tree [30] of sludge wastes [31]; by pyrolysis of biomass [32] and by gasification of biomass [33]. This good performance in thermal treatment is due to the high mass transfer [34] and heat transfer [35], produced by the vigorous cyclic movement of the particles and the vigor of the fluid-particle regime in countercurrent allows to handle fine particles [36,37], and avoid particle stickiness and segregation [25]. Thermal processes such as drying, pyrolysis, and combustion involve heat and mass transfer. To improve the design of spouted bed reactors for thermal processes, it is advisable to determine the heat transfer coefficients. Some authors have quantified the heat transfer coefficient in spouted beds by the change in temperature from the inlet air temperature at various axial and radial positions within the reactor, as measured by several thermocouples [38,39]. Several correlations as a function of dimensionless moduli have been proposed by other authors to estimate the heat transfer coefficient based on the total surface area of particles and on the overall effective temperature difference, mainly for drying and coating in spouted beds [39]. There are few studies on the local heat transfer coefficient in conical spouted beds, but some researchers have measured local heat transfer coefficients in fluidized beds and spouted beds by locating a small probe to avoid disturbing the flow at various radial and longitudinal positions within the bed comprised of different materials [40,41].

This study focuses on the feasibility of using avocado seed and skin wastes from industrial biomass wastes and home consumption as a replacement for conventional fuels in a conical spouted bed reactor by a combustion process with very low polluting gas emissions. Since the green energy produced might be utilized by guacamole production companies and for home consumption, it may contribute to the circular economy, battle climate change, achieve climate neutrality, and decarbonize the environment. Adequate operating conditions for the combustion of these wastes were studied, as well as the local heat transfer coefficients inside the bed. An exhaust gas analysis was performed to improve the combustion efficiency, and the emission gas ratios and combustion efficiencies were determined. Moreover, the influence of the moisture content of the wastes, operating temperature, and percentage of seed and skin wastes in the mixtures on the combustion efficiency was analyzed.

2. Materials and methods

2.1. Equipment

Thermal treatment of avocado seed wastes was conducted in an experimental plant designed at purpose at pilot plant scale with two configurations, Fig. 1, the configuration provided with a conical combustor, Fig. 1a, and the configuration with a conical dryer and a conical combustor, Fig. 1b. The plant consists of a blower, an electrical heater designed for the purpose (Reyter, Spain), located prior to the combustor for heating the inlet gas, and two high-efficiency cyclones at the dryer outlet to collect fine particles and at the combustor outlet to collect ashes. A mass flowmeter, located before the electrical heater, measure gas flow rate operated by a computer (accuracy ±0.5%). The exhaust gas is cleaned by passing it through a vertical extractor hood connected to a chimney with a filter medium to minimize the environmental impact. The combustor is a conical spouted bed which does not require a distributor plate nor inert material as combustion adjuvant, resulting in a lower cost than the fluidized bed.

The conical spouted bed dryer and combustor are made of AISI-310S stainless steel with the same geometry (Table 1) and with cone angle 36° [30,31] as displayed in Fig. 1. Electrical heaters were wrapped around the external wall surface of the reactor, provided by Schneider Electric controller (France, accuracy ±0.5%) to minimize heat loss. This controller is based on a set temperature determined by a thermocouple aligned within the dryer that can be set up in various positions. The heaters were insulated with 0.05 m quartz fiber and a cylindrical jacket of AISI-310S stainless steel covered the reactor.

Moreover, a K-type thermocouple placed at the combustor inlet measured the temperature of the air provided by the blower and heated by the electrical heater, controlled by Selecta Electemp-TFT (J.P. Selecta, Spain, accuracy ±0.1 °C). Similarly, K-type thermocouples were employed to measure air temperature at the exit and within the conical reactors (relative error of ±0.75% or ± 2.2 °C). Furthermore, air temperature and humidity content at both the inlet and outlet of the reactors were monitored by thermal conductivity detectors Alhborn MT8636-HR6 (Ahlborn, Germany, accuracy ±2% relative humidity), and the data were recorded in the Alhborn Almemo 2290–8 data logger.

Minimum spouting velocity corresponding to the velocity at the fountain onset, the beginning of the spouted bed regime, was determined by pressure drop fluctuations with a standard deviation <10 Pa [42]. Bed pressure drop signal data and air velocity data measured every second by a differential pressure transducer (Siemens Teleperm) were logged and processed by the AMR-Control program to obtain pressure drop evolution with air velocity.

Table 1
Geometric factors of the conical spouted bed reactor.

Conical spouted bed reactor		
Contactor angle	γ (deg)	36
Diameter of the reactor bottom	D_i (m)	0.03
Gas inlet diameter	D_o (m)	0.015, 0.02 and 0.03
Upper diameter of the cone	D_c (m)	0.225
Upper diameter of the stagnant bed	D_b (m)	$D_i + 2\ H_o \tan(\gamma/2)$
Height of the conical section	H_{cone} (m)	0.30
Height of the cylindrical section	H_{cilin} (m)	0.20
Stagnant bed height	H_o (m)	between 0.05 and 0.30
Thickness of the reactor wall	X_{steel} (m)	0.002
Thickness of the insulation	X_{ins} (m)	0.05

The local heat transfer coefficient of a fluid particle in a conical spouted-bed combustor was experimentally determined by the heat supplied by the probe immersed in the bed. The heat transfer probe is comprised of a 316 stainless steel cylinder 50 mm long and 22 mm in diameter. The heat flux values were measured using a microfoil heat flux sensor (FHF03 Hukseflux, The Netherlands). The heat was supplied by a small cartridge heater (Aloña, Spain) inserted into a cylinder and provided by a power regulator and thermocouples (K-type). The heat transfer coefficient was evaluated by placing the probe in various radial and longitudinal positions on beds comprised of avocado seed, skin, and binary mixtures of both wastes. The local heat transfer coefficient, h (W/m^2 K) is calculated by using Newton's law by the power input of the cartridge heater, q (W), and by surface temperature, T_s (°C), and bed temperature, T_b (°C).

2.2. Materials

The biomass used was waste of Hass avocado variety, Fig. 2, biogenic fuel type E [43], seed of density, 1526 kg/m^3, moisture content of 117 wt% (dry basis, d.b.) (Mettler Toledo HB43-S Halogen hygrometer), a Sauter mean diameter of 27.8 mm and sphericity of 0.93, and avocado

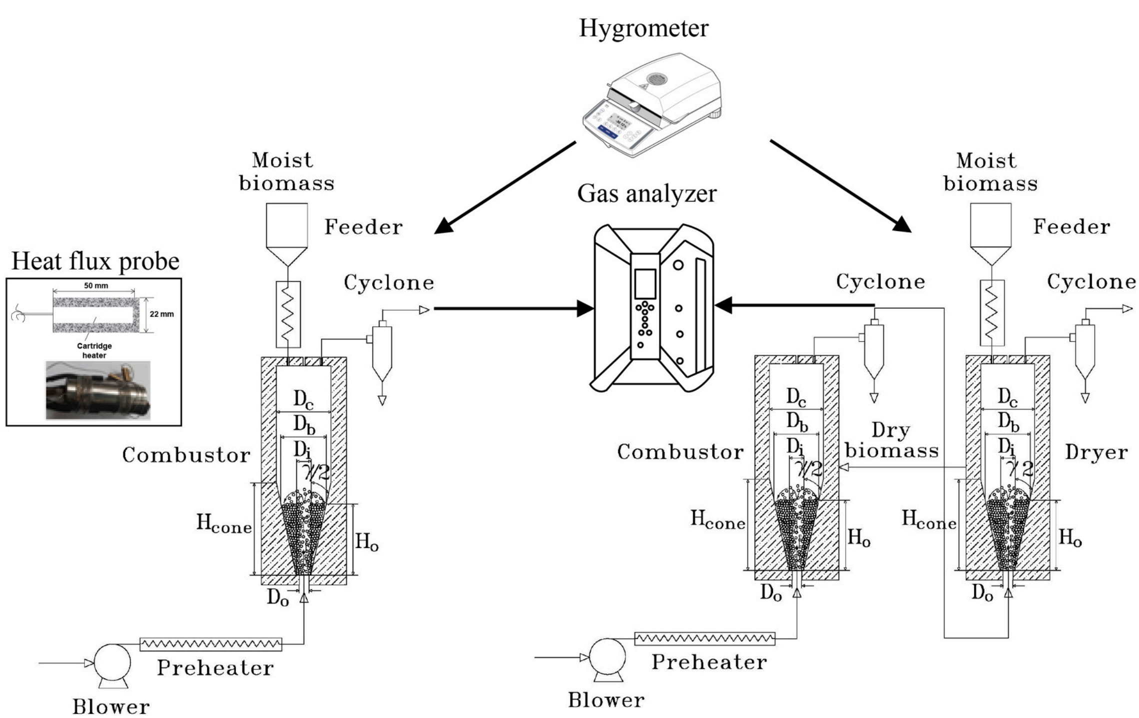

Fig. 1. Schematic diagrams of the experimental equipments. (a) conical spouted bed combustor; (b) conical spouted bed dryer and combustor.

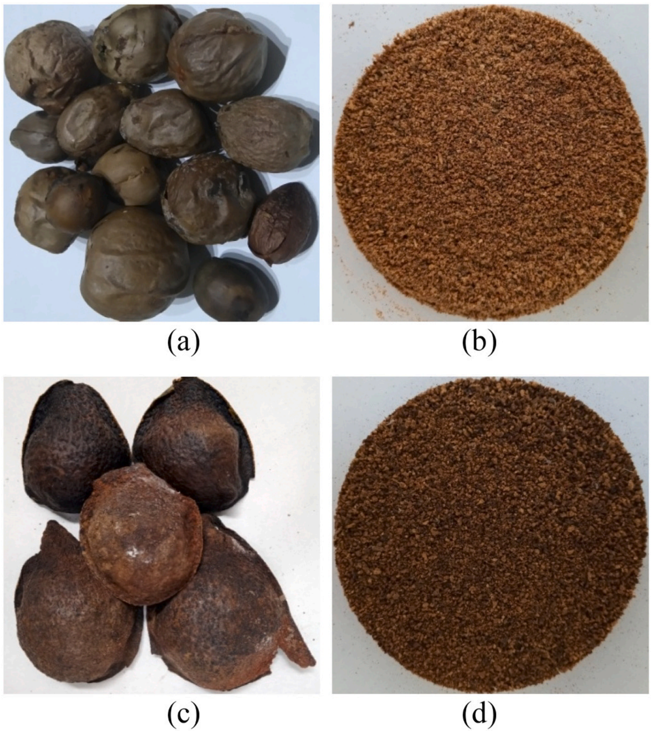

Fig. 2. Hass avocado waste: (a) seeds, (b) grinded seeds particles, (c) skin and, (d) grinded skin particles.

skin of density, 611 kg/m^3, and moisture content of 100 wt% (d.b.). Avocado seeds and skin were grinded by a mill (Fritsch Pulverisette 15, Fritsch, Germany) to a fraction of Sauter particle diameter of 1.09 mm. Solid particles were separated by size using a sieving machine (Filtra FTI-0300, Filtra Vibracion, S.L, Spain) and belong to D Geldart group. The density of the avocado seeds, after grinding and drying, was 1136 kg/m^3 and of the avocado skin 440 kg/m^3.

Avocado wastes were characterized by ultimate and proximate analyses and by the higher heating value (HHV) and lower heating value (LHV) determined by the National Institute of Coal (INCAR) of the Spanish National Research Council (CSIC).

The combustion of beds comprised of moist and dry avocado wastes, dried in a conical spouted bed dryer, was performed in the spouting bed regime by preheating the combustor with air supplied by the blower and heated by an electrical heater at the combustor inlet at the minimum air velocity, which is over the stoichiometric flow, providing good gas-solid contact. Before combusting the dry avocado waste, the blower was connected to the dryer to dry the first batch of waste. Once the wastes were dry, the process was continued with combustion-drying cycles, as shown in Fig. 1b. Dry avocado wastes were fed into the combustor when the set combustion temperature was achieved. The concentrations of CO, CO_2, HC, and O_2 gases, as well as the temperature in the exhaust gas, were monitored over time by probes placed at the combustor gas outflow. The gas concentration was measured using a Testo 350 gas analyzer (Testo SE & Co. KGaA, Germany) calibrated by the supplier. The relative error for the CO_2 measurement was ±0.3%vol, for CO ±2 ppmv, for O_2 ± 0.2%vol, and ± 10 ppmv for HC and that for temperature was ±0.4 °C (for the −100-200 °C range) and ± 1 °C (for other temperature ranges). The gas analyzer was set to zero by subtracting the atmospheric air concentration. The combustion process was conducted in triplicate at each bed temperature, and the mean values and standard deviations were calculated.

3. Results and discussion

3.1. Avocado wastes characterization

To assess the qualities of avocado wastes as biofuels, these wastes were characterized by experimental determination of ultimate and proximate analysis, higher and lower heating values, and by calculation of the combustibility index, CI, along with the H/C and O/C atomic ratios.

The experimental data of the ultimate analyses of avocado wastes, summarized in Table 2, show that both avocado seeds and skin wastes contain comparable elemental compositions with high carbon and oxygen percentages, and low hydrogen, nitrogen, and sulfur percentages. These percentages are similar to those previously reported for avocado seed waste [17], Hass avocado waste [16], and avocado seeds (Hass and Bacon) cultivated with two different fertilizers [15]. However, avocado skin has slightly higher carbon and nitrogen amounts and slightly lower amounts of hydrogen and oxygen, as reported by García-Vargas et al. [16]. In addition, the carbon, nitrogen, and hydrogen percentages of avocado wastes are similar to those of wood [44]; however, the oxygen and sulfur percentages of avocados are slightly lower, with higher ash content. The ash content in avocado seeds (1.13%) was lower than in avocado skin (5.48%) and other biomass, such as oak wood pellets (3.32%) [45]. Moreover, these values are higher than those contained in other solid biofuels from agricultural and forestry wastes like olive stone (0.77%) and almond shells (0.55%) [17]. The possibility of noxious emissions by the formation of nitrogen oxides in the combustion of avocado wastes is low due to the low nitrogen percentage, ≤ 1.3 wt%, and the experiments were carried out at temperatures up to 600 °C. SO_2 formation is not very relevant because of the low content of S in the waste (≤ 0.1 wt%), as reported by García-Vargas et al. [16].

The experimental results of the higher heating value (HHV) and lower heating value (LHV) determined by the IKA C4000 calorimeter using the ISO 1928 standard are in agreement with the correlations given for the higher heating value (HHV) of coal by Boie [46] and for the lower heating value (LHV) of avocado seeds by Sánchez et al. [18]. The fitting presents maximum errors of 0.32% for the first correlation and 0.5% for the second one. Considering these results, these avocado wastes

Table 2
Ultimate and proximate analysis.

	Avocado seed	Avocado skin	Standard	Equipment
Ultimate analysis (wt% d.b.)				
C	47.33	52.29	ASTM D4239	LECO CHN-2000
H	6.27	6.19	ASTM D4239	LECO CHN-2000
O	44.88	39.6	By difference	
N	0.9	1.30	ASTM D4239	LECO CHN-2000
S	0.08	0.1	ASTM D5865	LECO S-632
Proximate analysis (wt% d.b.)				
Volatile matter (VM)	78.77	71.93	ASTM D7582	LECO TGA701
Fixed carbon (FC)	20.1	22.59	By difference	
Ash	1.13	5.48	ASTM D7582	LECO TGA701
Moisture	3.54	6.35	ASTM D7582	LECO TGA701
Heating values				
HHV (MJ/kg)	19.01	21.61	ISO 1928	IKA C4000
LHV (MJ/kg)	17.73	20.34	ISO 1928	IKA C4000

are suitable for energy valorization, as their higher heating values (HHV) (above 19 MJ/kg for avocado seeds and over 21 MJ/kg for avocado skin) are within the usual range of HHV (15–20 MJ/kg) of biomass [47], of the same order as those of wood [44], and higher than those of other biofuels such as olive stones, almond shells, and olive wood pellets [48].

To estimate the potential use of avocado wastes as fuel for combustion, the combustibility index (CI) or volatile matter to fixed carbon ratio (VM/FC) and atomic ratios (H/C and O/C) were calculated from the ultimate analysis. Furthermore, the van Krevelen diagram [49] is a practical tool for predicting and comparing the heating values of various fuels based on their H/C and O/C atomic ratios. According to this diagram, the lower the atomic ratio, the higher the energy content of the fuel because the higher proportion of O and H relative to C reduces the energy of the fuel because the energy contained in C—O and C—H bonds is lower than that in C—C bonds [50]. The combustibility index is 3.92 for avocado seed, slightly higher than that of olive stone as a solid fuel (3.84) [17] and slightly lower than that of avocado skin (3.18). The H/C and O/C ratios of both avocado wastes were within the range of biomass in the van Krevelen diagram. It is worth mentioning that the H/C and O/C ratios of the avocado skin (1.42 and 0.57, respectively) were lower than those of the avocado seed (1.59 and 0.71), supporting the higher combustibility of avocado skin.

3.2. Hydrodynamics of beds consisting of avocado wastes in conical spouted bed combustor

The operating conditions for the thermal treatment of the avocado seed waste beds, corresponding to the spouted bed regime, were delimited in a conical spouted bed reactor.

The experimental values of the minimum spouting velocity, u_{ms}, of beds consisting of moist avocado seed and skin wastes, and these wastes dried to equilibrium moisture contents, are depicted in Fig. 3. The bed mass, M, (corresponding to stagnant bed height in the range 0.02–0.20 m) is plotted against gas velocity, u, for experimental systems taken as an example for beds of skin, seed, and three binary mixtures of avocado seed and skin with different mass percentages. A scheme of the particle position inside the conical spouted bed in the fixed bed and spouted bed regimes is also shown in Fig. 3a.

Beds of avocado wastes are stable in the spouted bed regime under all the studied experimental conditions without slugging. Beds consisting of binary mixtures present low segregation with a mixing index of 0.95, which was calculated as the ratio between the experimental values of the weight fraction of particles of the greater diameter or density in the upper volume half of the bed, $(\overline{X_H})_u$, and the weight fraction in the whole bed, $\overline{X_H}$ [51]. The photo in Fig. 3b illustrates the movement of avocado seed particles in the spouted bed regime inside the conical spouted bed reactor, for example, where the three zones characteristic of this regime are distinguished: spout zone, annular zone, and fountain. Starting in the fixed bed, increasing gas enters through the reactor bed bottom to achieve a spouted bed regime at the minimum gas velocity, u_{ms}, for every bed mass. In addition, an increase in bed mass promotes higher values of minimum spouting velocity almost proportionally. However, the increase in stagnant height corresponding to different bed masses is less than proportional in the same bed. As observed, the minimum spouting velocity for beds of avocado seed particles is higher than for beds of avocado skin, and beds consisting of binary mixtures have an intermediate minimum spouting velocity. In addition, in conical spouted beds, a homogeneous mixture without segregation is achieved, which is an improvement compared to the fluidized bed, in which the denser particles are more concentrated in the lower part of the bed. Moreover, the minimum spouting velocity of the mixture in conical spouted beds is lower than that in fluidized beds, with the drawback that the lighter particles can elutriate.

3.3. Heat transfer. Local heat transfer coefficients of fluid-particle

Longitudinal profiles of the average heat transfer coefficients obtained at a radial distance of 0.01 m from the axis at three axial positions (z = 0.02, 0.10, and 0.20 m) of the conical spouted bed combustor in beds of avocado seed and skin wastes of a stagnant bed height of 0.20 m are shown in Fig. 4a. As observed, the local heat transfer coefficient decreased, following the same trend for both wastes. The heat transfer coefficients of avocado seeds were slightly higher than those of the skin. The heat transfer coefficients decreased from the bed surface (210 W/m^2 °C for the seed and 183 W/m^2 °C for skin) towards the contactor base (55 W/m^2 °C for the seed and 39 W/m^2 °C for the skin) and were almost proportional in the upper half of the bed and less than proportional in the lower half.

Radial profiles of the average heat transfer coefficients for beds

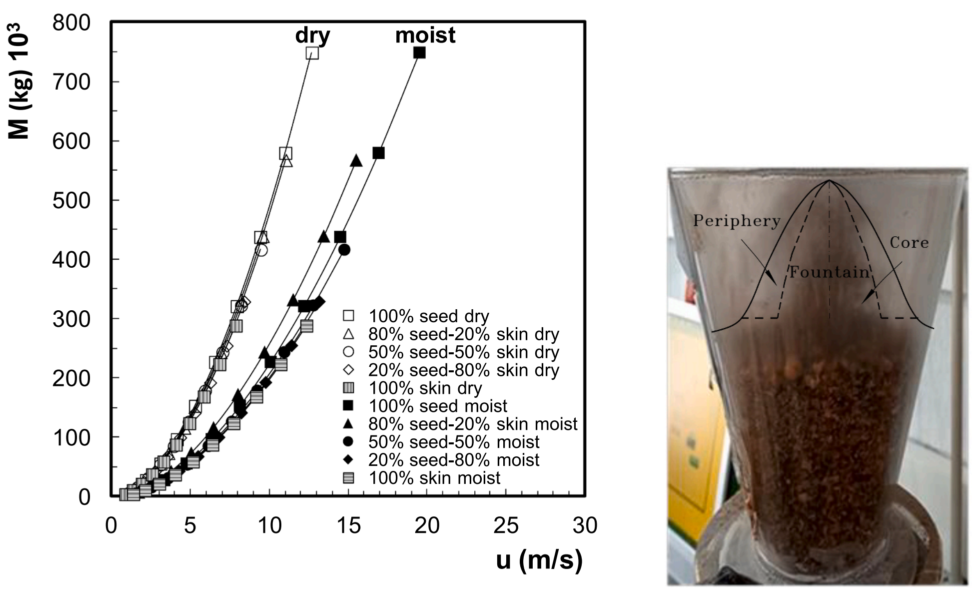

Fig. 3. Experimental system: $\gamma = 36°$, $D_o = 0.03$ m, a) Operating map of bed mass versus gas velocity of binary mixtures of avocado seed and skin with different mass percentage. b) Photo illustrating the movement of avocado seed particles in the spouted bed regime.

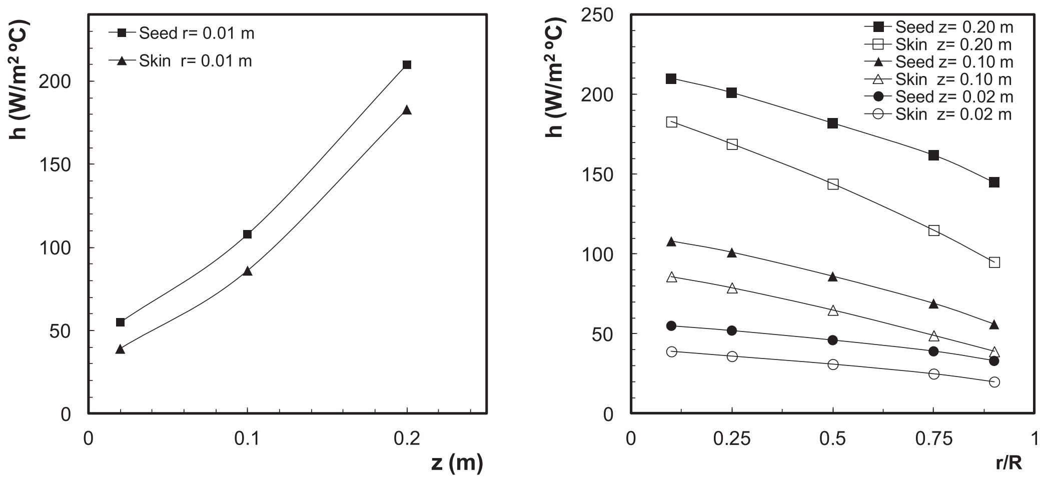

Fig. 4. Heat transfer coefficient in beds of avocado seed and skin wastes. Experimental system: $\gamma = 36^\circ$, $D_o = 0.03$ m, $H_o = 0.20$ m. a) radial profiles and b) longitudinal profiles.

consisting of avocado seed and skin wastes for a stagnant bed height of 0.20 m are plotted in Fig. 4b at five dimensionless radial positions at different bed levels. It has been experimentally determined that the heat transfer coefficients decrease slightly with radial position from the combustor axis towards the wall, and this effect is more noticeable at higher bed levels. At a bed level of 0.2 m, the heat transfer coefficient decreased from 210 W/m^2 °C at $r = 0.01$ m to 145 W/m^2 °C at the reactor wall for seed and from 183 W/m^2 °C at r = 0.01 m to 95 W/m^2 °C at the reactor wall for skin, with both following the same trend. At a bed level of 0.02 m, the heat transfer coefficients decreased from 55 to 33 W/m^2 °C for seed and from 39 to 20 W/m^2 °C for skin. The heat transfer coefficients of the seed (33–210 W/m^2 °C) were higher than those of the skin (20–183 W/m^2 °C), and the radial effect was more pronounced.

Comparing the local heat transfer coefficients of beds consisting of avocado wastes (seed, skin, and their mixtures) in conical spouted beds with those of beds consisting of sawdust [52], the local heat transfer coefficients in avocado waste beds are of the same order as those in beds of sawdust, and in beds of avocado skin, the heat transfer coefficients are slightly higher than those in beds of sawdust.

3.4. Combustion of beds consisting of avocado wastes in conical spouted bed reactor. combustion efficiency

To cover the lack of results of exploitation of these wastes in combustion in this study, avocado wastes, seed, skin, and their binary mixtures were used to obtain clean energy in a conical spouted bed reactor. Beds consisting of different masses of avocado waste, seeds, and skin and their binary mixtures (20, 40, 50, 60, and 80 wt% of skin) were burned at temperatures ranging from 300 to 600 °C, with temperature increments of 25 °C at the minimum spouting velocity corresponding to each experimental system.

The gas concentrations in the flue gas were monitored using a Testo 350 gas analyzer during the combustion of the avocado waste. The temperature of the exhaust gas was measured at the combustor outlet, and it was determined that the gases were released at a temperature of 35 ± 2 °C. The time profiles of CO_2 (% volume) and CO (ppm) with time are shown in Fig. 5 at 500 °C for some experimental systems. After a short delay between the feeding of avocado wastes and the start of combustion, the signals of CO_2 and CO rose from zero, reached a sharp peak, and then declined to zero and slightly skewed to the right.

The experimental combustion efficiency values of beds consisting of avocado wastes were calculated by integrating the data curves of the mean concentrations of CO_2 and CO gases monitored over time in the flue gas in the three experiments performed at each temperature, as $\eta = [CO_2/(CO + CO_2)]\ 100$. This equation was taken as a reference from the combustion process in conical spouted beds of vineyard pruning waste [24,29], fruit tree pruning waste [30], sludge waste [31], and anthracite coal and wood pellets fluidized beds [45]. To apply this equation, the ash content was not considered from the beginning.

3.4.1. Influence of moisture content of the fuel in combustion efficiency in conical spouted bed reactor

The influence of the moisture content of avocado waste on combustion efficiency was determined by comparing the combustion experiments conducted in the spouting bed regime at 500 °C with beds comprised of four different masses of dry and moist avocado seeds. It was determined that although there is a slightly longer time delay for moist seeds (approximately 85 s) than for dry seeds (approximately 50 s), the combustion efficiency calculated from the concentrations of CO_2 and CO is slightly higher for dry seeds (94.01%), compared to moist seeds (93.75%). In addition, the ratio between the peak values of CO_2 and CO was larger for dry seeds than for moist seeds. Therefore, the results indicate that, in addition to improving combustion efficiency, pre-drying avocado wastes saves energy by reducing the flow rate required to reach the spouted bed regime and the combustion time.

Based on the results and the weight reduction of avocado waste, the following combustion experiments were carried out with dry avocado waste.

To determine the minimum combustion temperature, as well as the influence of temperature on combustion efficiency, batch combustion of avocado seed waste was performed between 300 and 600 °C with a temperature increase of 25 °C. The seeds were not burnt between 300 °C and 375 °C, and a peak with a negligible amount of CO_2 was obtained. At 400 °C they burned, although the unburned component consisted of 2.52 wt% HC and 7 wt% ash. At 425 °C, the unburned component consisted of 2.5 wt% HC and 5 wt% ash, and at 450 °C, 2.41 wt% HC and an ash percentage of 4.1 wt% were obtained.

3.4.2. Influence of mixture composition in combustion efficiency in conical spouted bed reactor

The combustion of dry avocado skin, seeds, and the five binary mixtures were carried out at 500 °C. The results of the time profiles of CO_2 (% volume) and CO (ppm) gas concentrations obtained during the batch combustion of dry avocado seeds (Fig. 5a) of three binary mixtures (20 wt% of skin, Fig. 5b, 50 wt% of skin, Fig. 5c, and 80 wt% of skin, Fig. 5d), and skin (Fig. 5e) are shown as examples. Avocado skin waste presented the highest peak value of the volume percentage of CO_2 (≈15.86%) obtained at approximately 62 s, Fig. 5e, followed by the

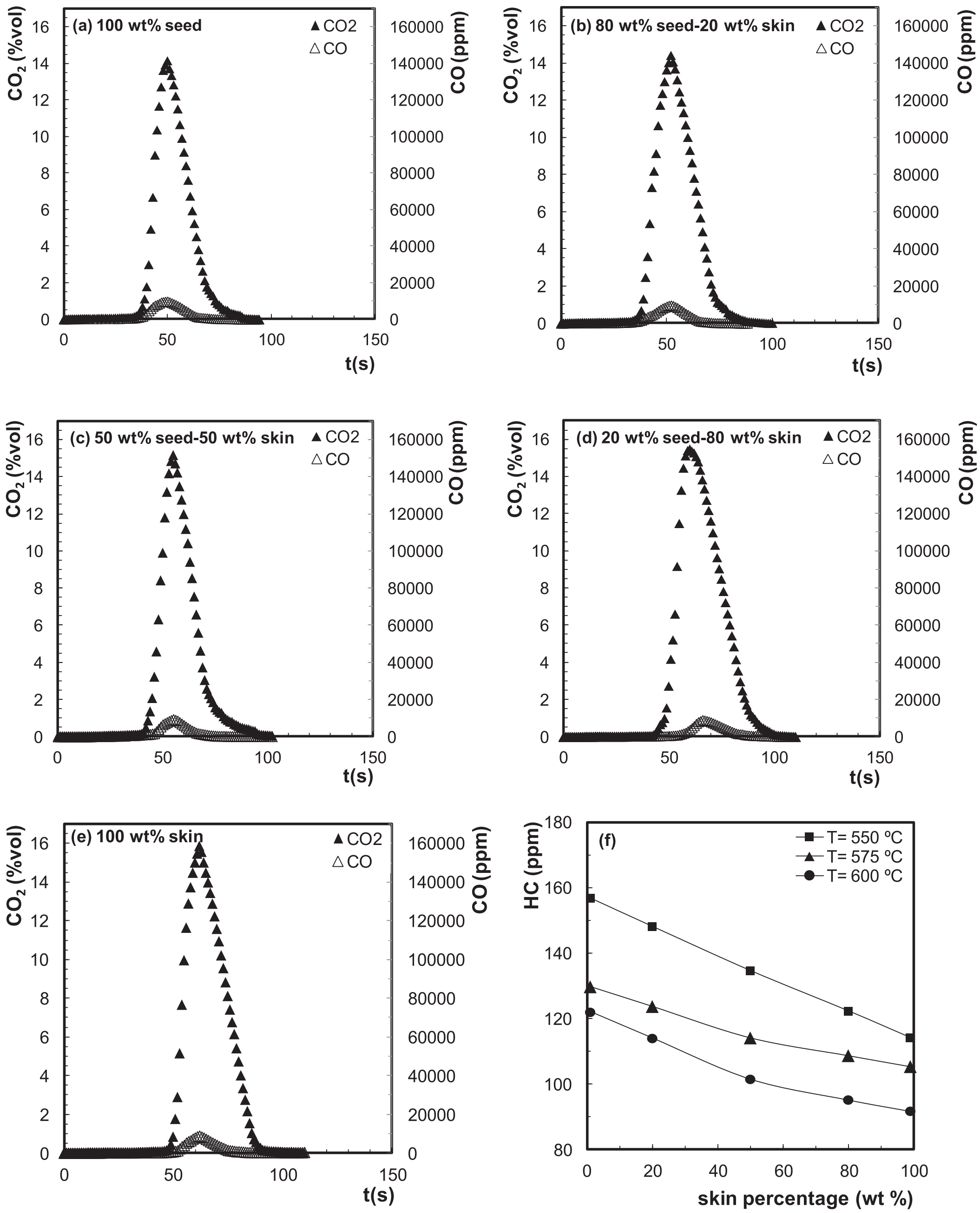

Fig. 5. Time evolution of CO_2 (% volume) and CO (ppm) concentration in the flue gases during the batch combustion process at inlet gas temperature of 500 °C at minimum spouting gas flow. (a) avocado seed wastes, (b) binary mixture of avocado seed and skin wastes 80–20 wt%, (c) binary mixture of avocado seed and skin wastes 50 wt%, (d) binary mixture of avocado seed and skin wastes 20–80 wt% of seed wastes, (e) avocado skin wastes, (f) evolution of HC (ppm) concentration with different skin percentage at three gas temperatures.

binary mixture of 80 wt% skin (≈15.67%) at approximately 60 s (Fig. 5d), then the mixture with 50 wt% skin (≈ 15.16%) at approximately 47 s (Fig. 5c), next the mixture with 20 wt% skin (≈ 14.42%) at approximately 52 s (Fig. 5b), and finally avocado seed presented the lowest peak value (≈ 14.16%) at approximately 50 s (Fig. 5a). The CO_2 generated can be used to obtain methane [53]. Regarding the maximum value of CO concentration, avocado skin presented the lowest value (≈ 8900 ppm) (Fig. 5e), followed by that for a binary mixture of 80 wt% skin (≈ 9100 ppm) (Fig. 5d), followed by that for a binary mixture of 50 wt% skin (≈ 9300 ppm) (Fig. 5c), then that for a binary mixture of 20 wt % skin (≈ 9800 ppm) (Fig. 5b). The highest concentration corresponded to avocado seed (≈ 10,000 ppm) (Fig. 5a). The CO_2/CO ratio at the peak for avocado skin waste was close to 18, above 17 for a binary mixture of 80 wt% avocado skin, over 16 for a binary mixture of 50 wt% skin, and above 14 for a binary mixture of 20 wt% avocado skin, as well as for avocado seed.

Furthermore, the time profile of the HC (ppm) gas concentration obtained for the combustion of avocado skin is plotted in Fig. 5e to compare its concentration with that of CO and CO_2. At any time, the points corresponding to the experimental values of HC concentration were close to the abscissa axis, therefore, low concentrations of HC were observed. Fig. 5f shows the HC (ppm) gas concentration obtained during the combustion of avocado waste for different avocado skin percentages at temperatures ranging from 550 to 600 °C. As shown here, the HC (ppm) concentration decreased with temperature and with an increase in skin percentage. The HC (ppm) concentration decreased nearly proportionally as the skin percentage increased at 550 °C, whereas at 575 °C and 600 °C, the decrease from 50 wt% skin was less pronounced.

From the results obtained for the combustion of avocado wastes, changes in the combustion efficiency of beds comprised of avocado seed, skin, and a binary mixture of 50 wt% avocado seed and skin wastes with combustion temperatures ranging from 475 to 600 °C are compared in Fig. 6a. The mean concentrations of combustion efficiency are represented by the experimental points, and the error bars indicate the standard deviation of the mean. This temperature range was chosen to ensure a low unburned content, with an HC content below 2 wt%. In this temperature range, for the seed waste, HC varied between 1.8 and 0.12 wt%, and the ashes were between 3.6 and 1.14 wt%. For the skin waste, HC represented 1.36 wt% at 475 °C, and 0.1 wt% at 600 °C, and ashes represented 7.9 wt% and 2.4 wt%, respectively. For binary mixtures of 50 wt% seed and skin wastes, HC ranged from 1.45 wt% at 475 °C to 0.12 wt% at 600 °C and ashes from 4.86 to 1.85 wt%.

The combustion efficiency for avocado waste was between 92.3 and 97.65% in a conical spouted bed combustor between 475 and 600 °C. As observed, the combustion efficiency increases with combustion temperature, and this increase is more pronounced from 475 to 550 °C, increasing by 4.5%, than from 550 to 600 °C, increasing by 0.5%. The combustion efficiency presented an asymptotical tendency between 550 °C and 600 °C. In addition, the increase in combustion temperature promoted a less-than-proportional increase in combustion efficiency. The highest combustion efficiency was obtained at 600 °C for skin (97.65%), followed by the 50 wt% mixture (97.38%), and finally for seed (96.94%). Combustion was not conducted at temperatures above 600 °C because the efficiency improvement from 500 °C to 600 °C was very low (<3.5%), so further increases were not likely to cause large improvements. Moreover, the combustion efficiency for avocado skin presented values slightly higher than those of the mixture, followed by those of the seed; this effect was less noticeable at higher temperatures.

To ascertain the influence of mixture composition on combustion yield, Fig. 6b compares the combustion efficiency of homogeneous beds comprised of avocado seed and skin and beds of five binary mixtures (20, 40, 50, 70, and 80 wt% skin) against the avocado skin percentage in combustion at 550 °C. As shown, increasing skin percentage in the seed and skin mixture led to a slight increase in combustion yield from 96.18%, corresponding to a bed of 100 wt% avocado seed, to 97.36% for a bed of 100 wt% avocado skin.

3.5. Comparison of combustion efficiencies of avocado wastes in conical spouted bed reactor with other biomass wastes

The combustion efficiencies of avocado wastes in a conical spouted bed at temperatures ranging from 450 to 600 °C are on the same order as those obtained in biomass combustion in fluidized beds [33,54] at much higher temperatures (800–1000 °C) [55], with a lower energy cost and lower initial cost to attain the combustion temperature in conical spouted beds than in fluidized beds. However, the CO concentration in the combustion of avocado wastes in spouted beds, even at the peak for avocado seeds (≈ 10,000 ppm), was slightly lower than that in the combustion of wood pellets in fluidized beds (≈ 11,000 ppm). The combustion efficiency values of avocado wastes are of the same order and slightly higher than those reported for combustion in conical spouted beds for other biomass wastes, such as fruit tree pruning waste [30], paper sludge waste [31], vineyard pruning waste [24], and vineyard pruning waste with a Pd/Al_2O_3 catalyst [29].

3.6. Emission ratios of environmental pollutants in conical spouted bed reactor

To determine an environmentally friendly combustion technology in conical spouted beds, the emission ratios of environmental pollutants were calculated. The production of gaseous carbon compounds other than CO_2 (CO and HC) was quantified using the emission ratio (ER) for each compound generated by biomass combustion, defined as the volume ratio ER = CO/CO_2 and HC/CO_2. Table 3 shows the emission ratios for CO and HC standardized with respect to CO_2 for avocado seeds, skin, and their mixture at combustion temperatures ranging from 550 to 600 °C. As shown in Table 3, emissions of CO and HC, quantified as emission ratios CO/CO_2 and HC/CO_2, were lower than 0.036 and 0.27 10^{-2}, respectively.

Table 3
Emission ratios of CO and HC of avocado wastes.

Biomass	T (°C)	550	575	600
Seed	CO/CO_2	0.036	0.032	0.0316
	HC/CO_2	0.27 10^{-2}	0.22 10^{-2}	0.20 10^{-2}
Skin	CO/CO_2	0.0273	0.025	0.023
	HC/CO_2	0.19 10^{-2}	0.17 10^{-2}	0.15 10^{-2}
Mixture	CO/CO_2	0.029	0.028	0.027
	HC/CO_2	0.22 10^{-2}	0.19 10^{-2}	0.17 10^{-2}

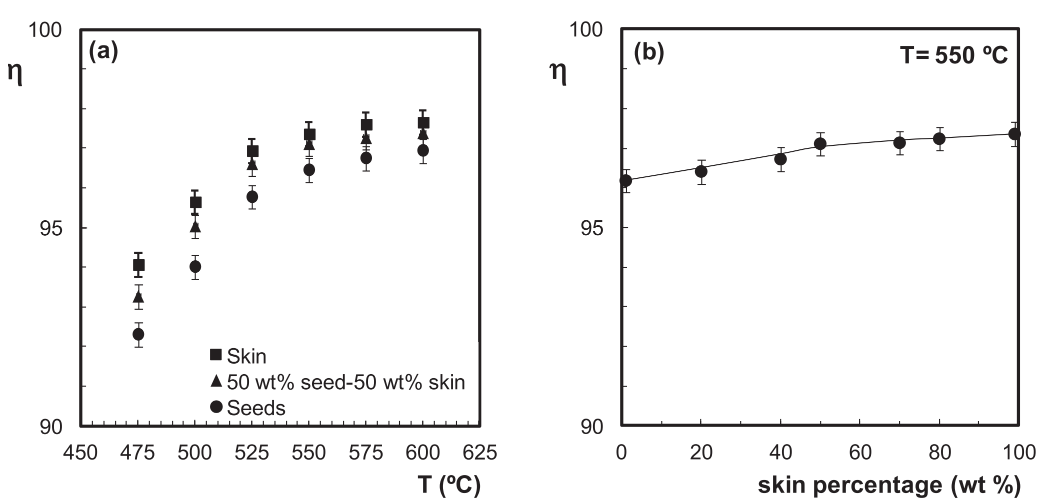

Fig. 6. Combustion efficiency of (a) beds of avocado seeds, skin and binary mixtures of 50 wt% of avocado seeds and skin wastes at temperature ranging between 475 and 600 °C; (b) binary mixtures of avocado seeds and skin with different skin percentage at 550 °C.

3.7. Global vision of evolution with the temperature of gas emissions of avocado wastes biomass biogenic combustion in conical spouted bed reactor

Furthermore, to achieve the global vision of evolving combustion technologies using temperature, the emission factors for CO_2, CO, and HC gases were calculated as the mass ratio of combustion product per kilogram of avocado waste at combustion temperatures ranging from 550 to 600 °C, increased from 1607 to 1769 g/kg for CO_2, and decreased from 37.81 to 29.33 g/kg for CO and from 1.33 to 0.94 g/kg for HC. As observed, the CO and HC emission ratios in avocado waste were low, especially for methane, and they presented lower values at higher combustion temperatures. In addition, emission factors and heating values for CO_2 and CO at every temperature were higher for avocado skin than for avocado seed and their mixture, which may be due to the higher mass fraction of carbon in the avocado skin.

The results obtained in this study demonstrate the usefulness of a conical spouted bed combustor for clean energy valorization of avocado wastes with uniform beds of a single waste (seed or skin) and their different mass percentage mixtures.

4. Conclusions

Spouted bed technology has been successfully applied in a novel conical combustor for the energy valorization of avocado waste as biofuels to produce renewable and sustainable clean bioenergy. The operating conditions were delimited in the spouted bed regime for all uniform beds and their mixtures of the two avocado wastes (seed and skin), which are appropriate for energy valorization. Beds consisting of binary mixtures of both avocado wastes do not present segregation in any percentage, which is a remarkable characteristic of conical spouted beds. In contrast to fluidized beds, elutriation of particles of lower-density avocado waste does not occur.

It has been experimentally determined that avocado waste exhibits high combustibility, high heating values, and high local heat transfer coefficients. The experimental values of local heat transfer coefficients in beds consisting of avocado waste in conical spouted beds are on the same order as those of sawdust and slightly higher for beds of avocado skin. The lowest combustion temperature for avocado waste in a conical spouted bed was 475 °C, obtaining over 95% efficiencies at temperatures between 500 and 600 °C. The highest combustion efficiency corresponded to 600 °C for beds consisting of avocado skin, followed by beds of binary mixtures with 50% of each waste and by beds of seeds. In addition, the combustion efficiencies obtained in a conical spouted bed are similar to those reported in the literature for biomass combustion in fluidized beds, although in fluidized beds, they were obtained at higher temperatures.

Therefore, the energy applicability of spouted bed technology in conical reactors, with high combustion efficiency and low polluting gas emissions, would contribute to fulfilling international climate commitments regarding mitigating climate change, reaching climate neutrality, and implementing the circular economy strategy.

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.

Data availability

I have shared the link of my data

Acknowledgement

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