Bioresource Technology Reports 32 (2025) 102418

Contents lists available at ScienceDirect

Bioresource Technology Reports

journal homepage: www.sciencedirect.com/journal/bioresource-technology-reports

Thermochemical conversion of avocado agro-industrial waste: Influence of operating conditions on biochar yield and properties

Manuel Antonio Flores-Izquierdo [a,b], César Javier Osorio Carrera [c], Juliana Gaviria-Restrepo [d], Benigno Cristofer Flores-Espinoza [e,*]

[a] Faculty of Engineering, Agroindustrial Engineering Program, San Ignacio de Loyola University, Lima, Peru
[b] Engineering and Projects Manager, FIMA Agroindustry Consulting, Peru
[c] Faculty of Chemical and Textile Engineering, Chemical Engineering Program, National University of Engineering (UNI), Lima, Peru
[d] Magnetic Materials Laboratory, Department of Physics CCEN UFPE, Av. Jorn. Aníbal Fernandes, s/n - Cidade Universitária, Recife, PE, 50740-540, Brazil
[e] Brazil Laboratory of Molecular Studies and Experimental Therapy—LEMTE, Department of Genetics, Federal University of Pernambuco, Recife, 50670-901, Brazil

ARTICLE INFO

Keywords:
Pyrolysis
Biochar
Avocado
Thermochemical conversion

ABSTRACT

Biochar production from agroindustrial waste is a promising strategy to meet the demand for renewable, sustainable energy. This study evaluated the thermochemical behavior of *Persea americana* var. Hass seeds during pyrolysis, focusing on the influence of particle size, residence time and temperature using a 2 × 2 × 3 factorial design. The highest biochar yield (48 %) was obtained with 1 mm particles at 300 °C and a 1 h residence time, whereas yields at 400 °C and 500 °C ranged from 33 %–34 %, respectively. The full factorial design and post hoc Tukey's HSD analysis confirmed that temperature, particle size, and residence time significantly influenced biochar yield. The resulting biochar exhibited a high calorific value (26.27 MJ/kg), high carbon concentration (69.85 %), and low sulfur concentration (0.27 %). These findings identify optimal conditions for maximizing biochar yield and quality, supporting the industrial-scale utilization of untreated agroindustrial residues while contributing to pollution reduction and resource efficiency.

1. Introduction

The growing international demand for avocado (*Persea americana*) has led to an increased generation of agroindustrial byproducts during its processing, necessitating sustainable valorization strategies (Cárceles Rodríguez et al., 2023). Annual global avocado production is estimated at four million metric tons, with the seed – a primary waste component – constituting 13–18 % of the fruit's mass. Current disposal through incineration raises environmental pollution and public health concerns (Tesfaye et al., 2022). As sustainable alternative, biorefinery processes aim to transform these waste byproducts into bioenergy and biofuels, representing key strategies to achieve zero-waste postharvest objectives (García-Vargas et al., 2020a; Ginni et al., 2021).

The biorefining of avocado-derived waste represents a comprehensive strategy with potential applications in pharmaceutical, biomedical, and environmental sectors, contributing to climate change mitigation while enabling the scientific development of biofuels, pharmaceuticals, bioplastics and others innovative products (Féliz-Jiménez and Sanchez-Rosario, 2024; Rodríguez-Martínez et al., 2022). A key characteristic of avocado waste – considered an agroindustrial byproduct – is its high carbon bioavailability and lignocellulose-rich composition (Bangar et al., 2022; Morcillo-Martín et al., 2024). This composition enables avocado seeds to be repurposed for: carbonaceous materials in water remediation, photocatalytic compound production, and environmentally compatible biofuel synthesis (Colombo and Papetti, 2019; Demissie et al., 2023; Solih et al., 2023). According to García-Vargas et al. (2020b) avocado seed exhibit an elemental composition of 42.05 % carbon, 42.20 % oxygen, 5.71 % hydrogen, and 0.66 % nitrogen, whit additional 70.90 % moisture and 3.81 % ash content. These characteristics establish them as robust agroindustrial byproducts with high potential for thermochemical conversion valorization.

The recycling potential of avocado byproducts stems from their continuous biomass availability, enabled by successive harvest cycles a characteristic that establishes the seed as a renewable organic energy source (Sandoval-Contreras et al., 2023). This fruit's biomass can be transformed through thermochemical processes like pyrolysis and gasification, yielding biochar as a solid byproduct (Haider et al., 2022). Biochar derived from lignocellulosic biomass pyrolysis is characterized

* Corresponding author.
E-mail address: benigno.cristofer@ufpe.br (B.C. Flores-Espinoza).

https://doi.org/10.1016/j.biteb.2025.102418
Received 30 May 2025; Received in revised form 27 October 2025; Accepted 9 November 2025
Available online 15 November 2025
2589-014X/

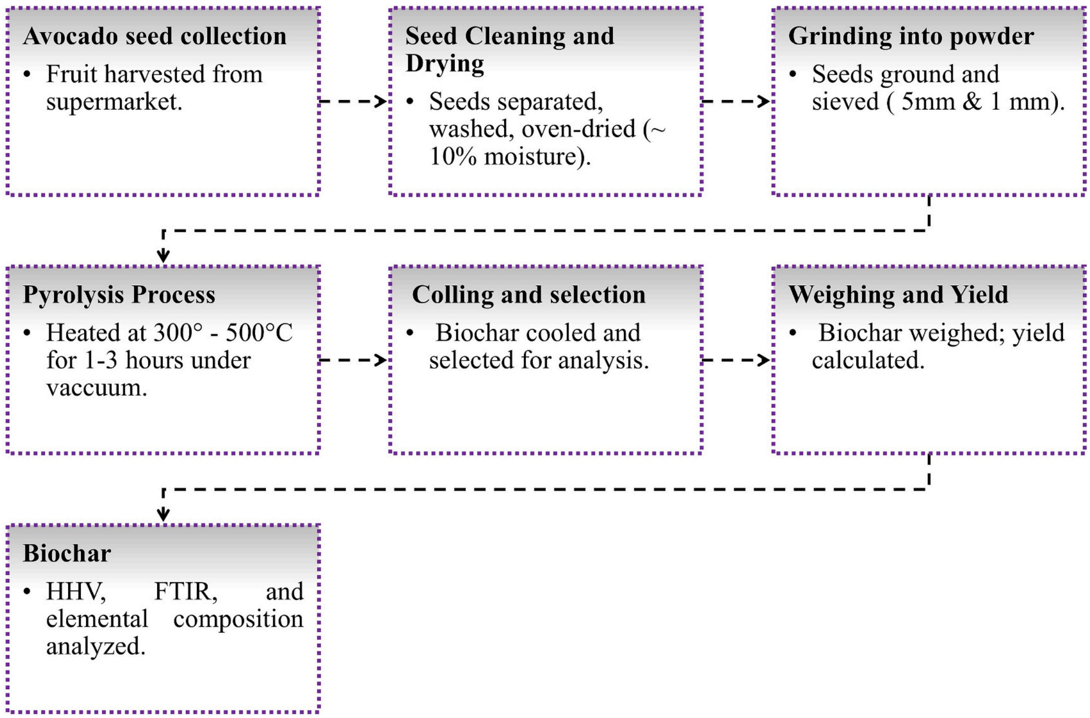

Fig. 1. Schematic overview of the experimental procedure of the biochar yield analysis.

by: high carbon content (65–69 %), mineral constituents including silicon, phosphorus, aluminum, iron, calcium, magnesium, potassium, titanium, sulfur, chlorine, sodium, and minor hydrogen and oxygen fractions (Kang et al., 2021; Li et al., 2020). These compositional features are feedstock and process-dependent. Furthermore, biochar's elevated surface area and thermal properties enable applications as a carbon storage medium, soil amendment (via enhanced surface interactions), carbon capture material, and green roofing insulation components (García-Vargas et al., 2020a).

Pyrolysis entails the thermal decomposition of lignocellulosic biomass at elevated temperatures (200–500 °C) under non- oxidizing conditions, yielding three principal products: (i) a liquid phase (bio-oil), (ii) a solid phase (biochar), and (iii) non condensable vapors (Yaashikaa et al., 2019; Yogalakshmi et al., 2022). Reaction conditions can be optimized to control product distribution: fast pyrolysis maximizes liquid yield, while slow pyrolysis enhances sold product formation (Arni, 2018; Kan et al., 2016). According to Akhtar et al. (2019) cellulose decomposes at temperatures between 240 °C and 500 °C, whereas Domínguez et al. (2014) reported that above 500 °C, solid, liquid and gas yields stabilize, indicating completion of thermal degradation processes. Finally, Liu et al. (2013) reported that temperatures above 250 °C yield energy-dense biochar whit superior calorific value, while Paniagua et al. (2021) demonstrated that gradual heating rates (10 °C/min, 20 °C/min, and 40 °C/min) significantly improve target product yields.

Given that the reaction conditions during the pyrolysis process can influence both biochar yield and the production of desired compounds, the presents study aims to evaluate the effect of *Persea americana* var. Hass seed particle size, pyrolysis time, and temperature on biochar yield. This evaluation is proposed as a strategy for the reduction of environmental pollution. Particle sizes of 1 mm and 5 mm were tested, with pyrolysis durations of 1 h and 3 h, and at temperatures 300, 400 and 500 °C.

2. Materials and methods

2.1. Physicochemical analysis of avocado seed

For the physicochemical analysis, 5 kg of *Persea americana* var. Hass clean avocado seed (without skin) (Supplementary 1), sourced from the Vivanda supermarket in the city of Lima, Peru, and with an initial ripening stage suitable for consumption, were sent to the Renewable Energies Laboratory (Energy Biomass Unit) of the National Agrarian University La Molina. The working condition and equipment used for this purpose are described below.

2.1.1. Compositional analysis of avocado seed

The avocado seeds were oven-dried at 105 °C for 24 h before analysis, and the milled to obtain a homogeneous sample. Before analysis, the avocado seeds were oven-dried at 105 °C for 24 h and the milled to obtain a homogenous powder. Elemental composition was determined in triplicate using LECO analytical instruments. Carbon (C), hydrogen (H), and nitrogen (N) contents were quantified using the CNH628 Elemental Determinator (LECO Corporation) in accordance with ASTM D5291-21 (2021). Sulfur (S) was measured using the Sulfur Add-On Module of the same series, following ASTM D4239-18 (2018). Finally, oxygen (O) content was determined using the O628 module adapted to the CHN628 system, with 2 mg of sample analyzed at 1300 °C under a high-purity helium atmosphere, in accordance with ASTM D3176-23 (2023).

2.1.2. Proximate thermogravimetric analysis (TGA) of avocado seed

The moisture, volatile matter, and ash content of avocado seed were determined by proximate thermogravimetric analysis using a TGA701 Thermogravimetric Analyzer (LECO Corporation), following the ASTM D7582-15 (2015). Before analysis, the samples were milled to a particle size of 250 μm and processed without pre-drying, according to the sample preparation protocols recommended by the equipment manufacturer, which refers to ASTM D2013/D2013M-21 (2021). For moisture determination, samples were heated from 25 °C to 107 °C at a rate of 15 °C/min under a nitrogen flow of 10 mL/min. Volatile matter content was analyzed by heating from 107 °C to 950 °C at 50 °C/min under nitrogen (10 mL/min). Ash content was determined by heating from 500 °C to 550 °C at 50 °C/min in oxygen atmosphere (3–50 mL/min). All analyses were performed using 1 g of avocado seed.

2.2. Biochar yield analysis

Pyrolysis is a thermal decomposition process of biomass under anoxic conditions. This study evaluated the influence of particle diameter, residence time, and temperature on the biochar yield obtained from avocado seeds. Only the treatment that resulted in the highest yield was subjected to further analyses, including High Heating Value (HHV), Fourier Transform Infrared spectroscopy (FTIR) and compositional analysis. The Fig. 1 present a schematic overview of the experimental procedure. The methodology is described below.

2.2.1. Avocado seed preparation

For the pyrolysis process, seeds (without seed coat) separated from the fruit were grated and dried in an oven at 105 °C for 24 h to achieve a moisture content of 10 %. After dehydration, the material was ground using a hammer mill and sieved through mesh No. 4 to obtain 5 mm particles and mesh No. 14 for 1 mm particles, following ASTM D5865-24 (2024) standards.

2.2.2. Effect of particle size, time and temperature on biochar yield

The pyrolysis process was conducted to analyze the effect of particle size, residence time and temperature on biochar yield. Experiments were performed using two particle diameters (1 mm and 5 mm), two residence times (1 h and 3 h), and three temperatures (300 °C, 400 °C and 500 °C), with 50 g loading of pretreated avocado seed samples having less than 10 % moisture content. Pyrolysis was carried out in a horizontal reactor under vacuum pressure (67,461 kPa abs.) with constant average heating rate of 8.40 °C/min. Each temperature condition was tested in duplicate to ensure consistency in the results. The equipment used the pyrolysis is a horizontal tubular reactor, not commercial, belonging to the Thermochemistry laboratory of the Faculty of Petroleum, Natural Gas, and Petrochemical Engineering at the National University of Engineering (UNI) – Lima – Peru.

The biochar yield was determined gravimetrically by weighing the dry feedstock before pyrolysis and the solid residue obtained after the process. The operating conditions employed during pyrolysis were those established by the laboratory protocol. Finally, the yield was calculated as the percentage ratio of the final mass of biochar to the initial dry mass of the sample introduced into the reactor, using the following formula:

$$\textbf{\textit{Biochar Yield}}\ (\%) = \frac{\text{Mass of biochar after pyrolysis}}{\text{Initial dry mass of feedstock}} \times 100$$

2.2.3. Calorific value determination and FTIR analysis of biochar

For determination for the Higher Heating Value (HHV) (kJ/kg), 1 g of sample used. The value was obtained using the AC600 instrument (LECO, Corporation) and following the methodology established in ASTM D5865-24 (2024). Functional group identification was determined using a Fourier Transform Infrared Spectrophotometer with Attenuated Total Reflectance (FTIR-ATR) (Perkin Elmer Inc., Waltham, MA, USA), in accordance with ASTM E1252-21 (2021). The spectrophotometric conditions were: 2 scans, 4 cm^{-1} resolution, MIR TGS detector (mid-infrared triglycine sulfate), KBr bean splitter (OptKBr: *Optical Potassium Bromide*), 0.20 cm/s scan speed, 15798.00 cm^{-1} IR-Laser wavenumber, spectral range of 4000–400 cm^{-1}, Universal ATR accessory and Diamond/KRS-5 crystal (synonym name: *thallium bromide-iodide*).

2.2.4. Compositional analysis of biochar

Samples of biochar were analyzed at the Research and Certification Laboratory (LABICER) of the National University of Engineering (UNI) in Lima, Peru, for compositional characterization.

Table 1
Dry basis analysis calculated from wet basis compositional analysis of *Persea americana* var. Hass seed.

Test	Volatile matter (%)	Ash (%)	Fixed carbon (%)
1	84.26	3.48	12.26
2	84.06	2.64	13.3
3	85.19	3.36	11.45
Standard deviation	0.603	0.454	0.927
Average (%)	84.5	3.16	12.34

The CHN628 elemental analyzer (LECO Corporation) was used to determine the hydrogen, nitrogen, and carbon content of the samples in accordance with ASTM 5291-21. A 0.10 g sample was analyzed under the following conditions: combustion temperature of 950 °C, post-combustion temperature of 850 °C, helium (99.99 %) as the carrier gas and oxygen (99.99 %) as the reactive gas, both supplied at a pressure of 35 psi (2.40 bar). Purge, equilibration and aliquot filling ties were set according to the manufacturer's specifications. Carbon and hydrogen were detected using non-dispersive infrared absorption spectroscopy (NDIR), while nitrogen was determined using a thermal conductivity detector (Tcell). The analysis time for each sample was approximately 5 min.

Finally, the S628 elemental analyzer (LECO Corporation) was used to determine the sulfur content in the biochar sample, following ASTM D4239-18 (2018). Samples (0.25 ± 0.001 g) were combusted at 1350 °C under ultra-high purity oxygen (99.50 %) supplied at 40 psi (2.80 bar ±10 %). The system employed magnesium perchlorate (anhydrous) as a desiccant, with analysis times ranging from 60 to 120 s. Sulfur was achieved through NDIR with calibration verified using certified sulfur standards (NIST-traceable).

2.3. Statistical analysis

All statistical analyses were performed using GraphPad Prism 9 (GraphPad Software, San Diego, CA, USA). A full factorial design (3 × 2 × 2) was applied to evaluate the effects of particle size (2 levels), residence time (2 levels), and pyrolysis temperature (3 levels) on biochar yield, resulting in a total of 12 treatment combinations. Each treatment was conducted in duplicate to ensure reproducibility and account for experimental variability. A three-way ANOVA was performed to assess the main effects and interactions among the factors. Statistical significance was considered at $p < 0.05$. When significant differences were detected Tukey's HSD (Honestly Significant Difference) post-hoc test was applied to identify specific treatment groups contributing to the variation in biochar yield, using a 95 % confidence level.

3. Results and discussion

3.1. Characterization of avocado seed

The whole fruit and its components play a fundamental role in the energy efficiency and yield of biochar production the avocado pulp and peel contain higher levels of moisture and volatile compounds than the seed, affecting the yield of biochar production during pyrolysis. In addition, the dry matter of the pulp varies with maturity from 22.6 % in green fruit to 27.3 % in ripe fruit, while the peel tends to have less fixed carbon and more extractable phenolic compounds (García-Ramón et al., 2023; Jimenez et al., 2021; Sandoval-Contreras et al., 2023). Given these characteristics, the clean avocado seed (without skin) was worked with; it is more suitable for biochar production due to its higher lignocellulosic density and lower moisture (García-Ramón et al., 2023).

The dry basis analysis of avocado seed (Table 1) revealed a high volatile matter content (84.50 %), suggesting its potential suitability for biofuel production, bioactive compound extraction, or biorefinery

Table 2
Elemental analysis on dry basis of *Persea americana* var. Hass seed.

Test	%C	%H	%N	%O	%S
1	37.92	7.029	0.461	50.883	0.13
2	37.37	7.021	0.446	52.286	0.14
3	37.72	6.986	0.46	51.234	0.14
Standard deviation	0.27	0.022	0.008	0.73	0.005
Average	36.67	7.01	0.46	51.47	0.13

applications (Dyjakon et al., 2022; Perea-Moreno et al., 2016; García-Vargas et al., 2020b). Furthermore, elevated volatile content is particularly advantageous for thermal conversion processes, at it enhances biomass reactivity and organic compound valorization (Soria-González et al., 2022).

Previous studies have reported varying compositional profiles for avocado seed, Nwaokobia et al. (2018) identified 27.55 % volatile matter and 58.35 % fixed carbon content in dried avocado seed. Similarly, Garcia-Vallejo et al. (2023) documented values of 79.91 % volatile matter and 17.22 % fixed carbon. These literatures values show notable discrepancies with the experimental results (Table 1), which may be attributed to several factors including differences in drying methodology and temperature parameters, agricultural conditions such as harvest timing and growing climate, specific cultivation practices, sample processing techniques, and genetic variations among avocado cultivars (Páramos et al., 2020).

The compositional analysis of avocado seed on a dry basis revealed an ash content of 3.16 % (Table 1). The findings show discrepancies with previous studies: Dávila et al. (2017) reported lower ash content (0.87 %) in dried avocado seeds, while Féliz-Jiménez and Sanchez-Rosario (2024) observed values ranging from 0.84 % to 3.82 % depending on avocado variety, and Soria-González et al. (2022) documented even broader variations (1.22–7.22 %) in *P. americana*, showing particle size dependent behavior. Compared to other lignocellulosic materials (rice husks, corn stover, poplar branches and hazelnut shells), the ash content measured in this study represents a significant advantage for industrial applications. The relatively low mineral content reduces common operational challenges including fouling, sintering, slag deposition and agglomeration phenomena, thereby potentially lowering maintenance costs in thermochemical conversion systems (Puri et al., 2024).

The elemental analysis of avocado on a dry basis (Table 2) showed oxygen as the most abundant element (51.47 %), followed by carbon (36.67 %), hydrogen (7.01 %), nitrogen (0.46 %) and sulfur (0.13 %). When comparing these results with previous studies on avocado seeds, the data obtained in this study are similar to those reported by García-Vargas et al. (2020b) who fund 50.79 % oxygen, 42.05 % carbon, 5.58 % hydrogen and 0.66 % nitrogen. However, differences were observed with other study Perea-Moreno et al. (2016) that reported 42.80 % oxygen, 48.01 % carbon, 5.76 % hydrogen, 0.45 % nitrogen and 0.10 % sulfur, as well as with the study by Nwaokobia et al. (2018) who obtained notably distinct values (9.49 % oxygen, 58.35 % carbon, 0.55 % hydrogen, 3.17 % nitrogen and 0.07 % sulfur). These variations could be attributed to factors such as cultivar differences, growing conditions and analytical methodologies. The elemental composition suggests that avocado seed is a promising feedstock for energy and industrial applications. Additionally, the low sulfur content (0.13 %) highlights its environmental advantages, including reduced emissions of toxic SO_2 gases during processing and minimal risk of soil acidification if used in agricultural applications, thereby supporting sustainable crop growth (Sharma et al., 2024; Narayan et al., 2022).

3.2. Thermogravimetric analysis

TGA was used to evaluate the physicochemical properties of the materials under precisely controlled conditions (Dyjakon et al., 2022).

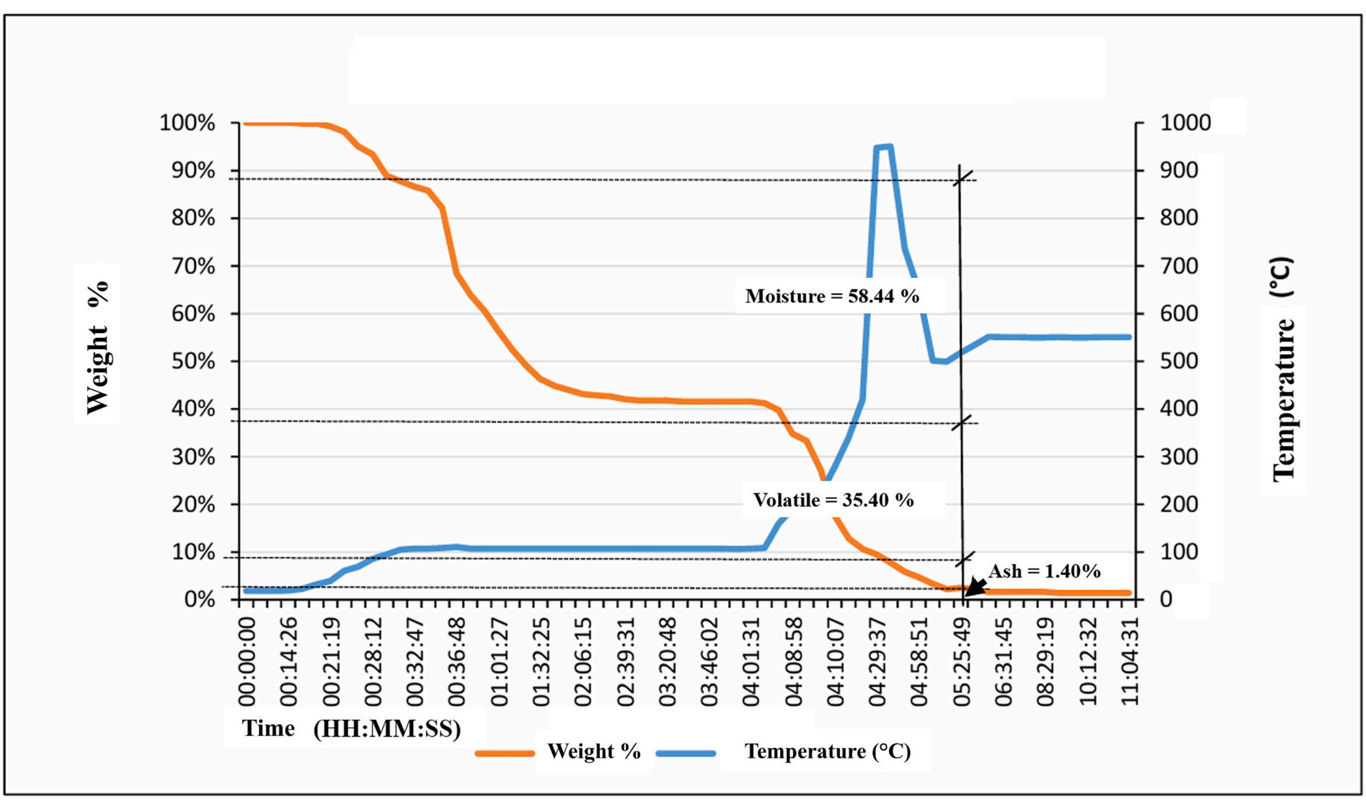

Fig. 2. Thermogravimetric curve of avocado seed. Evaluation of moisture, volatile components, and ash content; the orange line represents the percentage mass loss, while the blue line shows the temperature increase, both as a function of elapsed time. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The results indicate that the thermal decomposition of avocado seed occurs in three main stages (Fig. 2). The first corresponds to moisture loss (58.44 %) at 100 °C, followed by volatile matter decomposition (35.40 %) between 100 °C and 500 °C, and finally ash formation (1.40 %) at temperatures above 500 °C. These findings differ from those reported in a previous study by Sánchez et al. (2017) who observed moisture loss (14.50 %) below 200 °C, volatile matter decomposition (54.60 %) between 200 °C and 400 °C, and ash formation (15.70 %) above 400 °C. These discrepancies may be attributed to differences in drying methodology (15 % moisture content) and sample size (<0.005 mm) used in their study. Additionally, the type of biomass analyzed significantly influences the results, as demonstrated in previous study by Xu et al. (2019) that reported thermal decomposition ranges of 150 °C–450 °C for volatile matter and 400 °C–700 °C for ash formation. The results obtained in this study suggest that avocado seeds have potential for sustainable applications in biopolymer production, bioenergy generation and biochar formation. While this study did not directly evaluate functional applications, the results suggest potential for future exploration in areas such as bioenergy generation and biochar production. These findings reinforce the versatility of avocado seeds as a renewable resource.

3.3. Biochar yield optimization analysis

After evaluating the physicochemical properties of avocado seeds, a meticulous analysis was conducted to determine whether particle size, pyrolysis time and temperature would influence biochar yield during pyrolysis, with all experiments performed in duplicate. Following confirmation of data normality, a three-way ANOVA was performed (Supplementary 1 and 2). The analysis revealed that temperature had a highly significant effect on biochar yield ($p < 0.0001$), accounting for 94.44 % of the total variation. Residence time also showed a statistically significant effect ($p = 0.0023$), although it contributed only 1.184 % to the overall variation. In contrast, particle size alone did not significantly affect the yield ($p = 0.7302$). Among the interaction terms, the combination of particle size and residence time was statistically significant ($p = 0.0100$), as was the three-way interaction between temperature, particle size, and residence time ($p = 0.0013$), indicating that the effect of one factor may depend on the levels of the others. Other interaction, such as temperature and particle size ($p = 0.0883$) and temperature and residence time ($p = 0.2702$), did not show significant effect on biochar yield. For further details on the statistical analysis, please refer to Supplementary 3.

These results underscore the critical role of temperature as the dominant factor in biochar producing efficiency, while also highlighting the nuanced time. Specifically, lower temperatures favor higher yields, but require precise control of other parameters to maintain performance. The presence of multiple statistically significant comparisons across temperature groups reinforces the importance of multifactor optimization in biochar synthesis protocols.

Post hoc multiple comparisons using Tukey's HSD test revealed statistically significant effects of treatment combinations on biochar yield across all pyrolysis temperatures. Although all pairwise comparisons were performed, only those showing statistical significance are discussed here to maintain clarity. Full results, including non-significant comparisons, are available in Supplementary 3. At 300 °C, yield differences were highly significant ($p < 0.0001$), indicating that specific combination of particle size and residence time substantially enhanced biochar output under low-temperature conditions. At 400 °C, the analysis identified multiple levels of significance ($p < 0.0010$, $p < 0.005$, and $p = 0.0191$), demonstrating that intermediate temperatures amplify the sensitivity of yield to the interaction between physical parameters. At 500 °C, significant differences ($p < 0.006$) persisted, suggesting that even at elevated temperatures, residence time remains a critical factor in maximizing yield. Overall, the results confirm that temperature is the primary driver of biochar production efficiency, yet its influence is

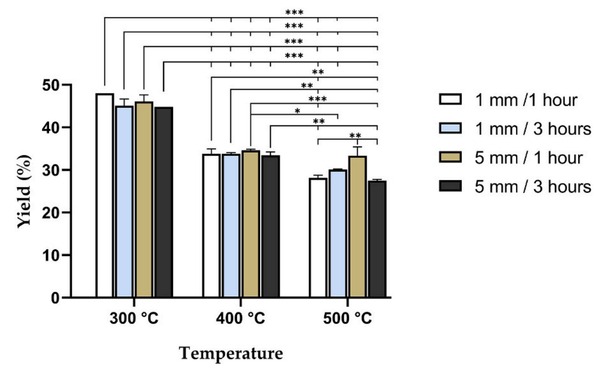

Fig. 3. Tukey's post-hoc comparisons of biochar yield under different conditions. Biochar yield was evaluated across combinations of particle diameter (1 mm and 5 mm), pyrolysis time (1 h and 3 h), and temperature (300 °C, 400 °C and 500 °C). Bars represent mean yield percentages and statistical significance between specific treatment groups was determined using Tukey's multiple comparisons test. Significant difference is indicated by asterisks: 300 °C (***$p < 0.0001$), 400 °C (***$p < 0.0010$; **$p < 0.005$; *$p = 0.0191$), and 500 °C (** $p = 0.006$). All pairwise comparisons were performed, but only statistically significant differences are shown to improve figure clarity. Full statistical results, including non-significant comparisons, are provided in Supplementary 3.

strongly modulated by particle size and residence time, particularly at 400 °C and 500 °C. These findings underscore the necessity of multi-parameter optimization in pyrolysis systems to achieve higher biochar yields. The results reveal that pyrolysis at 300 °C, when combined with optimized particle size and residence time, achieved the highest biochar yields, ranging from 45 % to 48 %, positioning it as the most favorable condition within the evaluated range. At 400 °C, yields decreased to 33 % - 34 %, yet remained consistent across treatments, indicating stable performance under intermediate thermal conditions. At 500 °C, biochar yield stabilized at 33 % suggesting that wile higher temperatures do not enhance yield, they may still offer predictable output when paired with appropriate process parameters. These findings highlight the influence of temperature on biochar production and confirm that 300 °C provide a particularly advantageous balance between yield and process control (Fig. 3).

Several authors report that temperature and time affect biochar yield-findings that were also observed in the present study. In studies using temperatures between 400 °C, 500 °C and 600 °C, Luo et al. (2015) demonstrated that temperatures above 400 °C decrease biochar yield by 10 %, while Das et al. (2021) reported reductions of up 23.80 % at 600 °C. Narzari et al. (2017) state that biochar yield decreases by up to 39.93 % when temperature increases from 350 °C to 650 °C. Finally, Khairy et al. (2024) report that 275 °C for 30 min gives the highest biochar yield. In a study by Xu et al. (2019) they determined that biochar obtained at 300 °C shows greater NH_4^+ sorption, making the biochar useful for wastewater treatment and soil improvement.

3.4. Higher heating value analysis of biochar

The HHV of the optimal biochar (1 mm particle size, 1 h pyrolysis at 300 °C), identified via ANOVA and Tukey's test, was analyzed to measure its total energy release upon complete combustions. The analysis revealed a substantial HHV of 26.27 MJ/kg, significantly exceeding values reported by other researchers: Paniagua et al. (2021) documented 18.74 MJ/kg for avocado seeds, Villanueva et al. (2011) reported 20.23 MJ/kg for eucalyptus and 20.50 MJ/kg for pine, while Perea-Moreno et al. (2018) found 18.05 MJ/kg for mango seeds. The notably elevated calorific valuable resource for energy and thermal applications, suggesting superior fuel quality compared to these alternative biomass feedstocks.

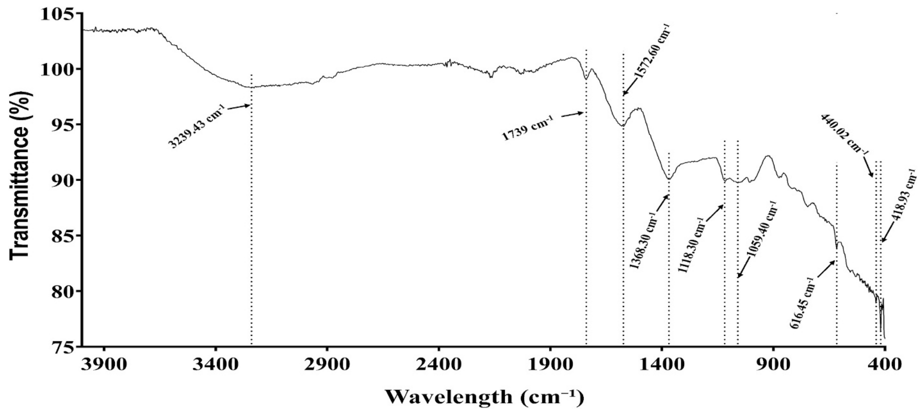

Fig. 4. Functional characterization of highest-yield biochar (1 mm/1 h/300 °C) by FTIR spectroscopy. The FTIR analysis identified the functional groups present in the biochar produced under our experimental conditions. The observed peaks at 3239.43 cm^{-1}, 1739 cm^{-1}, 1572.60 cm^{-1}, 1368.30 cm^{-1}, 1118.30 cm^{-1}, and 1059.40 3 cm^{-1} correspond to characteristic vibrations of chemical bonds including —OH, C═O, C═C, —CH_3, and C—O, respectively.

3.5. Analysis of biochar chemical characteristics

The chemical structure of the highest – yielding biochar (1 mm, 1 h and 300 °C) was examined using FTIR. FTIR is a method that enables identification of functional groups such as alcohols, ketones, esters, carboxylic acids, etc., from analyzed organic materials (Perea-Moreno et al., 2016). Understanding the chemical composition provides insight into the biochar's stability for storage and application purposes.

The results this work, reveal the presence of diverse functional groups in the biochar's chemical composition. Fig. 4 shows an absorption at 3239.43 cm^{-1} attributable to hydroxyl groups (-OH) in alcohols (Sánchez et al., 2017), while the 1739 cm^{-1} band suggested carbonyl groups (C═O) (Luo et al., 2015), characteristic of aldehydes, ketones, esters and carboxylic acids. The 1572.60 cm^{-1} peak, typical of C═C bonds, is associated with aromatic compounds that contribute to biochar stability (Enders et al., 2021; Luo et al., 2015). Methyl groups (-CH_3) observed at 1368.30 cm-1 indicate residual organic compounds (Zhang et al., 2017). Wavenumbers at 1118.30 cm^{-1} and 1059.40 cm^{-1} correspond to C—O bonds characteristic of esters and ethers (Sánchez et al., 2017), while signal in the low energy region (616.45 cm^{-1}, 440.02 cm^{-1} and 418.93 cm^{-1}) are difficult to assign to specific functional groups without additional information.

It is important to highlight that the resolution FTIR results varies depending on both the pyrolysis temperatures employed (Das et al., 2021; Luo et al., 2015), and the type of organic material used for biochar production (Zhang et al., 2017). Sánchez et al. (2017) reported that temperatures below 300 °C allow better identification of functional groups in avocado seed biochar, with characteristic wavenumbers for C—O (1011 cm^{-1}), CH_3 (1520–1612 cm^{-1}) and OH (3000–3500 cm^{-1}), consistent with the spectral features identified in the present analysis. Furthermore, Şahin et al. (2020) analyzed FTIR spectra of avocado seed, identifying notable peaks including a broad —OH band at 3250 cm^{-1} indicative of alcohols, phenols or carboxylic acids.

The high carbon percentage appears to be a characteristic feature of biochar derived from organic matter. Elemental analysis revealed a substantial carbon content (69.85 %) in the avocado seed biochar, supporting its potential for energy and environmental applications. These findings align with those reported by previous authors, such as Durak and Aysu (2015), who reported 71.62 % carbon content. Comparable results were observed in other biomass sources: Azuara et al. (2016) documented fixed carbon levels up to 90.40 % in corn stover, while Jian et al. (2018) obtained 48.10 % fixed carbon in rice husk biochar, and Khairy et al. (2024) reported 55.10 % and 39.91 % carbon content in bean husks and sesame stalks, respectively. The elevated carbon concentration suggests multiple applications: (1) as a renewable alternative to conventional fossil fuels, (2) for agricultural soil enhancement through nutrient retention and promotion of beneficial microbial growth, and (3) in environmental remediation through lead compound adsorption, thereby improving water and soil quality (Das et al., 2021; Shen et al., 2015).

The other compounds in smaller percentages nitrogen (1.70 %), hydrogen (3.59 %) and particularly sulfur (0.27 %), could indicate that the combustion of this material is environmentally friendly and makes it an efficient biofuel.

4. Conclusion

According to the findings, the yield of biochar derived from of *Persea americana* var. Hass seeds is critically affected by pyrolysis time and temperature. The optimal condition for energy utilization is 300 °C for 1 h with a particle size of 1 mm, while at 500 °C, a particle size of 5 mm treated for 1 h yielded the highest performance. The resulting biochar exhibits a high calorific value (26.27 MJ/kg), low sulfur content and high carbon concentration, indicating significant potential as a biofuel for thermal recovery and environmental applications. Due to the self-funded nature of the study, it was not possible to perform more extensive physicochemical analyses. Nevertheless, the results open avenues for future research aimed at deepening the understanding of biochar properties and assessing its scalability. Subsequent studies could explore variations in vacuum pressure and heating rates, perform more detailed physicochemical analyses (X-ray diffraction, Raman spectroscopy, and texture analysis), and include the assessment of the biochar's adsorption capacity for pollutants and its contribution to soil enhancement, thereby further expanding its environmental utility.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biteb.2025.102418.

CRediT authorship contribution statement

Manuel Antonio Flores-Izquierdo: Writing – original draft, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **César Javier Osorio Carrera:** Methodology, Investigation, Data curation. **Juliana Gaviria-Restrepo:** Writing – review & editing, Visualization, Formal analysis. **Benigno Cristofer Flores-Espinoza:** Writing – review & editing, Visualization, Validation, Formal analysis.

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

Data will be made available on request.

References

Akhtar, A., Ivanova, T., Jiříček, I., Krepl, V., 2019. Detailed characterization of waste from date palm (Phoenix dactylifera) branches for energy production: comparative evaluation of heavy metals concentration. J. Renew. Sustain. Energy 11, 013102. https://doi.org/10.1063/1.5027578.

Arni, S.A., 2018. Comparison of slow and fast pyrolysis for converting biomass into fuel. Renew. Energy 124, 197–201. https://doi.org/10.1016/J.RENENE.2017.04.060.

ASTM D2013/D2013M-21, 2021. Standard Practice for Preparing Coal Samples for Analysis.

ASTM D3176-23, 2023. Standard Practice for Ultimate Analysis of Coal and Coke.

ASTM D4239-18, 2018. Standard Test Method for Sulfur in the Analysis Sample of Coal and Coke Using High-Temperature Tube Furnace Combustion.

ASTM D5291-21, 2021. Standard Test Methods for Instrumental Determination of Carbon, Hydrogen, and Nitrogen in Petroleum Products and Lubricants.

ASTM D5865-24, 2024. Standard Test Method for Gross Calorific Value of Coal and Coke.

ASTM D7582-15, 2015. Standard Test Methods for Proximate Analysis of Coal and Coke by Macro Thermogravimetric Analysis.

ASTM E1252-21, 2021. Standard Practice for General Techniques for Obtaining Infrared Spectra for Qualitative Analysis.

Azuara, M., Baguer, B., Villacampa, J.I., Hedin, N., Manyà, J.J., 2016. Influence of pressure and temperature on key physicochemical properties of corn stover-derived biochar. Fuel 186, 525–533. https://doi.org/10.1016/J.FUEL.2016.08.088.

Bangar, S.P., Dunno, K., Dhull, S.B., Siroha, A.K., Changan, S., Maqsood, S., Rusu, A.V., 2022. Avocado seed discoveries: chemical composition, biological properties, and industrial food applications. Food Chem.: X 16, 100507. https://doi.org/10.1016/J.FOCHX.2022.100507.

Cárceles Rodríguez, B., Durán Zuazo, V.H., Franco Tarifa, D., Cuadros Tavira, S., Sacristan, P.C., García-Tejero, I.F., 2023. Irrigation alternatives for avocado (*Persea americana* Mill.) in the Mediterranean subtropical region in the context of climate change: a review. Agriculture 13, 1049. https://doi.org/10.3390/agriculture13051049.

Colombo, R., Papetti, A., 2019. Avocado (Persea americana Mill.) by-products and their impact: from bioactive compounds to biomass energy and sorbent material for removing contaminants. A review. Int. J. Food Sci. Technol. 54, 943–951. https://doi.org/10.1111/ijfs.14143.

Das, S.K., Ghosh, G.K., Avasthe, R.K., Sinha, K., 2021. Compositional heterogeneity of different biochar: effect of pyrolysis temperature and feedstocks. J. Environ. Manage. 278, 111501. https://doi.org/10.1016/J.JENVMAN.2020.111501.

Dávila, J.A., Rosenberg, M., Castro, E., Cardona, C.A., 2017. A model biorefinery for avocado (Persea americana mill.) processing. Bioresour. Technol. 243, 17–29. https://doi.org/10.1016/J.BIORTECH.2017.06.063.

Demissie, H., Gedebo, A., Agegnehu, G., 2023. Agronomic potential of avocado-seed biochar in comparison with other locally available biochar types: a first-hand report from Ethiopia. Appl. Environ. Soil Sci. 2023, 7531228. https://doi.org/10.1155/2023/7531228.

Domínguez, M.P., Araus, K., Bonert, P., Sánchez, F., Miguel, G.S., Toledo, M., 2014. The avocado and its waste: an approach of fuel potential/application. In: The Handbook of Environmental Chemistry, pp. 199–223. https://doi.org/10.1007/698_2014_291.

Durak, H., Aysu, T., 2015. Effect of pyrolysis temperature and catalyst on production of bio-oil and bio-char from avocado seeds. Res. Chem. Intermed. 41, 8067–8097. https://doi.org/10.1007/s11164-014-1878-0.

Dyjakon, A., Sobol, Ł., Noszczyk, T., Mitręga, J., 2022. The impact of torrefaction temperature on the physical-chemical properties of residual exotic fruit (avocado, mango, lychee) seeds. Energies 15, 612. https://doi.org/10.3390/en15020612.

Enders, A.A., North, N.M., Fensore, C.M., Velez-Alvarez, J., Allen, H.C., 2021. Functional group identification for FTIR spectra using image-based machine learning models. Anal. Chem. 93, 9711–9718. https://doi.org/10.1021/ACS.ANALCHEM.1C00867.

Féliz-Jiménez, A., Sanchez-Rosario, R., 2024. Bioactive compounds, composition and potential applications of avocado agro-industrial residues: a review. Appl. Sci. 14. https://doi.org/10.3390/APP142110070.

García-Ramón, F., Malnati-Ramos, M., Rios-Mendoza, J., Vivar-Méndez, J., Nieva-Villegas, L.M., Cornelio-Santiago, H.P., Sotelo-Méndez, A., 2023. Avocado Hass peel from industrial by-product: effect of extraction process variables on yield, phenolic compounds and antioxidant capacity. Front. Sustain. Food Syst. 7. https://doi.org/10.3389/fsufs.2023.1255941.

Garcia-Vallejo, M.C., Agudelo Patiño, T., Poveda-Giraldo, J.A., Piedrahita-Rodríguez, S., Cardona Alzate, C.A., 2023. Alternatives for the valorization of avocado waste generated in the different links of the value chain based on a life-cycle analysis approach. Agronomy 13, 2229. https://doi.org/10.3390/agronomy13092229.

García-Vargas, M.C., Contreras, M. del M., Castro, E., 2020a. Avocado-derived biomass as a source of bioenergy and bioproducts. Appl. Sci. 10, 8195. https://doi.org/10.3390/app10228195.

García-Vargas, M.C., Contreras, M. del M., Gómez-Cruz, I., Romero-García, J.M., Castro, E., 2020b. Avocado-derived biomass: chemical composition and antioxidant potential. Proc 70, 100. https://doi.org/10.3390/foods_2020-07750.

Ginni, G., Kavitha, S., Kannah, R.Y., Bhatia, S.K., Kumar, S.A., Rajkumar, M., Kumar, G., Pugazhendhi, A., Chi, N.T.L., Banu, J.R., 2021. Valorization of agricultural residues: different biorefinery routes. J. Environ. Chem. Eng. 9, 105435. https://doi.org/10.1016/J.JECE.2021.105435.

Haider, F.U., Coulter, J.A., Cai, L., Hussain, S., Cheema, S.A., Wu, J., Zhang, R., 2022. An overview on biochar production, its implications, and mechanisms of biochar-induced amelioration of soil and plant characteristics. Pedosphere 32, 107–130. https://doi.org/10.1016/S1002-0160(20)60094-7.

Jian, X., Zhuang, X., Li, B., Xu, X., Wei, Z., Song, Y., Jiang, E., 2018. Comparison of characterization and adsorption of biochars produced from hydrothermal carbonization and pyrolysis. Environ. Technol. Innov. 10, 27–35. https://doi.org/10.1016/J.ETI.2018.01.004.

Jimenez, P., Garcia, P., Quitral, V., Vasquez, K., Parra-Ruiz, C., Reyes-Farias, M., Garcia-Diaz, D.F., Robert, P., Encina, C., Soto-Covasich, J., 2021. Pulp, leaf, peel and seed of avocado fruit: a review of bioactive compounds and healthy benefits. Food Rev. Int. 37, 619–655. https://doi.org/10.1080/87559129.2020.1717520.

Kan, T., Strezov, V., Evans, T.J., 2016. Lignocellulosic biomass pyrolysis: a review of product properties and effects of pyrolysis parameters. Renew. Sustain. Energy Rev. 57, 1126–1140. https://doi.org/10.1016/J.RSER.2015.12.185.

Kang, K., Klinghoffer, N.B., ElGhamrawy, I., Berruti, F., 2021. Thermochemical conversion of agroforestry biomass and solid waste using decentralized and mobile systems for renewable energy and products. Renew. Sustain. Energy Rev. 149, 111372. https://doi.org/10.1016/J.RSER.2021.111372.

Khairy, M., Amer, M., Ibrahim, M., Ookawara, S., Sekiguchi, H., Elwardany, A., 2024. The influence of torrefaction on the biochar characteristics produced from sesame stalks and bean husk. Biomass Convers. Biorefin. 14, 17127–17148. https://doi.org/10.1007/S13399-023-03822-9/FIGURES/12.

Li, Y., Xing, B., Ding, Y., Han, X., Wang, S., 2020. A critical review of the production and advanced utilization of biochar via selective pyrolysis of lignocellulosic biomass. Bioresour. Technol. 312, 123614. https://doi.org/10.1016/J.BIORTECH.2020.123614.

Liu, Z., Quek, A., Kent Hoekman, S., Balasubramanian, R., 2013. Production of solid biochar fuel from waste biomass by hydrothermal carbonization. Fuel 103, 943–949. https://doi.org/10.1016/j.fuel.2012.07.069.

Luo, L., Xu, C., Chen, Z., Zhang, S., 2015. Properties of biomass-derived biochars: combined effects of operating conditions and biomass types. Bioresour. Technol. 192, 83–89. https://doi.org/10.1016/J.BIORTECH.2015.05.054.

Morcillo-Martín, Ramón, Tarrés, Quim, Aguado, Roberto J., Espinosa, Eduardo, Delgado-Aguilar, Marc, Rodríguez, Alejandro, Morcillo-Martín, R., Espinosa, E., Rodríguez, A., Tarrés, Q., Aguado, R.J., Delgado-Aguilar, M., 2024. Avocado pruning residues for the formulation of bio-based polyethylene/fiber-based biocomposites for sustainable food packaging. Adv. Sustain. Syst. 8, 2300600. https://doi.org/10.1002/ADSU.202300600.

Narayan, O.P., Kumar, P., Yadav, B., Dua, M., Johri, A.K., 2022. Sulfur nutrition and its role in plant growth and development. Plant Signal. Behav. 18, 2030082. https://doi.org/10.1080/15592324.2022.2030082.

Narzari, R., Bordoloi, N., Sarma, B., Gogoi, L., Gogoi, N., Borkotoki, B., Kataki, R., 2017. Fabrication of biochars obtained from valorization of biowaste and evaluation of its physicochemical properties. Bioresour. Technol. 242, 324–328. https://doi.org/10.1016/J.BIORTECH.2017.04.050.

Nwaokobia, K., Oguntokun, M.O., Okolie, P.L., Ogboru, R.O., Idugboe, O.D., 2018. Evaluation of the chemical composition of Persea americana (Mill) pulp and seed. J. Biosci. Biotechnol. Discov. 3, 83–89. https://doi.org/10.31248/JBBD2018.071.

Paniagua, S., Reyes, S., Lima, F., Pilipenko, N., Calvo, L.F., 2021. Combustion of avocado crop residues: effect of crop variety and nature of nutrients. Fuel 291, 119660. https://doi.org/10.1016/J.FUEL.2020.119660.

Páramos, P.R.S., Granjo, J.F.O., Corazza, M.L., Matos, H.A., 2020. Extraction of high value products from avocado waste biomass. J. Supercrit. Fluids 165, 104988. https://doi.org/10.1016/J.SUPFLU.2020.104988.

Perea-Moreno, A.J., Aguilera-Ureña, M.J., Manzano-Agugliaro, F., 2016. Fuel properties of avocado stone. Fuel 186, 358–364. https://doi.org/10.1016/J.FUEL.2016.08.101.

Perea-Moreno, A.-J., Perea-Moreno, M.-Á., Dorado, M.P., Manzano-Agugliaro, F., 2018. Mango stone properties as biofuel and its potential for reducing CO2 emissions. J. Clean. Prod. 190, 53–62. https://doi.org/10.1016/j.jclepro.2018.04.147.

Puri, L., Hu, Y., Naterer, G., 2024. Critical review of the role of ash content and composition in biomass pyrolysis. Front. Fuels 2, 1378361. https://doi.org/10.3389/FFUEL.2024.1378361.

Rodríguez-Martínez, B., Romaní, A., Eibes, G., Garrote, G., Gullón, B., del Río, P.G., 2022. Potential and prospects for utilization of avocado by-products in integrated biorefineries. Bioresour. Technol. 364, 128034. https://doi.org/10.1016/j.biortech.2022.128034.

Şahin, R.Z.Y., Örenay, O., Dolaş, Y., Yargıç, A.Ş., Özbay, N., 2020. Experimental study of thermal pyrolysis of avocado seed for liquid fuel production. Int. J. Innov. Approaches Agric. Res. 4, 447–452. https://doi.org/10.29329/IJIAAR.2020.320.6.

Sánchez, F., Araus, K., Domínguez, M.P., Miguel, G.S., 2017. Thermochemical transformation of residual avocado seeds: torrefaction and carbonization. Waste Biomass Valoriz. 8, 2495–2510. https://doi.org/10.1007/S12649-016-9699-6/TABLES/5.

Sandoval-Contreras, T., González Chávez, F., Poonia, A., Iñiguez-Moreno, M., Aguirre-Güitrón, L., 2023. Avocado waste biorefinery: towards sustainable development. Recycling 8, 81. https://doi.org/10.3390/recycling8050081.

Sharma, R.K., Cox, M.S., Oglesby, C., Dhillon, J.S., 2024. Revisiting the role of sulfur in crop production: a narrative review. J. Agric. Food Res. 15, 101013. https://doi.org/10.1016/J.JAFR.2024.101013.

Shen, Z., Jin, F., Wang, F., McMillan, O., Al-Tabbaa, A., 2015. Sorption of lead by Salisbury biochar produced from British broadleaf hardwood. Bioresour. Technol. 193, 553–556. https://doi.org/10.1016/J.BIORTECH.2015.06.111.

Solih, F.A., Buthiyappan, A., Abdul Raman, A.A., Tan, Y.Y., 2023. Carbonaceous material from agricultural waste for treating colored wastewater: characterization and adsorption performance evaluations. Chem. Pap. 77, 2985–3001. https://doi.org/10.1007/s11696-023-02682-x.

Soria-González, J.A., Tauro, R., Alvarado-Flores, J.J., Berrueta-Soriano, V.M., Rutiaga-Quiñones, J.G., 2022. Avocado tree pruning pellets (*Persea americana* Mill.) for energy purposes: characterization and quality evaluation. Energies 15. https://doi.org/10.3390/EN15207514.

Tesfaye, T., Ayele, M., Gibril, M., Ferede, E., Limeneh, D.Y., Kong, F., 2022. Beneficiation of avocado processing industry by-product: a review on future prospect. Curr. Res. Green Sustain. Chem. 5, 100253. https://doi.org/10.1016/j.crgsc.2021.100253.

Villanueva, M., Proupín, J., Rodríguez-Añón, J.A., Fraga-Grueiro, L., Salgado, J., Barros, N., 2011. Energetic characterization of forest biomass by calorimetry and thermal analysis. J. Therm. Anal. Calorim. 104, 61–67. https://doi.org/10.1007/s10973-010-1177-y.

Xu, D., Cao, J., Li, Y., Howard, A., Yu, K., 2019. Effect of pyrolysis temperature on characteristics of biochars derived from different feedstocks: a case study on ammonium adsorption capacity. Waste Manag. 87, 652–660. https://doi.org/10.1016/J.WASMAN.2019.02.049.

Yaashikaa, P.R., Kumar, P.S., Varjani, S.J., Saravanan, A., 2019. Advances in production and application of biochar from lignocellulosic feedstocks for remediation of environmental pollutants. Bioresour. Technol. 292, 122030. https://doi.org/10.1016/J.BIORTECH.2019.122030.

Yogalakshmi, K.N., Devi, T.P., Sivashanmugam, P., Kavitha, S., Kannah, R.Y., Varjani, S., AdishKumar, S., Kumar, G., Banu, J.R., 2022. Lignocellulosic biomass-based pyrolysis: a comprehensive review. Chemosphere 286, 131824. https://doi.org/10.1016/J.CHEMOSPHERE.2021.131824.

Zhang, H., Chen, C., Gray, E.M., Boyd, S.E., 2017. Effect of feedstock and pyrolysis temperature on properties of biochar governing end use efficacy. Biomass Bioenergy 105, 136–146. https://doi.org/10.1016/J.BIOMBIOE.2017.06.024.