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Biorefineries, Reducing the Volume of Agro-industrial Waste and Generating Products with High Added Value

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The environmental problems of the modern world arise from the use of non-renewable resources including fossil fuels, heavy metals, among other examples, and from the poor disposal of the waste generated. For this reason, biorefineries constitute a strategy that allows the use of biomass and its waste in fuels and/or high-value products including chemical compounds, biodegradable polymers, among other examples. On this occasion, we present three experiences of biorefineries that have been designed on an experimental scale for the use of three agricultural products of significant relevance in Latin America, including: avocado, cocoa and cannabis. The avocado is a product of which only the pulp is used, while the seed and the peel are waste. In this work, added value was given to the avocado peel and seed. Cocoa is mostly used in the production of chocolate from the seeds, but the other waste is not used. The coca shell was used because it is the waste with the largest amount in the fruit. Finally, cannabis is of interest for the bioactive components present in the flower, while the leaves and stems are not used. We used cannabis stems and leaves. The bioproducts obtained included biochar with favorable properties for energy use or as an adsorbent and extracts containing bioactive components of interest including chlorophyll in the case of avocado peel, flavonoids as catechins and epicatechins in the case of avocado seeds, theobromine, catechin and epicatechin in cocoa shell extract, and cannabinoids in cannabis leaf extract. We concluded that it demonstrates the feasibility to obtain high-value products from agricultural products and their waste in a sustainable way, reducing waste, reducing the associated carbon footprint and generating more profits for farmers..

* 1. Introduction

Nowadays, humans consume many products including clothing, footwear, ultra-processed foods, packaging, plastics, pesticides, drugs, household items, among many others. This overconsumption is negatively affecting the planet due to the high use of natural resources as raw materials, the use of fossil fuels as energy sources for production processes, high water consumption and the generation of emissions, wastewater and a large amount of waste that is released into the environment causing serious impacts. For this reason, biorefineries are presented as an opportunity to sustainably use biomass and its residues in fuels and/or high value-added products. A biorefinery is a facility that, through the integration of biomass conversion processes and equipment, can produce fuels and chemical products (Rabelo et al., 2011). A biorefinery is an opportunity to give a second chance to biomass-derived waste. In the case of agroindustry, agricultural waste is initially generated, which is the residue of the crop, since normally only one part of the plant is used for commercial purposes. Additionally, agro-industrial waste is generated, which is the residue of processing. Biorefineries take advantage of the different constituents of plants and allow the sustainable use of agricultural and agro-industrial waste, obtaining multiple value-added products, generating value for the residual biomass (Mallarino-Miranda et al., 2022).

Avocado (*Persea americana*) is a fruit native to Mesoamerica, specifically the highlands of central and eastern Mexico, Guatemala, and El Salvador. Global avocado production has been increasing in recent years. Over the last decade, avocado production has doubled from 4.07 million Tons (MT) in 2011 to around 8.06 MT in 2021 (Restrepo-Serna & Cardona-Alzate, 2024). The main producing countries are Mexico, Dominican Republic, Peru, Indonesia, Colombia, Brazil, Kenya, Venezuela, Chile, United States, New Zealand and South Africa. The presence of phytochemicals and fat-soluble nutrients in avocado give it a high nutritional content and benefits for human health. It can be consumed directly or in value-added products such as oils, guacamole, ice cream, puree, etc. (Romero-Hernández et al., 2021). The presence of lipids in avocado pulp has been reported in ranges between 12 and 24%, it is rich in polar lipids, such as glycolipids and phospholipids, which are important in various cellular processes in cell membranes, as well as in monounsaturated fatty acids, which are effective in reducing blood levels of undesirable low-density lipoproteins and increasing levels of beneficial high-density lipoproteins (Cowan, 2016). Avocado oil contains high levels of monounsaturated fatty acids (oleic and palmitoleic acids), low amounts of polyunsaturated fatty acids and a significant amount of saturated fatty acids (palmitic and stearic acids) (Araújo et al., 2018). This fruit is consumed fresh, but it also has applications in the food sector such as in the production of guacamole or oil and in the cosmetics sector (Nyakang'i et al., 2023). In addition, it contains minerals, vitamins, sugars, including sucrose and seven-carbon carbohydrates such as d-mannoheptulose, pigments, tannins, polyphenols, phytoestrogens and perseitol. The part of the fruit that is used for consumption or the production of oils is the pulp, while the seed and peel, which make up approximately 20% of the fruit's weight, are discarded. One of the main uses of avocado seed has been as an adsorbent. For instance, in Mexico, activated biosorbents were developed from avocado waste for the treatment of municipal wastewater (Orozco et al., 2024). In another study, activated carbon was produced from avocado seeds and paper waste and used to remove ibuprofen and paracetamol from water (Mabalane et al., 2024). Avocado seeds have also been used to obtain novel materials. For example, in a recent study, avocado seed waste was chemically treated and used as a cellulose-rich filler for the synthesis of gelatine-based films (Sekar Tri Wulan et al., 2024). Another research used avocado seeds for the biosynthesis of Polyhydroxybutyrate and ethyl levulinate (Gnaim et al., 2023). Avocado waste has also been investigated for use as a fuel. For example, a recent study evaluated the use of avocado waste, seed and peel, as a fuel in a conical bed combustor (San Jose et al., 2023). In other work, low-cost dual-chamber microbial fuel cells were fabricated using zinc and copper as electrodes and avocado waste as fuel (Rojas-Flores et al. 2022). Avocado waste was used as raw material to produce biodiesel by obtaining oil from avocado seeds and peels using a solvent extraction technique (Collins-Chimezie et al., 2023). Avocado residues have been a source of chemical compounds. For example, oligosaccharides and polyphenols were recovered by hydrothermal treatment of avocado peel (Del Castillo-Llamosas et al., 2021).

On the other hand, cocoa (*Theobroma cacao* L.) is a plant native to tropical and subtropical regions of South America that is the raw material for producing chocolate, an edible product used worldwide. Criollo cocoa is grown mainly in Mexico, Guatemala and Nicaragua in small quantities, also in Venezuela, Colombia, Caribbean islands, Trinidad, Jamaica and the island of Granada (Acosta et al., 2018). It is also known as sweet cocoa because its seeds have a somewhat sweet taste and a color between pinkish and white. It is a long and thin fruit. Only the beans of the cocoa fruit are used to obtain cocoa oil, chocolate and cocoa paste, and the rest of the fruit is discarded. Cocoa by-products consist of cocoa pod husk (70% of the fruit), cocoa shell and pulp. The cocoa pod is rich in dietary fibber, lignin and bioactive antioxidants such as polyphenols that are generally wasted (Bhirawa Anoraga et al., 2024). Some studies have focused on obtaining components from cocoa residues. For example, a recent work proposed a circular economy approach through the valorisation of pectin derived from cocoa pod husks for tissue engineering (Girón-Hernández et al., 2024). Another study used microwave-assisted extraction of cocoa residues to determine the uronic acid and total phenol content (Mellinas et al., 2020). Polysaccharides were extracted from cocoa pod shell waste and their hydration efficacy was demonstrated (Tantapakul et al., 2024). Cocoa residues have also been used in the manufacture of adsorbents. For example, the production of hydrochar by low-temperature hydrothermal carbonization of residual biomass from cocoa production for the adsorption of mercury in acidic aqueous solutions (Ormaza-Hugo et al., 2024). Cocoa residues have also been used to obtain new foods, for example, cocoa shells were used to obtain a phenol concentrate and formulate a matrix with isolated whey protein particles (Valencia et al., 2024). In another study, organic soil additives derived from cocoa pod husks were prepared (Mwafulirwa et al., 2024).

Cannabis is the most widely consumed illicit substance in Europe and the United States. Although its sale and use are still generally prohibited, European public policies have evolved in recent years by legalizing cannabis for medical use and considering its legalization for recreational use (Billion and Hein, 2024). Due to this, this crop has gained great importance in tropical and subtropical countries. However, the increase in its use has generated a large amount of waste, becoming a source of environmental pollution. Among the cannabis species, Cannabis sativa and Cannabis indica stand out for containing a wide variety of valuable secondary metabolites, especially cannabinoids, which are valued for their clinical relevance (Thuan Lu et al., 2023). However, these components are concentrated in the flowers, and the other parts of the plant become waste. Cannabis waste has been used for a variety of purposes. For example, extract from the hulled seeds of C. sativa was used to produce films (Dobrucka et al., 2025). Waste from the medicinal cannabis industry was valorised through the synthesis of activated carbon (Bavio et al., 2024). Another study used waste hemp to isolate cellulose nanomaterials by phosphoric acid hydrolysis (Hancock et al., 2023). Another study proposes the valorization of cannabis waste, specifically hemp, through the gasification process, using a downdraft gasifier and a mixture of air and steam as a gasifying agent to produce synthesis gas (Bezerra Lopes et al., 2024). Activated carbon absorbents have also been produced from residual cannabis biomass for pesticide removal (Vukčević et al., 2015).

Considering that the circular economy presents an opportunity in agribusiness by maximizing the value of resources and reducing waste generation through practices that promote reuse, recycling, and innovation in production processes, the objective of this project was to minimize the amount of waste generated in the processing of avocado, cocoa, and cannabis, encouraging its reuse to obtain new products including biochar and bioactive compounds. This promotes innovation and the development of new businesses and contributes to environmental and social sustainability by promoting responsible use of resources and reducing the environmental impact of agro-industrial production.

* 1. Materials and Methods

The waste of avocado, cocoa and cannabis in this study came from crops northern Colombia. Avocado seeds, cocoa shell and cannabis stems were subjected to rapid pyrolysis at 873 K during 1 min to obtain biochar. The functional groups present in the biochar were identified through Fourier transform infrared (FTIR) -Spectroscopy. The adsorption capacity was calculated by permanence tests with methylene blue, and the calorific power of the biochar was determined using a calorimetric pump. Additionally, avocado seeds, avocado peels, cocoa shell and cannabis leaves were subjected to extraction using different methods and solvents to recover bioactive compounds with pharmacological interest. The extracts were analyzed by high performance liquid chromatography.

* 1. Results and discussion
		1. Biochar

FTIR analysis of the biochar obtained from the pyrolysis of the avocado waste showed the presence of functional groups such as aromatic CO groups and aliphatic O-alkylated groups (HCOH). Whereas, biochar obtained from cocoa shells contained functional groups such as presence of hydroxyl functional groups (O-H), C-C bonds, carbonyl groups (C=O) and C-O bonds. In the case of biochar from cannabis waste, FTIR analysis revealed the presence of peaks associated with the adsorption of alcohols, phenols, organic acids, amines, esters, ethers and compounds with aromatic structures and carbonyl groups. The functional groups found in the biochar obtained from the pyrolysis of avocado, cocoa and cannabis waste resemble those found by other authors who analyzed the biochar of other waste such as the waste of seeds of *Prosopis juliflora* (Díaz-Uvibe et al., 2022); fiber biomass (Xu et al., 2020); soy straw (Vyavahare et al., 2021); *Eucheuma spinosum* biomass (Gurav et al., 2021), among others. Methylene blue adsorption tests allowed to evaluate the adsorption capacity of the biochar obtained. The table 2 shows the adsorption capacity using the biochar obtained in this research and others reported in the literature.

Table 2. Comparison of adsorption capacity of biochar from different biomass

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Waste | Pyrolysis conditions | Adsorption Temperature (K) | Adsorption capacity (mg/g) | Reference |
| Avocado seeds | 873 K; 1 min | 303 | 267.74 | This work |
| Cocoa shell | 873 K; 1 min | 303 | 239.27 | This work |
| Cannabis stems | 873 K; 1 min | 303 | 305.35  | This work |
| Rapeseed straw | 673 K; 2 h | 298 | 84.51 | Hou et al., 2023 |
| Bagasse cane | 673 K; 2 h | 298 | 104.69 | Hou et al., 2023 |
| Walnut peel  | 673 K; 2 h | 298 | 74.41 | Hou et al., 2023 |
| Banana peel | 1073 K; 3 h  | 303 | 390 | Amin et al., 2019 |
| Orange peel | 1073 K; 3 h | 303 | 478 | Amin et al., 2019 |
| Coffee grounds | 573, 673 and 773 K; 2 h | 298 | 20.35, 19.52 and 41.98 | Rocha do Nascimento et al., 2024 |

Although it is difficult to compare the results of methylene blue adsorption with other works due to the variety of conditions under which biomass pyrolysis (temperature, time, particle size) and adsorption (initial methylene blue concentration, pH, temperature, time) are carried out, it can be observed in Table 2 that the adsorption capacity of the biochar obtained from avocado, cocoa and cannabis residues in this work are similar to those reported by other authors who used biochar obtained by high temperature pyrolysis (Amin et al., 2009).

Regarding the energy utilization potential, when comparing the calorific values ​​of the obtained biochar (19.11 - 32.76 MJ/kg) with those of wood, it is observed that they are higher or at least comparable. The calorific value of wood ranges between 17 and 19 MJ/kg (Jasinskas et al., 2020). Compared to solid fossil fuels, the calorific value of the obtained biochars is slightly lower than that of coal, which is in the range between 21 and 33 MJ/kg (Tic et al., 2021), and like that of lignite, which ranges between 6 and 25 MJ/kg (Yaman et al., 2021). The table 3 shows the comparison between the calorific values ​​between biochar from different biomass sources

Table 3. Comparison of calorific value of biochar from different biomass

|  |  |  |
| --- | --- | --- |
| Waste | Calorífica Value (MJ/kg) | Reference |
| Avocado seeds | 19.11 | This work |
| Cocoa shell | 32.76 | This work |
| Cannabis stems | 22.33 | This work |
| Sunflower hulls | 26.8 | Kazimierski et al., 2022 |
| Corncob | 27 | Kazimierski et al., 2022 |
| Coconut shells | 32.3 | Kazimierski et al., 2022 |
| Walnut husks | 21.2 | Kazimierski et al., 2022 |
| Pistachio husks | 30.1 | Kazimierski et al., 2022 |
| Buckwheat husks | 29.4 | Kazimierski et al., 2022 |
| Giant goldenrod and Canadian goldenrod | 20.26 to 22.90 | Łapczyńska-Kordon et al., 2022 |
| Pistachio shells | 31.35  | Jeníček et al., 2023 |
| Walnut shells | 30.55 | Jeníček et al., 2023 |

The energy potential of cannabis leaf and stem biochar showed approximately 70% of the calorific value of mineral coal. The results obtained show that the percentage of metal adsorption is in a range between 40% and 90%, with lead showing the best adsorption results.

**3.2 Bioactive compounds**

The table 4 displays the composition of bioactive compounds in the residue extracts analyzed.

**3.2.1 Avocado.** The chlorophyll content in the avocado peel was 9.8% in ethanolic extract and 10.2% in acetone extract. The acetone extract of the avocado seed showed the presence of phenolic compounds such as catechin, epicatechin, routine, caffeic acid, vanillic acid and epigallocatechin gallate, showing that it has a great antioxidant potential. It is noted that the acetone extract had a higher content of bioactive compounds than the ethanolic and aqueous extracts. Our results are like those reported by Tremocoldi et al. (2018) and Kosińska et al. (2012).

**3.2.2 Cocoa.** The ethanolic extract of cocoa shells contained 127 µg/kg of theobromine and 20.3 mg GAE/g of total phenols. These values ​​are like those reported by Nieto-Figueroa et al. (2020), who used a centrifugation extraction method and an acetone–water–acetic acid mixture as a solvent.

**3.2.3 Cannabis.** The cannabinoid content of cannabis leaves depended on the extraction method used. The cold maceration method generated low concentrations of CBD and CBN but high concentrations of THC, unlike the Soxhlet and ultrasound methods. In another investigation with cannabis leaves, in which the extraction method was ultrasound with methanol as a solvent, cannabinoids were detected in THC concentrations between 0.1 and 37.2% and CBD between 0 and 77.3% (Chen et al., 2024).

Table 4. Composition of bioactive compounds

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Plant | Type of waste | Extraction method | Solvent | Bioactive compounds |
| Avocado | Peel | Maceration | EthanolAcetone | Chlorophyll (9.8%)Chlorophyll (10.2%) |
| Seed | Soxhlet | Ethanol(mg/kg)  | Epicatechin (159.2), Catechin (86.3), Caffeic acid (24.5), Rosmarinic acid (11.6), Rutin (30.4)  |
| Water (mg/kg) | Epicatechin (669.5), Catechin (293.3), Caffeic acid (27.5), Rosmarinic acid (11.2), Rutin (62.6) |
| Acetone(mg/kg) | Epicatechin (41.4), Catechin (86.6), Caffeic acid (22.6), Rosmarinic acid (10.4), Rutin (23.3) |
| Cocoa | Shell | Soxhlet | Ethanol | 127 µg/kg of theobromine and 20.3 mg GAE/g of total phenols |
| Cannabis | Leaves | Maceration | Ethanol | CBD 0.8%, CBN 0.4%, THC 26.8% |
| Soxhlet | Ethanol | CBD 15.5%, CBN 1.6%, THC 1.2% |
| Ultrasonic assisted | Ethanol | CBD 30.7%, CBN 1%, THC 3% |

GAE: Gallic acid equivalent; CBD: Cannabidiol; CBN: Cannabinol; THC: Tetrahydrocannabinol

* 1. Conclusions

It is possible to obtain high-value products from agricultural products including avocado, cocoa and cannabis and their waste in a sustainable way, reducing waste, reducing the associated carbon footprint and generating more profits for farmers. The products obtained can also solve current environmental problems including the replacement of non-biodegradable plastics or adsorbent materials for the removal of pollutants.

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