Improving small-scale value chains in tropical forests. The Colombian case of annatto and açai

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Introduction

Nowadays, most tropical countries rely heavily on agriculture as a source of economic income through export activities. For example, the EU is interested in tropical fruits as they consume 50% of world fruit exports (FruitLogistica, 2021). The " major fruits " are grown and consumed on a large scale as their trade is industrialized. In contrast, wild and exotic fruits are not cultivated as much, consumed regionally or according to cultural practices, and have limited export. The annatto (*Bixa orellana* L.) is an exotic fruit of reddish-yellow color that is mainly used to extract natural dyes, emphasizing its use in the food, cosmetic and pharmaceutical industries. The main interest of annatto is the bixin extraction, as it usually comprises more than 80% of the total carotenoid content. Moreover, a wide variety of linear and cyclic molecules (apocarotenoids) can also be found (Rivera-Madrid et al., 2016). Different dye extraction methodologies are reported in the literature, focusing on mechanical abrasion and solvent extraction (Taham et al., 2015). To date, no studies have been reported concerning the extraction performance considering the particle size influence. On the other hand, the açai (*Euterpe oleracea* Mart.) is a wild fruit of high interest in tropical countries for pulp consumption due to its nutritional value. Açaí has been highlighted for the production of caloric beverages due to its rich composition of bioactive substances, protein, fiber, and lipids (Matta et al., 2020).

Throughout the life cycle of annatto and açai, considerable residues are generated. The annatto valorization focuses on seed utilization, usually 5% by weight of the tree, generating residues from both crop (e.g., branches, leaves, pods) and processing (exhausted seed). Likewise, about 95% of the seed is destined as waste for bixin extraction. On the other hand, the processing of açai produces a large number of residues per day since 5-15% of the fruit is edible and the remaining 80% corresponds to the seed weight (Buratto et al., 2021). Therefore, the valorization of these residual fractions is important for the sustainability of the process through the integral use of the raw material. The first challenge focuses on the scale of feedstock production, as the crops are usually found in tropical and high humidity areas. Therefore, low-cost and low-technological valorization alternatives must be proposed, such as anaerobic digestion. Although several processes produce energy from waste, anaerobic digestion may be a suitable technology to manage and dispose of food industry waste. This work aims to study the production of açai pulp and the extraction ratio of bixin and norbixin as natural colorants from different sizes of annatto seeds. To evaluate the cost/benefit of these low-scale crops, a study of biogas production from the crop residues of both fruits was carried out. These processes were assessed in technical, economic and environmental terms.

Methodology

The açai fruit and red annatto seeds were obtained from local crops of the Chocó region (Colombia). The experimental procedure was divided into four main sections. (i) Both raw materials as well as their residues were characterized based on international standards. (ii) The extraction of bixin and norbixin was performed consecutively considering two particle sizes (natural and ground). First, bixin was extracted with ethanol, and then norbixin was extracted with NaOH (0.1 N). Ten extraction sequences were performed to ensure dye depletion. Bixin and norbixin were quantified by HPLC (Noppe et al., 2009). (iii) Açaí pulp was obtained based on the expertise of local Colombian factories. (iv) Anaerobic digestion of the residues of both raw materials was carried out. From annatto, the branches, leaves, and capsules were considered. Meanwhile, the seed and peel of the açai were used. For the simulation procedure, the comparison of processes based on the raw material (extraction of dyes along with biogas production, and production of acai pulp with biogas) was proposed. The simulations were performed using the Aspen Plus software (Aspen Technology Inc.), assessed in energy and economic aspects using Colombian economic indices. In addition, the carbon footprint was carried out considering a life cycle analysis through SimaPro software (PRé Sustainability, Netherlands).

Results

Table 1 shows the results of bixin extraction sequences for ground and natural seeds. It is possible to observe that the solvent is not selective to bixin; instead, trace amounts of norbixin are also extracted. Regarding ground seed, the bixin yield shows an increase when sequential extractions are performed. The maximum concentration is reached at the third extraction (414.94 mg L^{-1}). This increase in yield was expected due to the surface destruction of the seed and the consequent easy interaction of the solvent with the solute. Concerning the norbixin, the extraction sequences achieved a total depletion of the colorant in the seed, achieved in extractions seven and nine for ground and whole seed, respectively. Similar to bixin, the maximum concentration was reached in the first extraction, with values of 73.4 mg L^{-1} for ground seed and 123.2 mg L^{-1} for whole seed. The results of pulp extraction showed yields of 0.51 L kg-1 of açai, with a content of 12.5, 39.1, and 40.8% by mass for solids, fat, and fiber, respectively. The anaerobic digestion results agreed with some studies in the literature, achieving maximum biomethane yields of 129.8 mL gVS^{-1} for the seed and 144.2 mL gVS^{-1} for the peel. Some differences were found between the biogas productivity results for annatto and açai residues. This variation can be explained by consuming high molecular weight carbohydrates and other major compounds in the açai residues, such as lipids, pectin, and protein. Lipids can be converted into methane by acetrophobic methanogenic microorganisms after the acidogenesis of glycerols. In addition, proteins serve as a source of methane after producing amino acids as a feedstock for acidogenic microorganisms.

Table 1. Comparison between particle size for bixin and norbixin extraction.

Parameter	Ground seed		Natural seed	
	Bixin	Norbixin	Bixin	Norbixin
Bixin extraction				
Max concentration (mg L^{-1})	1780.5	158.3	1385.5	82.6
Overall yield (mg g^{-1})	84.1	5.5	76.4	3.5
Norbixin extraction				
Max concentration (mg L^{-1})	0	73.4	0	123.1
Overall yield (mg g^{-1})	0	5.6	0	13.8

Concerning the simulation results, the annatto process (colorant with biogas production) has the highest capital expenditure (CapEx), which was expected due to the higher use of processing units. This capital investment involved the cost of equipment, instrumentation, installation civil work, piping, and electrical accessories. Regarding operating expenses (OpEx), it was observed that the annatto processing scenario is the most expensive, being almost ten times more expensive compared to the processing of açaí. This difference in variable costs is due to the high cost of raw materials. The annatto price was calculated based on the agricultural production of 1 kg of seed in Colombia, considering labor, fertilizers, cultivation accessories, and machinery cost. From the perspective of environmental analysis, the production and dosage of substrates and fertilizers in the agronomic growth stage have the greatest participation in the production system of both annatto and açai. However, the carbon footprint is lower than some tropical fruit trees such as tomato, mango, lulo, and golden berry. In the present work, the achiote crop has a total carbon footprint of 0.48 kg of CO_2 eq per hectare (0.0071 kg of CO_2 per kg of achiote seed), while for açai is 0.05 kg of CO_2 eq per kg of fruit.

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