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Circular Pathways to Food and Bioenergy from Fruit and Agro-Industrial Biowaste

Margarida Moldão[1,*], Diana Santos[1], André Azevedo[1], Elizabeth Duarte[1], Vitor Alves[1] and Marta Abreu[2]

[1]*Universidade de Lisboa, Portugal*
[2]*INIAV, Portugal*

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Abstract

The fruit and vegetable sector generates substantial quantities of by-products and waste, including produce that does not meet commercial standards. These streams represent a significant environmental and economic challenge; they remain biologically active and are rich sources of bioactive compounds that can be valorised into high-value products. This study explored integrated strategies for the valorisation of fruit and vegetable by-products and wastes, aiming to develop innovative food, bioactive ingredients and renewable energy solutions within a circular bioeconomy framework. By-products and waste streams from fresh-cut and juice-processing industries were quantified, characterised, and assessed as feedstocks for food and bioenergy recovery. Through a multidisciplinary approach combining food science, biotechnology, and anaerobic digestion technologies, innovative processing strategies were developed to produce functional fruit purees, bioactive extracts, and powdered ingredients with enhanced biological activity. The focus was on pineapple residues, which were identified as valuable sources of bromelain and antioxidant compounds with potential applications in the food, packaging, and pharmaceutical sectors. The results demonstrated that pineapple by-products respond to abiotic stress by increasing their bioactive content, acting as natural “bioreactors”. Bromelain activity in pineapple shells increased by up to 262%, reaching 20 mg tyrosine·min^{-1}·g^{-1} dry matter. Optimised solid–liquid extraction and spray-drying processes enabled the production of stable bioactive extracts encapsulated with inulin. The resulting powders exhibited high phenolic content (11.10 ± 0.01 mg GAE/g dry matter) and strong antioxidant activity, with values of 91.79 ± 1.98 and 174.50 ± 9.98 µmol Trolox/g dry matter in the DPPH and FRAP assays, respectively. These ingredients were successfully incorporated into food applications, demonstrating their technological and functional potential. For biomass fractions unsuitable for food valorisation, anaerobic co-digestion was employed to bioenergy recovery as biogas/biomethane. The addition of fruit and vegetable biowastes as co-substrates improved anaerobic co-digestion performance and increased methane production, demonstrating an effective pathway for energy recovery from residual biomasses. By transforming fruit and vegetable by-products into functional ingredients and renewable energy, the proposed approach contributes to waste reduction, resource efficiency, and the transition towards a sustainable circular bioeconomy.

Keywords: Circular bioeconomy, food waste valorisation, functional food ingredients, anaerobic co-digestion