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Life Cycle Assessment of Humic Acid Extraction from Digestate: Comparing Conventional, Ultrasound-assisted, and Ultrasound-microwave Pathways

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Abstract

Humic acid (HA) is gaining attention as a multifunctional biostimulant for sustainable agriculture, offering potential to improve soil health and reduce reliance on synthetic fertilisers (Ampong et al., 2022; Canellas et al., 2015). Recovering HA from digestate, a by-product of anaerobic digestion, aligns with circular bioeconomy goals by converting waste into value-added products (Shiju et al., 2026; Sarlaki et al., 2024). However, the environmental performance of alternative HA extraction routes remains poorly understood, as selection cannot be based solely on yield. Therefore, this study compares the environmental impacts of three digestate-based HA extraction pathways using life cycle assessment (LCA). The three pathways evaluated were conventional alkaline extraction (CE), ultrasound-assisted extraction (UAE), and ultrasound-microwave extraction (USMW). The functional unit was 1 kg of HA produced, with the system boundary being gate-to-gate and covering laboratory-scale extraction and separation, employing OpenLCA and using background datasets from ecoinvent. Six primary environmental impact categories were assessed using ReCiPe 2016 Midpoint (H): global warming, freshwater eutrophication, marine eutrophication, fossil resource scarcity, mineral resource scarcity, and water consumption. UAE consistently showed the lowest environmental impacts across all categories, with values 59–65% lower than CE. USMW was intermediate, with impacts 38–45% lower than CE. For global warming, CE recorded 283.21 kg CO_2 eq per kg HA, compared with 99.97 kg CO_2 eq for UAE and 157.01 kg CO_2 eq for USMW. Electricity consumption was the dominant contributor across all pathways, accounting for 60–98% of impacts depending on category and pathway, while potassium hydroxide and hydrochloric acid contributed secondarily, particularly to water consumption and freshwater eutrophication. The ranking of pathways (UAE < USMW < CE) was consistent across all impact categories. These findings demonstrate that process intensification can substantially improve the environmental performance of digestate-derived HA recovery, with UAE emerging as the most sustainable route due to its higher extraction efficiency and lower electricity demand per kilogram of HA. The results further support the development of waste-derived humic products that align with the EU Fertiliser Action Plan's priorities on nutrient circularity, bio-based alternatives, and digestate valorisation. By identifying the lowest-impact extraction pathway, this work also supports the scale-up of circular bioeconomy processes that contribute to the EU Farm to Fork Strategy's targets of reducing fertiliser use by 20% and nutrient losses

by 50% by 2030.

Keywords: Humic acid, digestate, life cycle assessment, waste valorisation, circular bioeconomy

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