https://doi.org/10.7250/CONECT.2026.065

SUSTAINABLE AGRICULTURE PRODUCTS FROM THE SEA: ENVIRONMENTAL ASSESSMENT OF SEAWEED BASED FERTILIZER ENCAPSULATES IN NORTHERN EUROPE

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Abstract – The transition toward climate smart agriculture in Europe demands alternative renewable, low impact nutrient sources that can substitute current synthetic fertilizers. Seaweed represents a rapidly emerging marine biomass resource with strong potential for integration into biorefinery applications. This study presents a comprehensive environmental assessment based on Life Cycle Assessment (LCA) approach of solid biofertilizers produced from *Ascophyllum nodosum* cultivated in Norway and processed through a multi stage biorefinery system combining blanching, mechanical treatment, alginate extraction, ansaerobic fermentation, and final encapsulation in biodegradable matrices. Primary data collected from a Norwegian farm representing the 2025 production year were used to compile the life cycle inventory (LCI), while background data were obtained from the European Reference Life Cycle Database (ELCD) and the ecoinvent database. The life cycle assessment (LCA) was conducted in openLCA software following the methodological framework of the Product Environmental Footprint (PEF) 3.1 guidelines. The study adopted a cradle-to-gate system boundary, with the gate defined at the production of the encapsulated biofertilizer. Allocation between co-products was performed using a physical approach based on the mass fraction of valuable elements (nitrogen, N). In total, 22 environmental impact categories were quantified, including global warming potential, eutrophication, water use, cumulative energy demand, and mineral resource depletion. The results indicate that thermal processing operations—particularly hot-water blanching and warm extraction—constitute the dominant contributors to total energy consumption. Nevertheless, Norway's low-carbon electricity mix significantly mitigates the associated climate impacts, underlining the influence of regional energy systems and process design on life cycle-based environmental performance. Avoiding biomass drying, integrating biowaste valorization, and adopting greener solvents emerged as key optimization pathways. Encapsulation improved nutrient retention and supports controlled release application, aligning with precision agriculture goals. Overall, the study demonstrates that seaweed based encapsulated fertilizers can achieve markedly lower environmental burdens than many terrestrial fertilizer systems, if processing energy is sustainably sourced. These findings offer actionable insights for scaling marine based fertilizer production in Europe and guiding industrial biorefinery design toward circular, low emission agricultural inputs.

Keywords – Circular bioeconomy; controlled-release biofertilizers; encapsulation; LCA; seaweed biorefinery

ACKNOWLEDGEMENT

Dr. Anna Trubetskaya acknowledges Norwegian Agriculture Agency (Landbruksdirektoratet), grant number 246574 for the financial support of the experimental part of this study.