Innovative ecological fertilizers based on waste biomass – concept and in vitro studies

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Introduction

The use of organic fertilizers derived from agricultural residues and waste streams, supplemented with mineral nutrients, can significantly reduce nutrient losses, aligning with the EU "Farm to Fork" strategy for sustainable food systems [1,2]. Maintaining a balance between organic and mineral fertilization is crucial for humus formation and soil fertility [1]. In Europe, 61–73% of soils are reported to be in poor condition due to erosion, organic carbon loss, nutrient imbalance, compaction, or salinization. To address this, the EU has proposed a Soil Monitoring Law to safeguard soil health. The International Federation of Organic Agriculture Movements (IFOAM) also emphasizes soil health as key to preserving this resource. Moreover, the FAO's 2023 report on food security highlights organic farming as a solution for providing healthy diets in urbanizing regions [4-6]. In this context, developing bio-based fertilizers from waste biomass supports circular economy goals and sustainable agriculture. Recent studies have demonstrated the feasibility of converting agricultural waste into slow-release fertilizers, enriching them with macro- and micronutrients [7-10].

This research aims to develop a technology for producing new organic granular fertilizers from renewable biomass. These fertilizers are designed to supply macronutrients (N, P, K), abundant organic carbon, and to deliver micronutrients (Zn, Mn, Cu) in a form bound to biomass, along with natural plant biostimulants. Such an approach seeks to improve nutrient use efficiency and reduce environmental pollution compared to conventional mineral fertilizers [10].

Material and methods

Fourteen renewable raw materials were evaluated as nutrient sources for the fertilizer formulations. These included: nitrogen sources: feather meal, horn meal, dried blood; phosphorus source: meat-and-bone meal; potassium source: biomass combustion ash; biostimulant-rich materials: comfrey root (*Symphytum officinale*), field horsetail (*Equisetum arvense*), nettle leaves (*Urtica dioica*), and seaweed (bladderwrack, *Fucus* sp.); cellulosic nutrient carriers: linseed cake, rapeseed cake, blackcurrant seed pomace; organic carbon fillers: leonardite and lignite (as sources of humic substances). All solid materials were dried, milled, and sieved prior to analysis. A multi-element characterization was performed using accredited methods: total C and N by elemental analysis (TCD detector), Hg by AAS (amalgamation technique), and other macro/micronutrients (Ca, Mg, S, Cu, Fe, Mn, Si, Zn, etc.) and toxic metals (As, Cd, Cr, Ni, Pb) by ICP-OES.

To incorporate micronutrients in an organically bound form, a biosorption process was developed. Three cellulosic biomasses (linseed and rapeseed cakes, and blackcurrant seeds) were tested as sorbents for Cu^{2+}, Zn^{2+}, and Mn^{2+} ions. To incorporate natural growth stimulants, extracts were prepared from selected plant materials (bladderwrack seaweed, nettle, comfrey, and horsetail). Two extraction methods were used: (1) aqueous extraction and (2) hydro-alcoholic extraction. Three optimal extracts were selected: E1 – field horsetail water extract (1 h, 40 °C, 1:35 w/v), E2 – bladderwrack (Fucus) water extract (2 h, 100 °C, 2.5:100 w/v), and E3 – field horsetail hydro-alcoholic extract (30% ethanol, 1 h, 2.5:30 w/v). These extracts are rich in bioactive phytochemicals and mineral constituents; seaweed extracts in particular are known to enhance plant growth and stress tolerance through their phytohormones and elicitor compounds [9]. A lab-scale granulation test was carried out to produce granular fertilizer prototypes. Leonardite and lignite were used as binder/filler materials during pan granulation to improve granule structure. Nine formulations (F1–F9) were formulated to target three crop groups. The finished granules were 3–5 mm in size, roughly spherical and porous. After curing, all formulations were subjected to comprehensive analysis.

Results and discussion

All nine fertilizer formulations met target ranges for macro- and micronutrient content. Granules contained N 2.2–3.4% (w/w), P (as P2O5) 1.0–3.9%, K (as K2O) 3.3–5.2%, and significant secondary nutrients (CaO 4–7%, MgO 0.27–0.73%, SO3 3.4–4.9%). Organic carbon content was high (24–34% C), reflecting the biomass-based nature. Each formulation provided micronutrients: B 2900–4300 mg/kg, Cu 3,300–6,900 mg/kg, Mn 3,300–7,200 mg/kg, and Zn 4,000–9,400 mg/kg. The biosorbed rapeseed cake enriched fertilizers above typical levels. Heavy metal contaminants (As, Cd, Hg, Ni, Pb) remained below permissible limits due to clean waste inputs. Adding 0.2% natural extract per formulation maintained target nutrient content.

Granules measured 3–5 mm (~4 mm average), with 45–85% within this range, ensuring suitability for mechanical spreading. They had a porous structure and hard surface, with a compressive strength of at least 33 N. No significant hardness differences were observed. Storage tests over 3 months showed no major nutrient loss or caking, with nitrogen content staying within 4% of the initial value.

Water-dissolution tests confirmed controlled nutrient release. Within 72 hours, 2–14% Cu, 3–10% Zn, 7–35% Mn, and 6–13% B dissolved, while Fe remained <2% due to sparingly soluble forms. Slow dissolution prevents rapid nutrient dumping, unlike conventional fertilizers [8]. Literature confirms prolonged nutrient release via organic or polymeric matrices [8]. Ali et al. (2021) noted gradual micronutrient release from seaweed-based fertilizers while maintaining bioavailability [9]. Slow-release behavior aligns nutrient availability with plant demand, reducing losses.

Plant extracts did not alter nutrient release but may enhance agronomic performance through hormones and elicitors [9]. Extracts contribute small additional nutrients (K, S, Mg) and bioactive compounds. This granulated fertilizer combines organic nutrients, sorbed micronutrients, and biostimulants for immediate and sustained release, improving soil health and supporting precision nutrient management [10]. Such fertilizers enhance efficiency and sustainability in modern agriculture [10].

Conclusions and further plans

A novel process was developed to produce complex organic-mineral fertilizers from waste biomass. Key innovations include the enrichment of a cellulosic carrier (rapeseed cake) with micronutrients via biosorption, and the incorporation of plant-derived biostimulants. The resulting granular fertilizers contain balanced NPK macro-nutrients, organically-complexed micronutrients, and high organic carbon content. Laboratory analyses confirmed that all formulations meet agronomic nutrient targets while remaining within safe limits for contaminants. The fertilizers exhibit good granular structure and mechanical durability, with no significant degradation or caking over 3 months of storage. In vitro tests indicate a favorable slow-release nutrient profile: only a small percentage of micronutrients are immediately leached, which will help in reducing nutrient runoff and increasing uptake efficiency. This slow release is complemented by the presence of immediately available nutrient fractions and biostimulatory compounds for early plant growth.

These in vitro results are promising for the use of waste-derived fertilizers in sustainable agriculture. The next steps will involve scaling up production to pilot scale (hundreds of kilograms) and conducting greenhouse and field trials. Germination and pot experiments are already underway and will be followed by field performance evaluations on vegetable, legume (protein crop), and cereal plants.

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