From Waste to Fertilizer: Phosphorus Organo-Mineral Products from Digestate and Ashes

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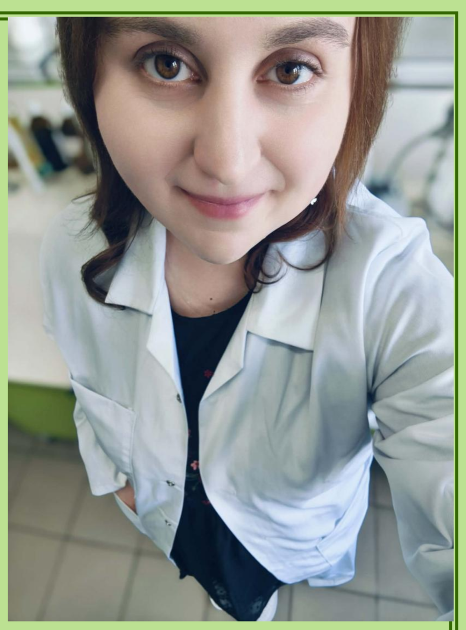

Introduction

The transition toward a circular economy in waste management requires effective strategies for nutrient recovery from underutilized waste streams. Municipal and agricultural wastes contain significant amounts of macro- and micronutrients, making them promising alternative raw materials for fertilizer production. Their valorization can reduce waste disposal, decrease the consumption of primary resources, and lower dependence on imported mineral fertilizers, supporting European Union environmental and resource-efficiency policies.

Sewage sludge ash (SSA), poultry litter ash (PLA), and dried digestate solids are particularly promising waste-derived materials for fertilizer production. SSA and PLA are rich in phosphorus and may partially substitute conventional phosphate resources, while dried digestate solids provide organic matter and amino compounds beneficial for soil quality. In this study, granular phosphorus organo-mineral fertilizers were produced exclusively from alternative raw materials, including SSA, PLA, PGPR-enriched ashes, dried digestate solids, and hydrolysate from waste feathers and down used as a granulation binder. The study aimed to evaluate whether integrating mineral and organic waste streams can produce fertilizers with suitable physicochemical and agronomic properties while improving soil biological activity and sorghum cultivation efficiency.

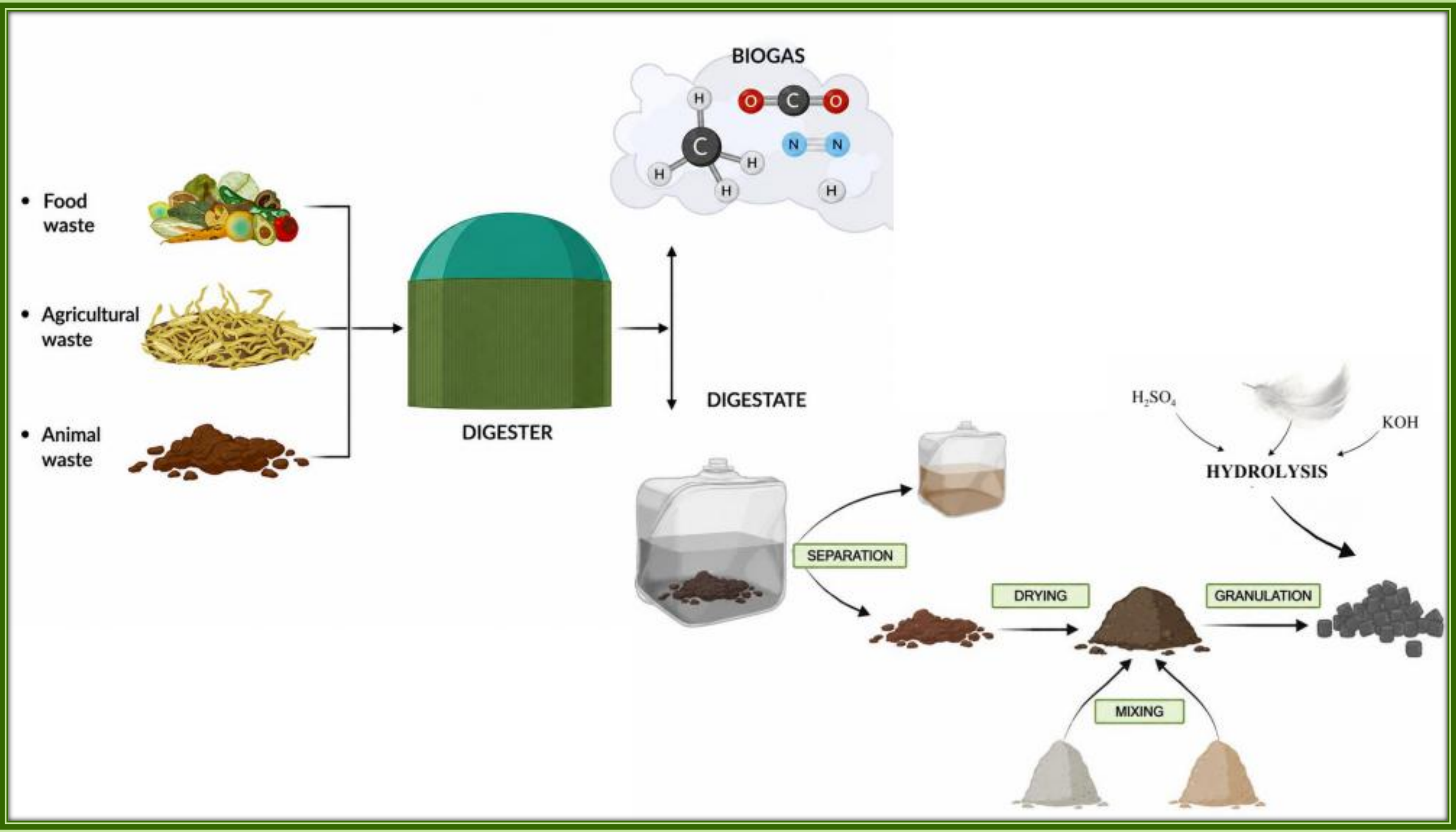

Figure 1. Scheme of experiment

Results & Discussion

The produced organo-mineral fertilizers were characterized by high organic matter content (55–65%) and organic carbon levels (22–25% d.m.), exceeding the minimum requirements for solid organo-mineral fertilizers classified as PFC 1(B)(I). The products also showed high nutrient content, with total nutrient concentrations ranging from 20 to 23% (m/m), including significant levels of potassium, calcium, and iron. Heavy metal concentrations were generally below the limits established by EU regulations. Cadmium and lead contents remained well within permissible values, while nickel concentrations in most formulations were around 20 mg/kg d.m., indicating safe application potential. Only SSA-based formulations with the highest organic matter share exceeded the nickel limit (>55 mg/kg d.m.) and were therefore excluded from further soil and pot experiments (Figure 2.).

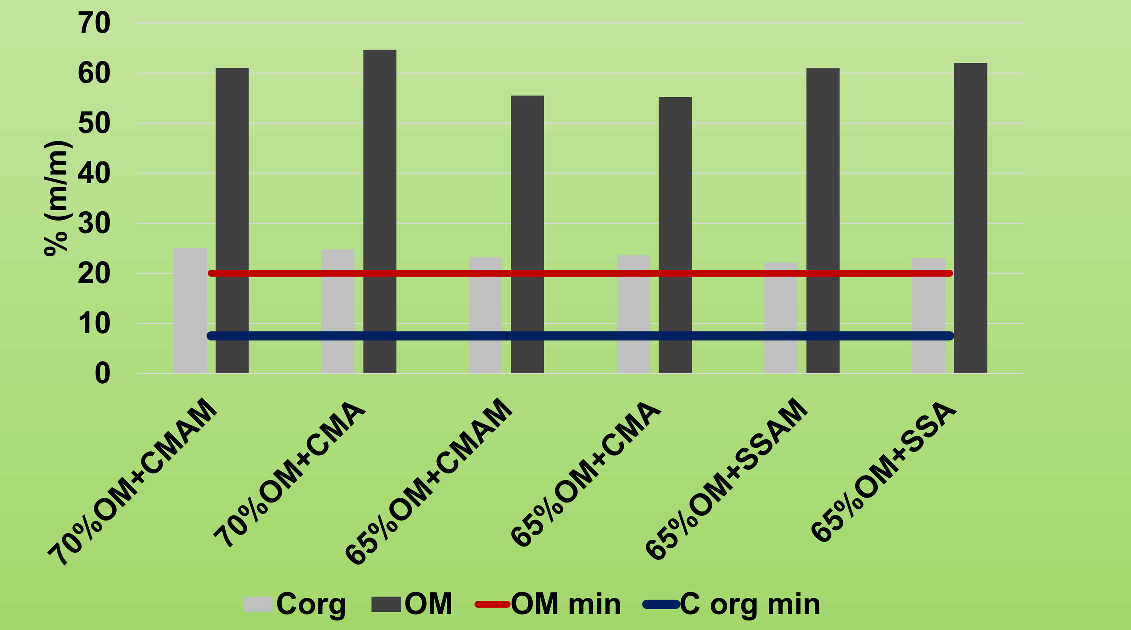

Figure 2. Percentage of organic carbon and organic matter in the fertilizers produced ; SSA – sewage sludge ash. SSAM – sewage sludge ash enriched with microorganisms. PLA – poultry litter ash. PLAM – poultry litter ash enriched with microorganisms; OM – organic matter

The developed products were designed as phosphorus organo-mineral fertilizers; therefore, particular attention was given to phosphorus composition and speciation. The P_2O_5 content reached approximately 6% in SSA-based fertilizers and around 5% in PLA-based products. Sequential phosphorus fractionation revealed a significant increase in the proportion of plant-available phosphorus in the final fertilizers compared to the raw materials. In both ashes and dried digestate solids, the share of readily available phosphorus fractions did not exceed 10%, whereas in the produced fertilizers it increased to nearly 30%. In SSA-based formulations, the proportion of poorly soluble calcium-bound phosphorus decreased substantially, while PLA-based products showed a marked reduction in residual phosphorus fractions. These results indicate that combining mineral ash fractions with organic waste-derived materials improves the phosphorus profile toward more bioavailable forms. The acidic granulation conditions likely promoted the transformation of poorly soluble phosphorus compounds into forms more accessible for plant uptake (Figure 3.)

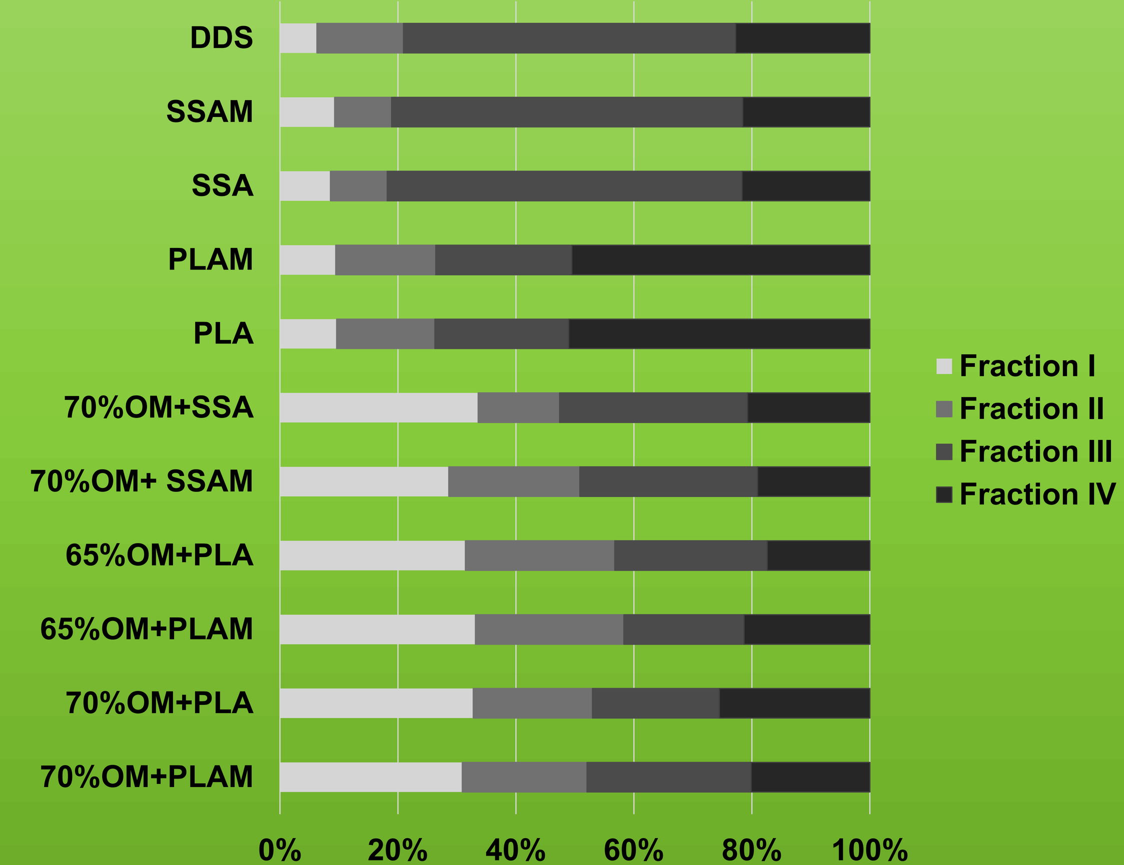

Figure 3. Percentage of individual phosphorus fractions in the extracted phosphorus compounds; SSA – sewage sludge ash. SSAM – sewage sludge ash enriched with microorganisms. PLA – poultry litter ash. PLAM – poultry litter ash enriched with microorganisms; DDS – solid. dried digestate fraction. OM – organic matter

A valuable feature of the developed fertilizers was their high amino acid content, reaching approximately 9.5% d.m. Free amino acids accounted for 4.7–6.0% of the total amino acid pool, enabling rapid plant uptake. Glutamic and aspartic acids were the dominant compounds, which may enhance nutrient utilization, plant metabolism, and tolerance to abiotic stress conditions (Table 1).

Table 1. Total amino acid and free amino acid content in the obtained products and in the organic raw material. SSA – sewage sludge ash. SSAM – sewage sludge ash enriched with microorganisms. PLA – poultry litter ash. PLAM – poultry litter ash enriched with microorganisms; OM – organic matter. [%] of dry matter of material

SAMPLE	TOTAL AMINO ACIDS	FREE AMINO ACIDS IN TOTAL	DOMINANT AMINO ACID IN TOTAL	
	[%]		Name	Contents [%]
70%OM+PLAM	9.53±0.02	5.5±0.00	Asp. Glu	11.75±0.06; 11.65±0.07
70%OM+PLA	9.57±0.02	6.0±0.00	Glu. Asp	12.23±0.05; 11.91±0.01
65%OM+PLAM	9.62±0.02	5.0±0.00	Glu. Asp	12.16±0.05; 11.85±0.03
65%OM+PLA	9.67±0.02	5.5±0.00	Glu. Asp	12.00±0.04; 11.89±0.04
70%OM+SSAM	9.53±0.01	5.4±0.00	Glu. Asp	12.38±0.02; 11.75±0.03
70%OM+SSA	9.71±0.01	5.5±0.00	Glu. Asp	12.36±0.04; 11.64±0.01
65%OM+SSAM	9.42±0.01	4.7±0.00	Glu. Asp	12.53±0.03; 11.78±0.03
65%OM+SSA	9.25±0.01	4.9±0.00	Glu. Asp	12.54±0.05; 11.89±0.04
DDS	11.20±0.01	5.1±0.00	Glu. Asp	12.41±0.04; 11.96±0.04

The biomass yield obtained with the experimental fertilizers ranged from 397 to 1471 kg/ha, compared to 257 kg/ha in the control treatment. However, ANOVA analysis showed no statistically significant differences between the treatments, indicating that the effect of the tested formulations on crop yield could not be conclusively confirmed (Figure 4.).

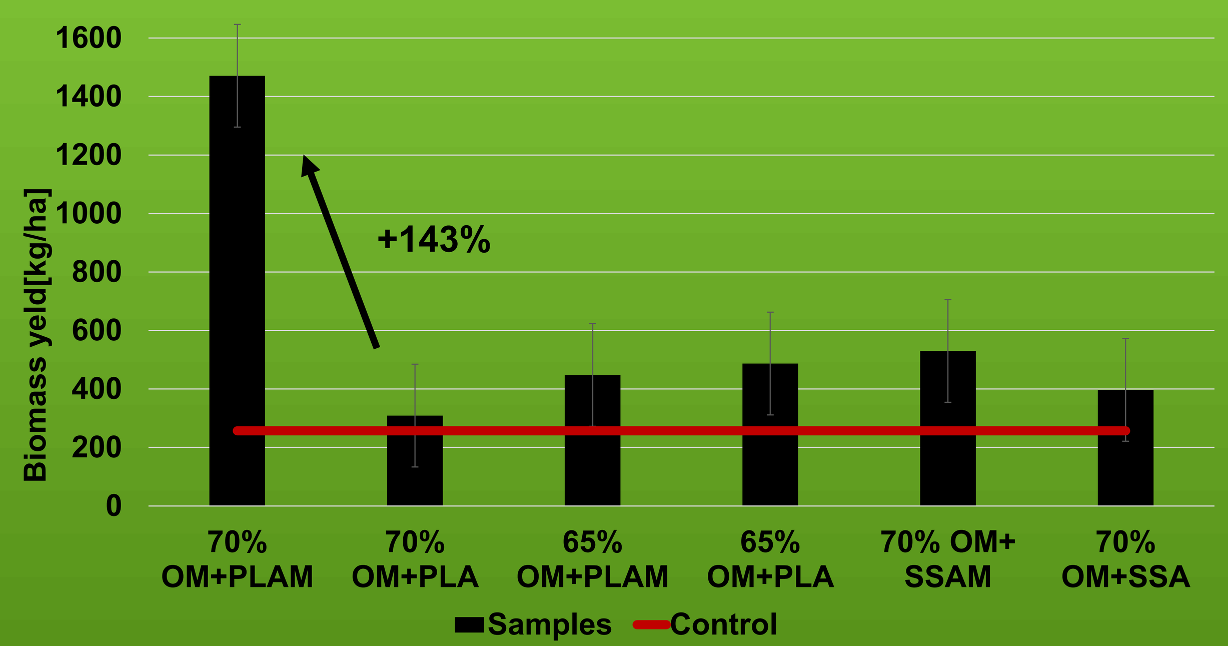

Figure 4. Biomass Yield Obtained in Soil Fertilized with Experimental Fertilizers; SSA – sewage sludge ash, SSAM – sewage sludge ash enriched with microorganisms, PLA – poultry litter ash, PLAM – poultry litter ash enriched with microorganisms, OM- organic matter

Conclusions

- Granular phosphorus organo-mineral fertilizers can be successfully produced exclusively from waste-derived raw materials, including SSA, PLA, dried digestate solids, and feather hydrolysate.
- The developed fertilizers fulfilled the requirements for PFC 1(B)(I) solid organo-mineral fertilizers due to their high organic matter, organic carbon, and nutrient content.
- Most formulations showed heavy metal concentrations below EU regulatory limits, confirming their environmental safety potential.
- Integration of ash-based phosphorus sources with organic waste matrices improved the proportion of plant-available phosphorus fractions in the final products.
- The fertilizers contained high levels of amino acids, particularly glutamic and aspartic acids, which may enhance plant metabolism and tolerance to abiotic stress.
- Although higher biomass production was observed in fertilized treatments compared to the control, no statistically significant differences in yield were confirmed by ANOVA analysis.
- The proposed approach demonstrates strong potential for nutrient recovery and waste valorization within a circular economy framework.