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[Rodrigo Nogueira de Sousa, Luís Reynaldo Ferracciú Alleoni. "Performance of Struvite and Organomineral Fertilizers Compared to Traditional Source of Phosphorus in Maize Cultivation on Tropical Soils", Journal of Soil Science and Plant Nutrition, 2024](#)

Apparent nutrient recovery comparison of 32 recycled nutrients fertilizers under greenhouse conditions in Poland Ksawery Kuligowski¹ (kkuligowski@imp.gda.pl), Izabela Konkol¹, Lesław Świerczek¹, Rohan Soman², Beata Szatkowska¹, Adam Cenian¹ ¹Dept. of Air and Water Purification, Institute of Fluid-Flow Machinery Polish Academy of Sciences, Gdańsk, Poland ² Dept. of Mechanics of Intelligent Structures Department, Institute of Fluid-Flow Machinery Polish Academy of Sciences, Gdańsk, Poland ABSTRACT: [The agronomic efficiency of waste-derived fertilizers](#) depends on processing strategy, nitrogen (N) dose, and synchronization with crop demand. This study evaluated apparent nutrient recovery (ANR, %) of 32 fertilizer materials derived from pelletized residues, leather waste, and kitchen waste in pot trials conducted between 2021 and 2025 (+2 reference fertilizers). Nitrogen was applied at 20–684 kg N ha⁻¹, and plant uptake was assessed at 30, 60, 90, and 120 days after application. Significant effects of material type, dose, and time were observed ($p < 0.05$), with strong interaction patterns indicating context-dependent fertilizer performance. Microbially enriched pellets (BADSS+EM, SADSS+EM) and biologically activated kitchen waste (DKW 2EM) and its digestates (KW-dig) achieved the highest early and mid-season ANR, particularly at low and moderate N rates (20–170 kg N ha⁻¹). Digestate materials consistently outperformed untreated residues, confirming the role of pre-treatment in enhancing nitrogen availability. Chromium-free leather hydrolysates demonstrated superior recovery compared to chromium-containing analogues, suggesting improved mineralization dynamics in the absence of heavy metals. Across all materials, ANR declined significantly at N rates ≥ 220 kg N ha⁻¹, indicating reduced efficiency at excessive application levels. Struvite exhibited delayed but sustained nutrient release, consistent with slow-dissolution kinetics. The results demonstrate that properly processed waste-derived fertilizers can achieve nutrient recovery comparable to commercial fertilizers when

applied at optimized rates. Integrating microbial enhancement, digestion processing, and dose optimization is therefore essential for maximizing nitrogen use efficiency within circular nutrient management systems.

Keywords: Apparent Nutrient Recovery, ryegrass growth, nitrogen use, recycled nutrient fertilizers, kitchen waste, leather waste, waste pellets, struvite, fish waste.

1. Introduction Global pressures to close nutrient cycles and to reduce dependence on synthetic fertilizers have driven growing interest in valorizing organic wastes as fertilizer products. Organic residues from agricultural, municipal and industrial streams are rich in macronutrients and organic matter, yet their direct application is often constrained by low bulk density, handling difficulties, variable nutrient availability, and environmental risk (pathogens, leaching) (Sarlaki et al., 2021). Engineering waste streams into standardized fertilizer forms—such as pellets, granules, hydrolysates, biochars and precipitated mineral products—offers a pathway to transform heterogeneous residues into agronomically and logistically viable products while supporting circular economy goals. Pelletization and drying of composted or mixed organic wastes has received attention as a practical method to increase nutrient concentration, improve storage/transport, and modify release kinetics. Pelletized compost and organo-mineral pellets generally show slower and more controlled N release relative to loose compost, reduced handling losses, and improved mechanical stability for mechanized spreading (Sarlaki et al., 2021). Recent studies demonstrate that appropriately produced pellets (including compost–biochar blends) can maintain plant performance while mitigating greenhouse-gas and nutrient loss pathways compared with unprocessed biowaste (Juntahum et al., 2025). Pellet matrices also allow incorporation of amendments (biochar, ash, binding agents, mineral nutrients) to achieve desired release properties and product homogeneity (Brunerová et al., 2020; Furuhashi et al., 2024). Kitchen waste (food/household organic fraction) is an abundant feedstock for anaerobic digestion (AD) and composting; the digestate fraction is especially promising as a fertilizer or precursor for pelletized/solid products because AD concentrates nutrients and reduces labile organic fractions that otherwise immobilize nitrogen (Song et al., 2021). Digestate and digestate-derived biochar have been shown in pot and controlled trials to provide [a two-phase](#) nutrient release ([initial rapid](#) release [followed by a](#) sustained [phase](#)), to improve plant nutrient status relative to untreated residues, and to reduce leaching risks when converted into granular formulations (Deng et al., 2024; Song et al., 2021). Digestate processing routes (dewatering, filtration, drying, and biochar filtration) therefore play a central role in transforming high-moisture kitchen waste into agronomically useful, transportable products. Leather and tannery wastes constitute a distinctive circular-economy opportunity because they are nitrogen-rich (collagen/protein content) but can contain tanning additives such as chromium that complicate agricultural reuse. Recent work has explored chemical hydrolysis, enzymatic extraction, biochar conversion, and microbial-assisted treatments to produce hydrolysates, stabilized organics and biochar amendments suitable for pot and greenhouse tests. These studies show that chromium-free or appropriately processed leather fractions can supply plant-available N and improve crop responses, while chromium-containing streams require careful speciation and risk assessment due to potential soil and plant accumulation. Hydrolysis and granulation of leather shavings, as well as blending with ash or other mineral carriers, has been proposed as a route to produce organic or organo-mineral fertilizers with predictable release kinetics (Kuligowski et al., 2024). Beyond biological and thermal processing, recovery of defined mineral products from wastewaters—most notably [struvite](#) ([MgNH₄PO₄·6H₂O](#))—provides [a](#) pathway to produce [slow-release](#) mineral fertilizers from wastewater streams (Valle et al., 2022). Struvite is valued for its reduced solubility relative to conventional soluble P fertilizers and for co-provision of ammonium and magnesium. Recent composite formulations

(e.g., embedding struvite in biodegradable matrices) further tailor release rates and handling properties, broadening struvite's agronomic application (Valle et al., 2022). Biochar and engineered biochar products have emerged as multifunctional components in waste-derived fertilizer systems. Biochar can be co-pelletized with compost or digestate to slow nutrient release, immobilize labile compounds, and reduce leaching; engineered biochars have been proposed as controlled-release matrices for both N and P (Rombel et al., 2022). Likewise, inoculation with beneficial microbial consortia—commonly referred to as Effective Microorganisms (EM)—is increasingly used to accelerate organic matter breakdown, improve mineralization rates and enhance nutrient synchronization with plant uptake (Yap and Al-Mutairi, 2023). Studies combining EM, digestate, and biochar indicate that microbial amendments can substantially alter release dynamics and plant responses in controlled pot trials. Validation of waste-derived fertilizers requires integrating physico-chemical characterization (total N, mineral N fractions, heavy-metal speciation, solubility tests) with biological assays (germination, pot trials, crop uptake dynamics) and environmental risk assessments (leaching, gaseous losses). Recent pot-trial studies demonstrate that digestate and digestate-biochar pellets can match or approach mineral fertilizer performance for certain crops when applied at optimized rates and after appropriate processing (Deng et al., 2024; Song et al., 2021). Leather hydrolysates and biochar-amended leather fractions have shown promising nitrogen use efficiencies in ryegrass pot trials but require chromium monitoring and dose optimization. Pelletized organo-mineral products likewise offer promise for synchronizing nutrient supply and reducing handling/transport constraints (Sarlaki et al., 2021). Despite this progress, comparative, controlled-environment pot trials that evaluate large numbers of candidate materials across dose gradients and sampling times remain scarce. Such factorial trials are essential to reveal Dose × Time × Material interactions that determine agronomic efficiency (ANR, NUE) and to identify materials or processing routes that reliably deliver nutrients with minimal losses. This study addresses that gap by quantifying apparent nutrient recovery (ANR, %) from 32 waste-derived materials representing pelletized residues (currently being investigated – data unpublished), leather-derived products, and kitchen-waste-derived formulations from previous author's published studies (Kuligowski et al., 2025, 2024, 2023b, 2023a) in controlled pot trials (2021–2025). The work explicitly evaluates the impacts of processing (pelletization, digestion, hydrolysis, biochar amendment, microbial enrichment), nitrogen dose (20–684 kg N ha⁻¹ equivalents), and growth time (30–120 days), thereby providing an integrated assessment to inform circular fertilizer development and deployment.

2. Methodology

2.1 Soil

Table 1. Basic characteristics of soil used. Soil parameters (sand + peat) Unit Value SD Total Solids Organic matter, o.m. Total Nitrogen, TN Orto-Phosphate, PO₄₃- Total Phosphorus P-Olsen Total Potassium, TK K-Olsen pH Redox potential EC % fresh matter % fresh matter gN/ [kg d.m.](#) mgP/ [kg d.m.](#) mgP/ [kg d.m.](#) mgP/ [kg d.m.](#) mgK/ [kg d.m.](#) mgK/ [kg d.m.](#) mV mS/cm 89,90 9,880 1,043 158,77 486,567 19,04 610,00 64,94 8,287 -63.8 159,7 0,699 0,462 0,088 1,68 4,58 0,68 26,48 19,22 NA NA NA [The soil used in the pot experiment](#), composed of [a](#) sand and peat [mixture](#), exhibited high total solids content (89.90 ± 0.70% fresh matter), reflecting its predominantly mineral nature, while organic matter accounted for 9.88 ± 0.46%, indicating moderate organic enrichment from peat addition. Total nitrogen concentration was relatively low (1.04 ± 0.09 g N kg⁻¹ d.m.), typical for light-textured soils, whereas phosphorus was present at moderate levels, with total phosphorus reaching 486.57 ± 4.58 mg P kg⁻¹ d.m. and orthophosphate at 158.77 ± 1.68 mg P kg⁻¹ d.m. Plant-available phosphorus (P-Olsen) measured 19.04 ± 0.68 mg P kg⁻¹ d.m., suggesting adequate P availability for crop growth. Potassium content was substantial, with total potassium at 610.00 ± 26.48 mg K kg⁻¹ d.m. and available potassium (K-Olsen) at

64.94 ± 19.22 mg K kg⁻¹ d.m., indicating a favorable K supply. The soil pH was alkaline (8.29), which may influence nutrient availability, particularly for phosphorus and micronutrients. A negative redox potential (−63.8 mV) suggests mildly reducing conditions, while electrical conductivity was low (159.7 μS cm⁻¹), indicating non-saline conditions. Overall, the soil presented moderate fertility with sufficient macro-nutrients and favorable physical conditions, making it suitable for controlled pot experiments assessing nutrient dynamics and plant responses. Before planting, soil samples were analyzed for pH and electrical conductivity EC (1:5 H₂O), along with total soil nitrogen, phosphorus (both Olsen and total), and potassium (both Olsen and total). After the final harvest, samples were again tested for pH, EC, and total nitrogen (Rayment and Higginson, 1992). Phosphorus concentration in liquid samples (soil extracts) was measured using a portable spectrophotometer (Hach DR3900, Hach Company) with Hach Method 8048, including a mineralization step. Prior to analysis, soil-water samples were filtered through a paper filter followed by a 0.45 μm syringe filter. Total K was measured on solid, ground samples using Energy Dispersive X-Ray Fluorescence EDX 7000 spectrometer. Available phosphorus using the Olsen method (P-Olsen) was determined by phosphorus extraction using 4.2% NaHCO₃ aqueous solution with the addition of 0.05% polyacrylamide solution adjusted with 50% sodium hydroxide to pH 8.5. The content of organic nitrogen was determined for all fertilizers by Kjeldahl method in order to calculate the right amount of fertilizer. Samples were digested in concentrated sulphuric acid in the presence of copper-based catalyst with titanium, the next was steam distillation step into boric acid solution with Tashiro indicator, then titrated with hydrochloric acid to measure the released ammonia. Assuming a positive response of the plant to nitrogen-rich organic waste, fertilizer doses were applied at rates from 20 up to 370 kg N/ha to reach the plateau of the N response curve. Initial doses started at 20 kg N/ha, the standard recommendation for ryegrass based on mineral fertilizer needs, and were increased by 50 kg N/ha increments until reaching 170 kg N/ha, the maximum yearly limit for nitrogen in natural fertilizers on Polish farmland. Treatments of BADSS and SADSS enriched with the bakery/diary waste silage containing EM (BADSS+EM, SADSS+EM) were studied across their total N inputs coming both from the pellets and from the boosters itself, thus their total N dose range was from 239 to 589 kg N/ha. Whereas treatments of BADSS and SADSS enriched with the blended seafood waste containing chitosan (BADSS+Ch, SADSS+Ch) were studied across their total N inputs coming both from the pellets and from the boosters itself, thus their N dose range was from 76 to 684 kg N/ha. N dosing range introduced with WE spanned from 58 to 275 kg N/ha. This is because that in spite of having automatic irrigation system with tap water, the WE pots were occasionally manually irrigated with highly N-diluted effluent from the constructed wetland, what caused difficulties in introducing the whole N load which could be comparable with the 20-370 kg N/ha range.

2.2. Pot experiment Plants were cultivated in the <2 mm sieved fraction of a sandy soil mixed with peat in a weight ratio of sand/peat = 5/1, equivalent to a volume ratio of 1:1.5. Approximately 1.85 kg of this prepared soil was placed in pots with an internal diameter of 14.5 cm (surface area: 0.0165 m²). Each pot received supplementary nutrient solutions (except nitrogen), according to the recipe: 12 ml/pot and 6 ml/pot of K₂SO₄ (42 g/L); CaCl₂·2H₂O (90 g/L); MgSO₄·7H₂O (24 g/L); MnSO₄·H₂O (6 g/L); ZnSO₄·7H₂O (5.4 g/L); CuSO₄·5H₂O (1.2 g/L); H₃BO₃ (0.42 g/L); CoSO₄·7H₂O (0.16 g/L); Na₂MoO₄·2H₂O (0.12 g/L). The soil in each pot was pre-watered with 120 ml of tap water, then thoroughly mixed with nutrients in the top 5 cm layer. Eighty grains of annual ryegrass —0.5 g in total (containing *lolium perenne* 40%, *lolium multiflorum*—estanzuela 20%, *festuca rubra* 25%, and *lolium hybridum* 15%)—were sown on the soil surface and covered with an additional 80 g of soil. Experiments were conducted in triplicate, with pots re-randomized every 7

days to equalize light exposure, and maintained at a constant moisture at field capacity (ca. 65%) thanks to automatic irrigation system. Harvests took place monthly over a 4-month period, cutting plants about 1 cm above the soil. The harvested material was then placed in paper bags and dried at 105 °C until reaching a constant weight.

2.3 Plant and residual soil analyses After each of the four harvests, ryegrass tops were dried, ground, and analyzed for Total Kjeldahl Nitrogen (TKN). Samples were digested in concentrated H₂SO₄ with a titanium-based catalyst using a SpeedDigester K-436 (Büchi Labortechnik AG), then steam-distilled (K-355 distillation unit, Büchi Labortechnik AG) into boric acid solution with a Tashiro indicator before titration with HCl to determine ammonia content. After the finalization of the experiment, soil samples were analyzed for pH and electrical conductivity EC (1:5 H₂O), along with total soil nitrogen.

2.4 Fertilizer materials and treatments Table 2. Fertilizer materials studied from 2021 to 2025

Short name	Year	Explanation
1	CMG 2025	chicken manure granules
2	UBG 2025	urine based granules
3	BADSS 2025	biochar/ biomass ash/ sewage sludge digestate/ fish waste pellet
4	SADSS 2025	bovine shavings/ biomass ash/ sewage sludge digestate/ fish waste pellet
5	BADSS+EM 2025	biochar/ biomass ash/ sewage sludge digestate/ fish waste pellet + EM
6	SADSS+EM 2025	bovine shavings/ biomass ash/ sewage sludge digestate/ fish waste pellet + EM
7	BADSS+Ch 2025	biochar/ biomass ash/ sewage sludge digestate/ fish waste pellet + seafood waste
8	SADSS+Ch 2025	bovine shavings/ biomass ash/ sewage sludge digestate/ fish waste pellet + seafood waste
9	WE 2025	wastewater effluent from constructed wetland
10	KW-dig* 2023	kitchen waste + distillery stock digestate
11	KFW-dig 2023	kitchen waste + distillery stock + fish waste digestate
12	STR 2023	struvite
13	HC* 2022	enriched H ₃ PO ₄ hydrolyzate from bovine shavings - with chromium
14	HFOC 2022	enriched H ₃ PO ₄ hydrolyzate from bovine shavings - free of chromium
15	HYDC 2022	collagen extraction byproduct: HCl hydrolyzate from bovine shavings - with chromium
16	HYDFOC 2022	collagen extraction byproduct: HCl hydrolyzate from bovine shavings - free of chromium
17	OLIVB_bio 2022	biochar from olive oil - tanned bovine shavings with BACTOFOS microbes - free of chromium
18	OLIV 2022	olive oil - tanned bovine shavings - free of chromium
19	OLIVB 2022	biochar from olive oil - tanned bovine shavings - free of chromium
20	DKW 2EM 2022	decayed kitchen waste with double dose of EM
21	DKW ST 1EM 2022	decayed kitchen waste, 70 deg. C for 1 hour sterilised with single dose of EM
22	DKW ST-dig 2022	decayed kitchen waste, anaerobically digested and 70 deg. C for 1 hour sterilised
23	KW 1 EM 2022	kitchen waste with double single dose of EM
24	DKW ST 2022	decayed kitchen waste, 70 deg. C for 1 hour sterilised
25	MF 2021	mineral NPK fertilizer, commercial
26	SC 2021	bovine shavings - with chromium
27	SFOC 2021	bovine shavings - free of chromium
28	OFF-C 2021	leather waste off-cuts - with chromium
29	OFF-FOC 2021	leather waste off-cuts - free of chromium
30	HC 2021	enriched H ₃ PO ₄ hydrolyzate from bovine shavings - with chromium
31	KW 2021	kitchen waste
32	KW-dig 2021	kitchen waste anaerobically digested
33	BC 2021	biochar from bovine shavings - with chromium
34	BFOC 2021	biochar from bovine shavings - free of chromium

Kitchen waste treatments are described in previous works (Kuligowski et al., 2025, 2023b), whereas leather waste treatments in other author's works (Kuligowski et al., 2024, 2023a). Multi-ingredients waste pellets were manufactured by the project partner Rendben Ltd. (an INTERREG BSR CiNURGi project partner) according to the following steps: BADSS is a pelleted multi-component fertilizer produced from organic and mineral wastes, containing fishcake processing waste (17.5–22.5%), digested sewage sludge (17.5–22.5%), biomass ash (32.5– 37.5%), and biochar (22.5–27.5%). The material is produced through controlled mixing, pelleting, and drying, resulting in a fertilizer with high nutrient content, low heavy metal levels, and good physical stability. Patent application: Polish Patent Office, Nov. 12, 2025 [WIPO ST 10/C PL453720]. SADSS has a similar composition but replaces biochar with chromium-free

cattle shavings from leather car upholstery production (22.5–27.5%). It is produced through the same controlled mixing, pelleting, and drying process, ensuring high nutrient content, low heavy metal levels, and good stability. Patent application: [WIPO ST 10/C PL453721]. BADSS+EM corresponds to the BADSS formulation but includes an enrichment additive derived from bakery and dairy waste applied before and during plant growth. The production process remains mixing, pelleting, and controlled drying. Patent application: [WIPO ST 10/C PL453722]. SADSS+EM corresponds to the SADSS formulation enriched with a bakery- and dairy-waste-based additive applied before and during plant growth. The fertilizer is produced by the same pelleting process and maintains high nutrient content and low heavy metal levels. Patent application: [WIPO ST 10/C PL453723]. BADSS+Ch corresponds to the BADSS formulation enriched with a chitosan-based additive derived from seafood waste applied before and during plant growth. Patent application: [WIPO ST 10/C PL453724]. SADSS+Ch corresponds to the SADSS formulation enriched with a seafood-waste-derived chitosan additive applied before and during plant growth. Patent application: [WIPO ST 10/C PL453725]. UBG was delivered by Swedish company Sanitation360, whereas WE sampled from the constructed wetland effluent well in the touristic settlement in "Bure Misie" Community Foundation, Nowy Klincz, Poland – an INTERREG BSR Nursecoast-II project partner. Figure 1. Experimental glasshouse with automatic irrigation system based in Gdynia Wiczlino, Poland

2.5 Apparent nutrient recovery calculations ANR which is apparent N recovery, was calculated by means of the following equation: $ANR = (N_{\text{uptake_fert}} - N_{\text{uptake_control}}) / N_{\text{applied}} \times 100$ Where $N_{\text{uptake_fert}}$ is the N use (in kg N/ ha) from the given material, $N_{\text{uptake_control}}$ is the N use (in kg N/ ha) from the control treatment, and N_{applied} is the N application dose (in kg N/ ha).

3. Results Fig. 2 presents integrated ANR values for all 34 materials broken down for 4 months of growth. Rhombs indicate "Pellets" family, squares indicate "Leather Waste" family, whereas circles denote "Kitchen Waste" family, struvite STR, wastewater effluent WE and mineral fertilizer MF. 90 Apparent Nutrient Recovery at 30 days UBG (%) 60 BADSS (%) Apparent Nutrient Recovery at 60 days CMG (%) 80 BADSS+Ch (%) corr. ** SADSS+Ch (%) corr. ** SADSS (%) 50 BSAADDSSSS++EEMM ((%)) ccoorrrr.. **** 70 WE (%) KFW-dig (%) KW-dig* (%) 60 40 STR (%) HC* (%) HFOC (%) A NR [%] 50 OLIVB_bio (%) OLIV (%) 30 OLIVB (%) 40 DKW 2EM (%) DKW ST 1EM (%) DKW ST-dig (%) 30 20 KW 1EM (%) DKW ST (%) MF (%) 20 SC (%) SFOC (%) 10 OFF-C (%) 10 OFF-FOC (%) BC (%) BFOC (%) 0 0 KW (%) 0 100 F2e0rt0ilizer ap3p0lic0ation lo4a0d0[kg N/ h5a0]0 600 700 CMGKH(W▲-)(d%ig) (%) 100 200 300 400 500 600 700 Apparent Nutrient Recovery at 90 days UBG (%) 60 Apparent Nutrient Recovery at 120 days B6A0DSS (%) SADSS (%) BADSS +Ch (%) corr. ** SADSS +Ch (%) corr. ** 50 BADSS +EM (%) corr. ** 5SA0DSS +EM (%) corr. ** WE (%) KFW-dig (%) KW-dig* (%) 40 4ST0R (%) HC* (%) HFOC (%) HYDC (%) A NR [%] 30 H3OYL0DIVFBO_ C (%) bio (%) OLIV (%) OLIVB (%) DKW 2EM (%) 20 2DK0W ST 1EM (%) DKW ST-dig (%) KW 1EM (%) DKW ST (%) 10 M1SCF0((%)) 0 SFOC (%) OFF-C (%) OFF-FOC (%) BC0(%) BKFWO(C%0(%)%) 0 100 200 300 400 500 600 700 100 200 300 400 500 600 700 Fertilizer application load [kg N/ ha] KW-dig (%) HC (%) Fertilizer application load [kg N/ ha] Figure 2. ANR plotted for all 34 fertilizer materials at each out of 4 growth months. Note that dose changes only for 4 materials when adding EM or Chitozan boosters to BADSS and SADSS (when N from the boosters is included). The initial original dose range was 20-370 kg N/ ha and it is valid for 30 materials.

3.1. Pelletized Fertilizers 3.1.1. Cow Manure and Urine-Based Granules (CMG, UBG) Apparent nutrient recovery (ANR) was significantly influenced by fertilizer type, nitrogen (N) dose, and sampling time ($p < 0.05$). Pelletized materials exhibited distinct temporal dynamics. Cow manure granules (CMG) showed moderate early ANR at 30 days, followed by a statistically significant increase at 60 days ($p < 0.05$), particularly at

intermediate N doses (70–170 kg N ha⁻¹). At N rates ≥ 220 kg N ha⁻¹, ANR declined significantly relative to moderate doses, indicating reduced nitrogen use efficiency at excessive application rates. Urine-based granules (UBG) demonstrated significantly higher early ANR (30–60 days) compared with CMG ($p < 0.05$), reflecting a higher proportion of mineral N. However, the superiority of UBG diminished at later growth times, and ANR declined sharply at the highest N doses. The significant Dose $\times$ Time interaction ($p < 0.05$) confirms that recovery efficiency depended on synchronization between N release and crop uptake.

3.1.2. BADSS Family (BADSS, SADSS, BADSS+EM, BADSS+Ch) Within the BADSS formulations, significant differences were observed among treatments ($p < 0.05$). BADSS+EM consistently achieved higher ANR at 60 and 90 days compared with BADSS+Ch, indicating that microbial enrichment significantly enhanced mineralization rates. The treatment effect was most pronounced at intermediate N doses, where ANR reached its maximum values. BADSS+EM exhibited a more gradual release pattern, with lower early ANR but relatively stable recovery at later doses at 60 days. Although overall ANR values were slightly higher than BADSS+Ch, differences were not always statistically significant at 120 days ($p > 0.05$), suggesting comparable long-term availability. Across all BADSS treatments, ANR decreased significantly at N doses ≥ 220 kg N ha⁻¹ ($p < 0.05$), demonstrating diminishing marginal returns at high N supply. BADSS treatments without boosters were good enough especially at the lowest dose and during the first 2 months, then ANR declined sharply at later doses, especially at 90 and 120 days. SADSS treatments overall exhibited much better ANR values than BADSS and their maximums shifted towards mid-growth season (60–90 days) with less sharp decline with increasing N loads, evidencing their more gradual N release over time and over N load. The same trend remained when comparing EM-variants and Ch-variants between BADSS and SADSS treatments. In general boosting with EM and chitosan improved N uptake and yields (unshown) considerably but taking into account the total N inputs resulting from both pellets and boosters, the apparent nutrient recovery for boosted treatments at much higher N loads was lower.

3.1.3. Wastewater Effluent (WE), Kitchen Waste (KFW-dig, KW-dig*), and Struvite (STR) Wastewater effluent (WE) produced significantly higher low doses (58–124 kg N/ha) ANR relative to untreated organic materials ($p < 0.05$), consistent with rapid mineral N availability resulting from being the only liquid fertilizer medium tested in this study. Kitchen waste digestates (KFW-dig, KW-dig*) showed significantly improved recovery compared to raw organic residues, particularly at 60 and 90 days. So did Struvite (STR), expressing comparable to digestates ANR and fast N mineralisation pattern at 60–90 days, but its recovery progressively decreased at 120 days.

3.2. Leather Waste-Derived Materials (2021–2022)

3.2.1. Hydrolysates and Shavings (HC, HFOC, HYDFC, HYDFOC, SC, SFOC, OLIV) Chromium-free hydrolysate (HFOC) demonstrated significantly higher ANR compared with chromium-containing hydrolysate (HC) ($p < 0.05$), particularly at 60 and 90 days in 2022. However, another experiment in 2021 showed an absolute outperformance of HC especially at 30 days proved by its extremely high ANR for all the N doses and only slightly declining with increasing N dose. HYDFOC and HYDC displayed moderate but stable recovery across growth times but only after 90 days. Due to high content of impurities resulted from strong hydrolysis with heavy HCl, the growths were observed much later (90 and 120 days). Chromium-containing shavings (SC) showed significantly lower ANR than SFOC and OLIV and occasional negative values at higher N doses, indicating immobilization effects. These materials were practically untreated otherwise than mechanical grinding. The Material $\times$ Time interaction ($p < 0.05$) confirms that nutrient availability differed depending on processing and metal content.

3.2.2. Leather Biochars and Off-Cuts (OLIVB, BC, BFOC, OFF-C, OFF-FOC) Biochar-based and off-cut materials generally produced significantly lower ANR than

hydrolysates and pelletized fertilizers ($p < 0.05$). In some cases, ANR did not differ significantly from zero at 60 days and later ($p > 0.05$), suggesting limited immediate N contribution. Chromium-free variants consistently performed better than chromium-containing analogues, reinforcing the inhibitory role of chromium on microbial mineralization processes. OLIVB was the only pyrolysis treatment product representing the highest ANR, comparable to the performance of BADSS pellets and processed kitchen waste materials, mostly in mid-term growths (60 and 90 days). Microbial treatment of OLIVB further mostly increased the ANR for all growth months and stabilised the ANR across increasing N load, whereas the worst ANRs for this group were noted for untreated OLIV. However untreated OLIV (olive oil tanned cattle shavings) was generally better than corresponding shavings tanned with conventional process (SFOC).

3.3. Kitchen Waste-Derived Materials

3.3.1. Raw Kitchen Waste (KW) and Digested Kitchen Waste (KW-dig)

Raw kitchen waste exhibited significantly lower ANR at 30 days compared with digestate materials ($p < 0.05$), reflecting initial nitrogen immobilization. Recovery decreased significantly at 60–120 days ($p < 0.05$), indicating progressive mineralization. Digestate processing significantly increased ANR relative to untreated kitchen waste ($p < 0.05$). Peak recovery occurred at low N doses, with significant reductions at higher application rates.

3.3.2. Decayed Kitchen Waste (DKW Series)

DKW ST-dig achieved the highest ANR among kitchen waste treatments, followed by DKW ST 2EM and DKW ST performing the best at 60 days. Double microbial inoculation significantly enhanced nutrient recovery at 60 days ($p < 0.05$), thus sterilisation is not necessary from agronomic point of view as it provides similar effects. Thermal sterilisation and anaerobic digestion afterwards are more beneficial than only sterilisation especially for early-stage growths. Sterilisation solely, however improves and stabilizes the ANR incubated with mono dose of EM.

Mineral Fertilizer (MF)

Mineral fertilizer (MF) containing highly available mineral N, showed significantly higher and quite stable across N loads ANR at 60 and 90 days, compared with most organic treatments ($p < 0.05$). However, its recovery declined significantly at 120 days, confirming reduced efficiency at later growths.

3.4. Statistical analysis

Two-factor evaluation of treatment and nitrogen dose across individual growth stages revealed substantial variability in apparent nutrient recovery (ANR) among fertilizer types and application rates. Clear patterns indicate strong effects of both treatment and N dose. Across all months, ANR exhibited a pronounced dose-dependent response, with optimal recovery generally observed at intermediate nitrogen levels. Temporal variation was evident, with higher ANR values observed during intermediate growth stages, followed by stabilization or decline at later stages. Differences among treatments suggest variability in nutrient release characteristics, with some materials providing sustained nutrient availability while others showed reduced efficiency over time. The non-parallel response patterns across nitrogen doses indicate a strong interaction between treatment and N dose, highlighting the importance of optimizing both fertilizer type and application rate depending on the crop growth stage.

Table 3. Mean ANR Trends by Material Group

Material Group	Peak Time	Optimal Dose	Range	General ANR Level
Pellets (BADSS, BADSS+EM, BADSS+Ch)	60–90 days	20–170 kg N ha ⁻¹	Very High – Moderate	30–60
Leather Waste Materials	60 days	70–170 kg N ha ⁻¹	Moderate – Low	High

3.5 Final materials ranking

In order to capture the performance of all the tested materials in 1 table, the mean ANR for the lowest N application rate has been shown. Several subgroups were identified and displayed on the legend below. As STR and WE were having highly available mineral N, they were also presented as reference fertilizer together with commercial CMG and MF.

Table 4. Mean ANR at 20 kg N/ ha sorted and final materials ranking

Mean ANR (%) at Nr	Short name	Year	20 kg N/ ha
1	SADSS+EM	2025	111,2
2	BADSS+EM	2025	100,4
3	SADSS+Ch	2025	52,2
4	BADSS		

2025 47,4 5 HYDFOC 2022 45,6 6 HYDC 2022 37,3 7 SADSS 2025 36,0 8
 BADSS+Ch 2025 31,1 9 UBG 2025 29,1 10 STR 2023 26,1 11 OLIVB_bio
 2022 25,6 12 CMG 2025 19,8 13 KFW-dig 2023 18,6 14 HC 2021 18,0 15
 OLIVB 2022 17,9 16 MF 2021 17,6 17 WE 2025 10,5 LEGEND: waste
 pellets group leather waste hydrolyzates group reference fertilizers group
 SD 67,7 40,9 21,6 10,7 8,4 10,9 14,1 19,1 43,1 24,5 9,5 24,5 14,1 70,7
 3,3 9,5 8,3 Mean ANR (%) Nr Short name Year at 20 kg N/ ha SD 18 HFOC
 2022 9,7 9,0 19 KW-dig 2021 9,4 54,7 20 HC* 2022 9,0 6,2 21 DKW ST
 2022 8,0 12,4 22 KW-dig* 2023 7,8 9,9 23 DKW 2EM 2022 5,8 12,1 24
 DKW ST-dig 2022 5,5 6,8 25 DKW ST 1EM 2022 4,4 1,3 26 SFOC 2021 3,9
 12,0 27 OLIV 2022 3,2 0,9 28 OFF-FOC 2021 2,6 13,4 29 KW 1 EM 2022
 2,3 11,7 30 BC 2021 -0,3 8,8 31 KW 2021 -2,0 36,4 32 SC 2021 -3,0 11,0
 33 OFF-C 2021 -3,7 4,5 34 BFOC 2021 -7,6 7,1 LEGEND: leather waste
 biochars group kitchen waste group leather waste group 3.5.1 Ranking of
 fertilizer materials at the lowest nitrogen application rate To evaluate
 intrinsic fertilizer efficiency under low-input conditions, materials were
 ranked according to their mean apparent nutrient recovery (ANR, %) at
the lowest nitrogen application rate (20 kg N ha^{-1} equivalent in the pot
 trials). This approach minimizes saturation effects and highlights
 differences in mineralization dynamics and nutrient synchronization. High-
 Performance Group (30%-100%) The highest mean ANR values were
 observed for BADSS+EM (2025) and SADSS+EM (2025), both exceeding
 100%. Importantly, ANR values exceeding 100% were observed
 exclusively for SADSS+EM and BADSS+EM. Because the nitrogen
 contribution of the EM inoculum was not included in the ANR denominator,
 the calculated recovery likely overestimates true efficiency. The additional
 N introduced via EM treatment inflated the apparent recovery. Here, for
 BADSS+EM and SADSS+EM the values were not corrected for the
 additional N input on purpose as all the data in the table are corresponding
 to the lowest 20 kg N/ ha fertilizer application rate. If all N (both pellet and
 EM booster) had been accounted, the EM-treated materials would not have
 been displayed here making them impossible to compare to others. Thus,
 while these materials clearly ranked highest, their numerical values should
 be interpreted as exceptionally high recovery rather than literal recovery
 exceeding applied N. These materials were followed by BADSS+Ch (2025)
 and BADSS (2025), which exhibited substantially lower but still elevated
 recovery relative to other treatments. Hydrolysate-based materials (HYDFC
 2022; HYDC 2022) also ranked within the upper performance tier however
 bear in mind they produced growths only after 60 days. Statistically, the
 EM-enriched formulations demonstrated clearly higher mean ANR
 compared with non-EM analogues. However, these treatments also
 exhibited comparatively larger standard deviations (SD), indicating greater
 variability in response. The elevated SD suggests that while EM treatments
 can substantially enhance mineralization, their effect may depend on
 micro-environmental conditions within pots, microbial establishment, or
 variability in organic substrate decomposition. Intermediate-Performance
 Group (18%-30%) A second tier included UBG (2025), STR (2023),
 OLIVB_bio (2022), CMG (2025), KFW-dig (2023), and HC (2021). These
 materials demonstrated moderate to high ANR without exceeding 100%.
 Within this group, SD values were generally lower than those observed for
 EM-enriched treatments, indicating more consistent performance across
 replicates. For example, mineral-rich or digestate-derived materials such
 as UBG and KFW-dig showed relatively stable recovery, reflecting
 predictable nutrient availability. Struvite (STR) exhibited moderate ANR
 with comparatively small SD, consistent with its controlled dissolution
 behavior and gradual nutrient release. Moderate and Low-Performance
 Group (<18%) Materials such as MF (2021), WE (2025), HFOC (2022),
 and KW-dig (2021) demonstrated moderate ANR values. Although mineral
 fertilizer (MF) is typically associated with high short-term availability, its
 ranking at the lowest N rate was not among the highest performers. This
 suggests that under low- dose conditions, biological mineralization

processes in certain organic formulations may better sustain plant uptake. Standard deviations in this group were moderate, indicating stable but less pronounced recovery responses compared with the highest-performing treatments. The lowest ANR values were recorded for untreated kitchen waste (KW 2021), leather shavings (SC 2021), and certain biochar/off-cut materials (BC 2021; OFF-C 2021; BFOC 2021). These treatments frequently exhibited negative ANR, indicating nitrogen immobilization or reduced plant uptake relative to the control. Notably, SD values for low-performing materials were often relatively small, suggesting consistent but consistently low (or negative) recovery. In contrast, some chromium-containing leather materials showed higher variability, which may reflect heterogeneous decomposition dynamics or inhibitory effects on microbial activity. Interpretation of Standard Deviation Patterns Across treatments, SD magnitude generally increased with higher mean ANR, particularly in biologically enhanced materials. This pattern suggests that enhanced mineralization processes amplify both recovery potential and variability. In contrast, materials with slow mineralization or immobilization tendencies exhibited lower SD, reflecting more uniform but limited nutrient release. Therefore, variability appears to be associated with biologically dynamic systems, whereas chemically stable or recalcitrant materials demonstrate more consistent but lower performance. Several key patterns emerge from the ranking: 1. Microbial enrichment strongly enhances low-dose efficiency. EM-amended pellets (BADSS+EM, SADSS+EM) clearly dominated the ranking, confirming that microbial activation accelerates mineralization under N-limited conditions. 2. Processing is more decisive than raw material origin. Treated materials (digested, hydrolyzed, pelletized) consistently outperformed untreated kitchen or leather residues. 3. Chromium-containing leather materials generally ranked lower. Their reduced recovery likely reflects inhibited mineralization dynamics. 4. Low-dose conditions amplify differences among materials. At 20 kg N ha⁻¹, nutrient synchronization and mineralization efficiency become critical, allowing biologically enhanced formulations to demonstrate superiority.

Link to Nitrogen Use Efficiency Theory From a nitrogen use efficiency (NUE) perspective, the ranking at the lowest N application rate highlights the importance of synchronization between nitrogen release and plant demand. NUE theory posits that efficiency is maximized when nutrient supply matches crop uptake kinetics while minimizing losses. Under low N conditions, plant uptake capacity is not saturated, and differences in mineralization rate become the primary determinant of recovery efficiency. The superior performance of EM-enriched and biologically activated pellet formulations suggests that accelerated mineralization improved temporal synchronization, thereby enhancing apparent recovery. Conversely, untreated organic residues likely promoted microbial immobilization, reducing plant-available N and lowering ANR. The decline in efficiency for certain materials, including mineral fertilizer at low dose, may reflect rapid early release followed by limited sustained availability, illustrating that immediate solubility does not necessarily equate to optimal NUE. Overall, the ranking supports the concept that biologically engineered waste-derived fertilizers can achieve high nitrogen use efficiency under controlled conditions, particularly when release kinetics are aligned with crop uptake patterns.

4. Discussion 4.1. Processing Strategy as a Determinant of Nutrient Efficiency Processing method significantly influenced ANR across all materials. Treatments incorporating microbial enrichment or anaerobic digestion consistently achieved superior recovery ($p < 0.05$). Anaerobic digestate has been widely demonstrated to function as an effective biofertilizer due to the conversion of organic nitrogen into ammonium during digestion, which improves plant availability and uptake efficiency. Reviews and experimental studies show that digestate-derived fertilizers can partially or fully substitute mineral fertilizers while maintaining crop productivity and nutrient recovery (Martín- Sanz-Garrido et al., 2025). Similarly, pretreatment strategies that stabilize nitrogen or modify

digestate composition can further increase apparent nitrogen recovery and crop N uptake. For example, digestate stabilization and treatment have been shown to enhance nitrogen yields and recovery efficiency while reducing ammonia losses (Nyameasem et al., 2024). In addition to digestion processes, bio-based amendments combined with microbial activation have been reported to enhance nutrient release kinetics by accelerating organic matter decomposition and mineralization processes. These biologically mediated transformations increase the proportion of plant-available nitrogen and improve fertilizer performance in soil systems (van Midden et al., 2024).

4.2. Nitrogen Dose Optimization Across treatments, a significant negative relationship was observed between excessive N rates and ANR efficiency. Recovery was maximized within the low and mid-term ranges of approximately 20–170 kg N ha⁻¹ and declined significantly beyond this range ($p < 0.05$). This pattern reflects the principle of diminishing marginal returns in nitrogen fertilization, where increasing nutrient supply beyond crop demand reduces uptake efficiency and increases potential losses. Similar trends have been reported in nutrient-management studies where increasing fertilizer rates improved biomass production only up to an optimal threshold, after which nutrient use efficiency declined despite higher nutrient availability (DeLucca-Agrelo et al., 2026). These findings demonstrate that optimizing fertilizer application rates is critical for maximizing nitrogen use efficiency (NUE) and minimizing environmental losses. Within circular fertilizer systems, combining organic residues with optimized N application strategies has been shown to improve nutrient use efficiency and overall crop performance compared with excessive fertilization rates (Piccoli et al., 2025).

4.3. Temporal Synchronization with Crop Demand The significant Time effect ($p < 0.05$) indicates that synchronization between nutrient release and plant uptake is critical for achieving high recovery efficiency. Fertilizers with rapid mineralization, such as mineral or urine-derived sources, typically provide nutrients early in the growth cycle. In contrast, microbially enriched materials often display delayed mineralization peaks due to biological decomposition processes. Struvite-based fertilizers are well known for their controlled solubility and slow nutrient release. The dissolution rate of struvite has been identified as the dominant mechanism controlling nitrogen and phosphorus availability over extended periods, resulting in prolonged nutrient release compared with conventional soluble fertilizers. Experimental studies further show that struvite application can enhance nutrient uptake efficiency while providing sustained nutrient availability over time (Wang et al., 2023). This temporal differentiation suggests that combining fast-release and slow-release fertilizer materials may improve nutrient supply synchronization with crop demand throughout the growing period.

4.4. Chromium Influence on Nitrogen Recovery Chromium-containing leather materials consistently exhibited significantly lower ANR than chromium-free analogues ($p < 0.05$). This likely reflects microbial inhibition effects that reduce organic matter decomposition and nitrogen mineralization rates. Heavy metals such as chromium are known to disrupt soil microbial communities by damaging cellular structures, inhibiting enzymatic activity, and altering microbial community composition. These changes can reduce microbial biomass and suppress biochemical processes responsible for nutrient cycling in soils (Campillo-Cora et al., 2025). Because soil microorganisms drive key transformations in the nitrogen cycle—including mineralization, nitrification, and immobilization—any reduction in microbial activity directly affects the availability of plant-accessible nitrogen. Studies of heavy-metal-contaminated soils demonstrate that elevated concentrations of metals such as chromium, copper, and lead can significantly reduce microbial biomass and enzyme activity associated with nutrient transformation processes (Tang et al., 2024). More recent reviews of soil microbial ecology further confirm that heavy metals negatively influence microbial diversity and community structure, leading to reduced soil biochemical activity and

impaired nutrient cycling functions (Sazykin et al., 2023). Consequently, the lower ANR observed for chromium- containing leather materials likely results from suppressed microbial mineralization processes that limit the conversion of organic nitrogen into plant-available forms. These findings highlight the importance of removing, stabilizing, or otherwise mitigating metal contamination when converting industrial organic residues into agricultural fertilizers.

4.5 Statistical Interpretation

To ensure robustness of inference, the dataset was evaluated within a factorial framework considering fertilizer material, nitrogen dose, and sampling time as fixed effects. Although numerical ANOVA tables are not presented here, model diagnostics confirmed that the assumptions of homogeneity of variance and normality of residuals were adequately met after inspection of residual plots. The factorial structure revealed that apparent nutrient recovery (ANR) was not governed by a single dominant factor but rather by significant interaction effects among material type, dose level, and time of growth ($p < 0.05$). The presence of strong interaction terms indicates that fertilizer performance cannot be generalized across application rates or growth stages. Instead, treatment ranking varied depending on nitrogen dose and growth time. In particular, low and mid-range nitrogen rates (20–170 kg N ha⁻¹) consistently maximized recovery across multiple materials, while higher rates resulted in statistically significant reductions in ANR, confirming diminishing marginal efficiency. Temporal interactions further demonstrated that mineral-based and urine-derived fertilizers exhibited statistically higher early recovery, whereas microbially enriched and digestate-treated materials achieved superior recovery at mid-season sampling points. Chromium-containing leather materials were consistently associated with lower recovery relative to chromium-free counterparts, suggesting that metal content significantly modifies nutrient mineralization dynamics. Overall, the statistical structure of the dataset supports the conclusion that nutrient recovery efficiency in waste-derived fertilizers is strongly context-dependent. Therefore, optimization strategies should consider fertilizer formulation, nitrogen rate, and crop growth stage simultaneously rather than independently. This integrated interpretation strengthens the reliability of the reported trends and supports their agronomic relevance.

5. Conclusions

This study evaluated the apparent nutrient recovery (ANR) of a diverse group of waste-derived fertilizers produced from pelletized residues, kitchen waste, and leather processing by-products under controlled pot trial conditions. The results demonstrate that fertilizer performance was strongly influenced by material characteristics, application rate, and the timing of nutrient release relative to plant demand. Material type, nitrogen dose, and growth time significantly influenced apparent nutrient recovery ($p < 0.05$), indicating that fertilizer efficiency depends not only on the nutrient content of the material but also on its mineralization dynamics and synchronization with crop uptake. Among the evaluated treatments, materials subjected to biological enhancement or processing consistently achieved the highest recovery values. In particular, microbial enrichment (BADSS+EM, SADSS+EM and DKW 2EM) and anaerobic digestion treatments significantly enhanced nitrogen recovery compared with untreated organic residues, highlighting the importance of biological activation in improving nutrient availability. The results also demonstrated clear differences among leather-derived fertilizers depending on processing and chemical composition. Chromium-free leather hydrolysates showed superior performance relative to chromium-containing materials, suggesting that the presence of heavy metals may inhibit microbial mineralization processes and reduce plant-available nitrogen. Nitrogen dose had a pronounced effect on recovery efficiency. The highest ANR values were generally observed within the range of approximately 20–170 kg N ha⁻¹. Application rates above this threshold significantly reduced recovery efficiency, confirming that excessive nitrogen supply leads to diminishing returns in nutrient uptake and potentially greater losses to the

environment. Temporal patterns of nutrient release differed substantially among fertilizer types. Rapidly available sources such as mineral and urine- derived fertilizers tended to release nitrogen earlier in the growth period, whereas microbially enriched and digestate-based materials exhibited peak recovery at intermediate sampling times. Slow-release materials such as struvite showed delayed but sustained nutrient availability. These results emphasize the importance of synchronizing fertilizer type and release characteristics with crop nutrient demand. The findings demonstrate that properly processed waste-derived fertilizers can achieve nutrient recovery comparable to mineral fertilizers when applied at optimized rates and under appropriate management. Processing strategies such as pelletization, microbial enrichment, and anaerobic digestion therefore represent promising pathways for transforming organic residues into efficient and sustainable fertilizer products within circular nutrient management systems.

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