

Multi-criteria screening and prioritisation of nutrient recovery and bio-based fertiliser technologies from secondary raw materials

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Nutrient recovery from secondary raw materials has become a central pillar in the transition towards a circular economy, particularly in the context of European agriculture, where dependence on mineral fertilisers coexists with increasing environmental and resource constraints. Large quantities of nutrients contained in manure, digestate, wastewater, sewage sludge and organic residues remain insufficiently valorised, despite their potential to partially replace synthetic fertilisers and reduce associated impacts such as eutrophication, soil degradation and greenhouse gas emissions. Recent studies highlight that closing nutrient cycles through recovery and recycling is essential to ensure long-term food security, resource efficiency and environmental protection in line with EU sustainability strategies (Saliu & Oladoja, 2021; Wu & Vaneckhaute, 2022).

Within this framework, the FertiCcovery project aims to identify and promote best available techniques for the recovery and recycling of fertilising products from secondary raw materials, supporting EU objectives related to circular economy, climate neutrality and sustainable agriculture. This study presents a comprehensive screening and prioritisation approach applied to a wide range of nutrient recovery and bio-based fertiliser technologies, with the objective of identifying the most promising solutions for further technical, environmental and socio-economic analysis and potential large-scale deployment.

A structured multi-criteria decision-making methodology was applied to an initial inventory of more than 150 existing nutrient recovery technologies identified across Europe and internationally. Technologies were first classified according to their main process type, including biological, chemical, physical and other innovative approaches. Six key evaluation indicators were defined to enable consistent comparison across heterogeneous solutions, addressing feedstock supply availability, technology maturity, availability and cost, regulatory and market frameworks, efficiency and agronomic applicability of bio-based fertilisers, contribution to EU strategic objectives, and the replicability and geographic distribution of value chains across Europe. Each technology was evaluated on a qualitative 1–5 scale by multiple experts, supported by internal consistency checks and review mechanisms to minimise bias and ensure robustness of the scoring process.

To complement expert judgement with practical perspectives, stakeholder input was incorporated through a participatory workshop involving researchers, industry representatives and policy-related actors. Stakeholders provided their views on feedstock suitability, preferred fertiliser characteristics and the relative importance of evaluation criteria. Their responses were statistically processed, normalised to a common scale and integrated with expert scores. A two-stage weighting procedure was then applied to balance expert and stakeholder inputs and to reflect the perceived relevance of each indicator. In addition, a sensitivity analysis was performed to assess the stability of technology rankings under alternative weighting scenarios, allowing the identification of robust solutions versus those more sensitive to changes in assumptions.

The application of this approach resulted in a refined shortlist of 35 nutrient recovery and bio-based fertiliser technologies. The selected technologies represent a balanced mix of process types, with a strong presence of anaerobic digestion, composting, hydrolysis and selected chemical recovery processes, reflecting their high performance, regulatory alignment and broad applicability. Importantly, the shortlist is strongly biased towards implementation-ready solutions, with 97% of the technologies at Technology Readiness Level 9, indicating full-scale operation and suitability for near-term replication. The sensitivity analysis highlighted a core group of technologies with consistently high rankings across scenarios, suggesting strong consensus between experts and stakeholders, alongside a smaller group showing higher variability and therefore requiring further scrutiny in subsequent assessments.

Beyond technological performance, the analysis also provides insights into structural and strategic aspects that influence the deployment of nutrient recovery solutions. Technologies associated with well-established value chains and widely available feedstocks tend to perform more consistently across indicators, underlining the importance of systemic integration, logistics and market readiness alongside technical efficiency. Conversely, solutions relying on more specialised feedstocks or facing regulatory uncertainties show greater variability, pointing to the need for targeted policy

support, harmonised standards and clearer end-of-waste criteria to unlock their full potential. These findings are in line with recent studies emphasising that institutional and regulatory conditions play a decisive role in the success of circular nutrient technologies (Rizzioli et al., 2023).

In addition, the comparative analysis highlights clear trade-offs between process complexity and deployment potential. Highly integrated or multi-step recovery systems may achieve superior nutrient recovery efficiencies or produce tailored fertiliser products, but they often require higher investment costs, advanced operational expertise and favourable regulatory conditions. Simpler and modular solutions, while sometimes less optimised in terms of nutrient concentration or product specificity, benefit from lower barriers to adoption and greater flexibility for decentralised implementation. This distinction is particularly relevant for regions with heterogeneous agricultural structures, where adaptable solutions can facilitate broader uptake and contribute to territorial cohesion within the European Union.

The results also underline the importance of aligning technological development with agronomic performance and farmer acceptance. Even highly efficient recovery technologies may face limitations if the resulting fertiliser products are not compatible with existing spreading equipment, crop requirements or fertilisation practices. Stakeholder feedback revealed a clear preference for fertiliser formats and nutrient profiles that can be seamlessly integrated into current agricultural systems, reinforcing conclusions from recent literature that agronomic usability is a key determinant of market uptake for waste-derived fertilisers (Hidalgo et al., 2025; Mancuso et al., 2024).

Moreover, the approach adopted allows the identification of cross-cutting patterns that go beyond individual technologies. The systematic comparison across indicators shows that high performance in a single dimension does not necessarily translate into overall viability, and that balanced solutions tend to outperform highly specialised ones when broader sustainability and deployment criteria are considered. This reinforces the need for integrated assessment frameworks capable of capturing technical, economic and institutional dimensions simultaneously, particularly in policy-oriented contexts.

Finally, the prioritisation framework presented in this poster contributes to bridging the gap between technological innovation and practical decision-making. By combining expert assessment, stakeholder participation and robustness analysis within a replicable multi-criteria framework, the approach offers a valuable tool for supporting strategic choices in nutrient management, policy design and investment planning. The identified technologies therefore constitute a solid basis for advancing towards more detailed assessments and for supporting informed choices by policymakers, industry and other stakeholders. Ultimately, this work contributes to accelerating the transition towards sustainable, circular nutrient management systems and to strengthening the resilience of European agriculture in the face of resource scarcity and environmental change.

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