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Robust PROMETHEE II screening of nutrient recovery technologies for cleaner production in wastewater treatment☆

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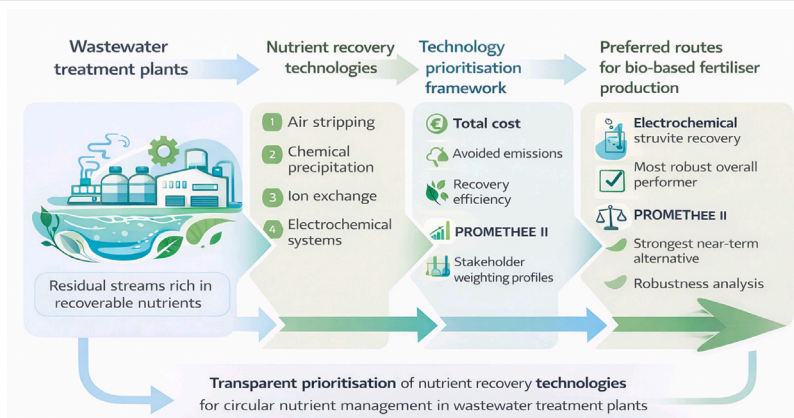
HIGHLIGHTS

- Robust PROMETHEE II framework prioritises nutrient recovery for cleaner production in wastewater treatment.
- Electrochemical struvite recovery leads across 405 runs (Top-3: 100%, first: 65.2%).
- Air stripping delivers lowest-cost circular nitrogen (€1.78 kg^{-1}, 90% efficiency) for near-term deployment.
- Sensitivity analysis reveals implementation-stable routes under stakeholder priority variation.
- Converts heterogeneous evidence into reproducible technology screening for WWTP upgrading.

GRAPHICAL ABSTRACT



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ABSTRACT

Wastewater nutrient recovery can support cleaner production by reducing dependence on primary fertilisers, but early-stage technology shortlisting remains difficult when evidence is drawn from heterogeneous studies and stakeholder priorities differ. This study develops a PROMETHEE II screening framework for seven pilot-to-near-market nutrient recovery configurations in wastewater treatment plants, covering air stripping, chemical precipitation, ion exchange with regeneration, and electrochemical systems. The alternatives are compared using a compact first-stage criterion set: total cost, potential climate-substitution benefit, and recovery efficiency, all expressed per unit of nutrient recovered.

Ranking stability is examined across 405 PROMETHEE II runs combining three preference-function scenarios, five stakeholder weighting profiles, and 27 threshold combinations. The results do not identify a universally superior technology, but rather robust candidates within the assessed dataset, retained criteria, and modelling assumptions. Electrochemical struvite recovery is the most stable high-performing option, remaining in the Top-3 in all runs and ranking first in 65.2%, with 90% recovery efficiency and 3.30 kg CO_2e avoided per kg nutrient. Air stripping on digestate ranks first in 34.8% of runs and represents the strongest cost-oriented

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candidate, with the lowest unit cost (€1.78 kg^{-1}) and 90% efficiency, provided that concentrated digestate streams are available.

The framework converts heterogeneous techno-economic evidence into reproducible early-stage shortlisting evidence, while final implementation requires site-specific techno-economic, regulatory, agronomic, operational, market, and life-cycle assessment.

1. Introduction

Recent geopolitical instability, energy-price volatility, and supply-chain disruptions have intensified concern over the security of mineral fertiliser supply in Europe, reinforcing interest in strategies that enhance domestic nutrient availability and reduce dependence on primary raw materials. In parallel, the transition towards cleaner production has strengthened the case for recovering valuable resources from residual streams rather than managing them solely as wastes. Within this shift, wastewater treatment plants (WWTPs) can be understood not only as infrastructures for pollutant removal, but also as platforms for circular resource recovery (Silva, 2023; Capodaglio, 2023b). In broader biorefinery configurations, WWTPs may also contribute to the recovery of water, energy, chemicals, biomaterials, and fertiliser products (Capodaglio, 2023a; Santamaria-Fernandez et al., 2020; Guven et al., 2023; Marín et al., 2024).

This study focuses on one specific component of that broader biorefinery and wastewater-mining agenda: the recovery of nitrogen (N) and phosphorus (P) for bio-based fertiliser production. These nutrients are essential for agricultural productivity, while their discharge without recovery entails both environmental impacts and the loss of potentially substitutable resources. When recovered and stabilised in usable products, they can contribute to bio-based fertiliser production, reduce reliance on virgin mineral fertilisers, and improve the resource productivity of wastewater systems (Chojnacka, 2023; Guven et al., 2023; Álvarez Salas et al., 2024; Marín et al., 2024; Kurniawati et al., 2023). The cleaner production relevance of nutrient recovery (NR) therefore extends beyond pollutant removal: it concerns whether WWTPs can move from an end-of-pipe function towards a preventive and circular model in which waste-derived nutrients are retained in productive use.

Despite this potential, implementation remains difficult. The available evidence is dispersed across studies adopting different system boundaries, functional references, assumptions, and operating conditions, which hampers direct comparison. Technology selection is also intrinsically multi-criteria: economic cost, environmental performance, and process effectiveness do not necessarily improve simultaneously, and implementation decisions depend on stakeholder priorities and on whether reported performance differences are considered operationally meaningful. The prioritisation of NR technologies therefore requires a decision-support framework capable of integrating heterogeneous evidence while making both stakeholder priorities and decision attitudes explicit (Van der Hoek et al., 2018; Kogler et al., 2021).

Existing studies have generated valuable knowledge on NR technologies, their environmental implications, implementation barriers, and the market prospects of bio-based fertilisers (Álvarez Salas et al., 2024; Kurniawati et al., 2023; Kogler et al., 2021; Chojnacka, 2023). Other contributions have examined wastewater-system transitions through scenario-based upgrade pathways or adaptation pathways (Abily et al., 2023; Van der Hoek et al., 2018), and multi-criteria decision-making (MCDM) methods have been applied to environmental and resource-recovery problems (Van der Hoek et al., 2018; Kogler et al., 2021). However, WWTP decision-makers still lack a transparent and implementation-oriented basis for early-stage technology shortlisting when the evidence is heterogeneous, stakeholder priorities differ, and small reported performance gaps may not be decision-relevant.

To address this gap, this study applies a multi-criteria decision analysis workflow based on the Preference Ranking Organisation METHod for Enrichment Evaluation (PROMETHEE) (Brans et al., 1986; Behzadian et al., 2010; Taherdoost and Madanchian, 2023). PROMETHEE II is adopted because it compares alternatives pairwise and allows the decision rule to reflect not only criterion weights, but also how performance differences are translated into preference intensities through criterion-specific preference functions (Brans et al., 1986; Behzadian et al., 2010). This feature is particularly relevant for literature-based NR comparisons, where modest differences in cost, avoided emissions, or recovery efficiency may reflect data variability or system-boundary differences rather than genuine implementation advantages. PROMETHEE II is therefore used not as a generic ranking device, but as a screening instrument for identifying which NR routes provide the most credible basis for early-stage implementation shortlisting under varied stakeholder priorities and alternative interpretations of meaningful performance differences.

The analysis focuses on three implementation-relevant criteria expressed per unit of nutrient recovered: total cost, avoided emissions, and recovery efficiency. Together, these criteria define a compact core set for first-stage comparative screening, capturing the main economic, environmental, and technical dimensions that shape near-term WWTP implementation choices (Chojnacka, 2023; Guven et al., 2023; Álvarez Salas et al., 2024; Marín et al., 2024). The avoided-emissions criterion is interpreted as a potential climate-substitution benefit associated with the displacement of primary fertiliser production, rather than as a full environmental performance indicator or a substitute for life-cycle assessment. Additional aspects such as product quality, contaminants, agronomic performance, regulatory compatibility, operational reliability, and technological maturity also matter (Kurniawati et al., 2023; Kogler et al., 2021; Álvarez Salas et al., 2024), but they are less consistently reported across the available evidence base and are therefore more appropriately addressed at a subsequent feasibility stage.

A case study is developed for seven NR configurations drawn from recent literature, and robustness is examined through a structured sensitivity design comprising 405 runs that combine alternative preference-function specifications, stakeholder weighting profiles, and threshold settings. The resulting rank acceptability profiles distinguish technologies that remain competitive across a broad range of plausible decision settings from those whose apparent attractiveness depends on narrower modelling assumptions. This design assesses stability within the preference-model space defined by these scenarios while remaining conditional on the harmonised input data; it therefore characterises robustness to decision-model assumptions rather than propagating uncertainty in the underlying data. The study accordingly quantifies ranking stability under evidence heterogeneity and stakeholder plurality without treating the resulting ranking as a definitive technology-selection recommendation.

The contribution of this study is threefold. First, it provides a transparent and reproducible screening framework for comparing NR technologies in WWTPs under implementation-relevant criteria aligned with cleaner production and circular nutrient management objectives (Chojnacka, 2023; Guven et al., 2023; Álvarez Salas et al., 2024; Marín et al., 2024). Second, it generates comparative evidence on which technological routes appear most robust when stakeholder priorities and interpretations of meaningful performance differences are allowed to vary. Third, it advances the methodological practice of MCDM-based technology screening by combining, within a single factorial design, preference-function specifications, stakeholder weighting profiles, and threshold settings. This distinguishes technologies whose comparative advantage is stable across a broad space of plausible modelling assumptions from those whose attractiveness is conditional on

narrower preference settings. The novelty therefore lies not in proposing a new PROMETHEE variant, but in adapting PROMETHEE II to an implementation-oriented cleaner production screening problem under heterogeneous evidence. The study is accordingly designed as a first-stage implementation screening exercise rather than as a full feasibility appraisal; detailed assessment of shortlisted alternatives should subsequently incorporate product quality, contaminants, regulatory compliance, agronomic performance, operational reliability, and plant-specific integration conditions (Kalbar et al., 2012, 2016; Kogler et al., 2021; Álvarez Salas et al., 2024).

The remainder of the paper is organised as follows. Section 2 presents the methodological framework and the PROMETHEE modelling choices. Section 3 introduces the case study and reports its implementation, including data preparation, preference-function scenarios, weighting profiles, and robustness analysis. Section 4 discusses the main findings and their implications for technology selection and circular nutrient management. Section 5 concludes. Appendix A summarises the PROMETHEE II method, including preference functions, aggregation, outranking flows, rank-acceptability profiles, and the rationale for adopting PROMETHEE II under heterogeneous evidence, while Appendix B provides detailed case-study documentation, including route-specific interpretation, data comparability constraints, N+P aggregation, product-substitution assumptions, and robustness-design details.

2. Multi-criteria framework for robust prioritisation of nutrient recovery technologies

Nutrient recovery (NR) from wastewater offers a concrete pathway for closing phosphorus and nitrogen cycles, reducing dependence on synthetic fertiliser production, and reintegrating recovered materials into agricultural supply chains. In practice, however, implementation requires technology choices that remain credible across economic, environmental, and technical dimensions, rather than performing strongly on only one indicator. Because reported performances are heterogeneous across studies and stakeholder priorities are not fixed, robust implementation screening requires a framework capable of comparing alternatives transparently across multiple objectives and of distinguishing stable from assumption-sensitive recommendations.

In operational terms, PROMETHEE II proceeds by comparing each technology pairwise against every other technology on each criterion. For each comparison, the observed performance difference is translated into a preference degree between 0 and 1, where 0 denotes no relevant preference and 1 denotes strong preference for one option over another. These criterion-level preferences are then weighted and aggregated into positive, negative, and net outranking flows. The net flow summarises, on balance, how strongly each technology outperforms the others after all criteria and stakeholder weights have been considered. Technologies with higher net flows are therefore ranked higher, although the ranking remains conditional on the selected criteria, preference functions, thresholds, and weights.

This study uses PROMETHEE II (Brans et al., 1986) for that purpose; the specific methodological properties that make it suitable for a heterogeneous, literature-based evidence base are detailed in Appendix A.4 (Behzadian et al., 2010; Taherdoost and Madanchian, 2023).

Three criteria are used in the comparative assessment: total cost, avoided greenhouse gas emissions, and nutrient recovery efficiency. These are not the only conceivable criteria, but they constitute a parsimonious and decision-relevant core set for first-stage implementation screening under comparable literature evidence. Total cost determines economic feasibility and therefore whether circular recovery is deployable at scale. Avoided emissions capture the potential climate-substitution benefit associated with displacing conventional fertiliser production by recovered nutrient products. Recovery efficiency indicates how completely influent nutrient loads are captured and made available for potential agricultural reuse, and therefore contributes directly to the substitution potential of each technology. Criteria bearing on product quality, regulatory compliance, agronomic performance, contaminant risks, and operational reliability are also relevant, but they require site-specific evidence that is not consistently available across the comparative literature and are therefore more appropriately addressed at the stage of detailed feasibility assessment. The construction of each criterion, including system boundaries, reference baselines, and harmonisation decisions, is specified in Section 3.2.

The methodological workflow is summarised in Fig. 1. Alternatives and criteria are defined alongside weighting profiles representing distinct stakeholder priorities. Preference functions and thresholds are specified to govern how performance differences are translated into decision-relevant preferences. Pairwise comparisons are aggregated into net outranking flows, and the resulting ranking is stress-tested through a structured robustness design. The two subsections below explain the preference-modelling and aggregation steps. The formal PROMETHEE II definitions are provided in Appendix A.1, the standard preference functions are summarised in Appendix A.2, and the aggregation, outranking-flow, and rank-acceptability formulations are reported in Appendix A.3.

2.1. Preference modelling

In literature-based comparisons of NR technologies, modest differences in cost, avoided emissions, or recovery efficiency frequently reflect variation in system boundaries or methodological conventions rather than genuine performance differentials. Treating such differences as automatically decisive can misrepresent the comparative evidence and promote technologies that are nominally superior on one indicator without offering a substantively better profile across the dimensions that determine circular production viability.

PROMETHEE addresses this issue through preference functions that map pairwise performance differences onto a common scale. The formal definition of these performance differences, and of the criterion-level preference function $P_j : \mathbb{R} \to [0, 1]$ that translates each difference into a preference degree, is given in Appendix A.1.

Preference functions that define indifference zones or graduated responses help ensure that only differences exceeding a specified decision-relevance threshold influence the ranking. This matters for implementation screening: a specification that is too sensitive could systematically favour technologies with a marginal advantage on one indicator, whereas a more tolerant specification can recognise that small differences may fall within normal methodological or operational variability. In this study, alternative preference-function scenarios are therefore used to test whether the prioritisation of NR technologies remains stable under different interpretations of what constitutes a meaningful performance gap. The standard PROMETHEE preference functions are documented in Appendix A.2; the specific functions and thresholds adopted for each criterion in the case study are justified in Section 3.2.

2.2. Aggregation and ranking

Criterion-specific preference degrees are aggregated into a global preference index using criterion weights. The operationalisation of stakeholder priorities through these weights and the formal aggregation expression are provided in Appendix A.3.

From these global preference indices, PROMETHEE II derives positive, negative, and net outranking flows. The positive flow measures the extent to which an alternative outranks the remaining options, whereas the negative flow measures the extent to which it is outranked by them. The net flow combines both components and provides the basis for the complete PROMETHEE II ranking. A technology with a high net flow therefore dominates competitors broadly rather than excelling on one criterion at the expense of others. For circular implementation,

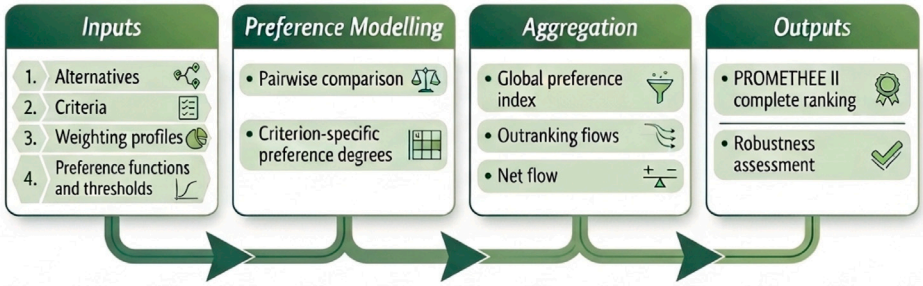

Fig. 1. Methodological workflow of the analysis used in this study, from the definition of alternatives, criteria, and decision parameters to the derivation of net-flow rankings and robustness analysis across weighting-profile and preference-function scenarios.

this distinction is substantive: a technology that achieves high recovery efficiency at disproportionate cost, or strong climate performance with poor nutrient capture, does not constitute an adequate cleaner production solution merely because it performs well on one indicator.

The rationale for relying on rank acceptability profiles rather than on a single weighting profile, and the composition of the $S = 405$ scenario space, are detailed in Appendix A.3.

The following section defines the criteria precisely: the cost boundary and what it excludes, the reference system against which avoided emissions are calculated, and how recovery efficiency is constructed to reflect substitution of primary nutrient inputs rather than simple mass removal. These definitions determine which technologies appear preferable and must therefore be transparent and replicable.

3. Case study: Comparative screening of nutrient recovery technologies for bio-based fertiliser production

This section applies the PROMETHEE II framework to seven NR configurations with demonstrated pilot or near-market relevance for WWTPs. The alternatives are evaluated on three criteria grounded in cleaner production practice — total cost (TC), avoided greenhouse gas emissions (EA), and recovery efficiency (RE) — each expressed per unit of nutrient recovered. The objective is not to provide a definitive ranking, but to identify which routes remain robust under systematic variation in stakeholder priorities and preference thresholds, and which are competitive only under narrower conditions. The results are therefore intended as decision-relevant early-stage screening evidence rather than as a final technology-selection recommendation. For readability, the detailed route descriptions, the full performance matrix, and the harmonisation, normalisation, and robustness-design documentation are reported in Appendix B, while the main text retains the criteria, modelling choices, results, and interpretive qualifications required to follow the screening.

3.1. Selected nutrient recovery configurations and their cleaner production relevance

The seven configurations span four process routes relevant to wastewater valorisation: air stripping, chemical precipitation, ion exchange with regeneration, and electrochemical treatment, with maturity ranging from pilot-scale validation to full-scale techno-economic assessment and near-market applicability. Technology Readiness Level (TRL) values are not assigned numerically because the source studies do not report them consistently; maturity is therefore characterised qualitatively from the system description and validation scope reported in each source. All configurations convert nutrient-bearing effluents into bio-based fertiliser (BBF) products with potential for agricultural reuse, subject to product quality, regulatory acceptance, and agronomic performance. The full performance matrix and technical specifications of each alternative — target effluent, recovered BBF product, annual BBF production, valuable nutrient recovered, annual mass of nutrients recovered, and assumed lifespan — are reported in Supplementary Table B.2, and the route-specific cleaner-production interpretations are provided in Appendix B.1.

3.2. Criteria, data harmonisation, and acknowledged scope limitations

The three criteria operationalise the principal dimensions along which cleaner production performance is assessed under current EU policy, which targets a reduction in fertiliser use of at least 20% by 2030 under the Farm to Fork Strategy (European Commission, 2020), classifies phosphorus as a critical raw material (European Parliament and Council, 2024), and provides a decarbonisation rationale for displacing energy-intensive synthetic nitrogen production (Erisman et al., 2008). The resulting TC–EA–RE set is thus a direct operationalisation of dimensions that regulators and operators are increasingly required to report and optimise jointly; the detailed policy rationale is given in Appendix B.

It must be emphasised that TC, EA, and RE constitute a compact screening set rather than a complete feasibility assessment. Factors that may decisively affect practical technology choice — product purity, contaminant risks, regulatory compliance under Regulation (EU) 2019/1009 (European Parliament and Council of the European Union, 2019), agronomic and fertiliser value, market acceptance, operational reliability, and sensitivity to energy and reagent prices — are not incorporated at this stage. This is an acknowledged scope limitation, consistent with the two-stage appraisal advocated in the cleaner production literature (Kalbar et al., 2012, 2016), in which MCDM screening precedes full techno-economic and life-cycle assessment of shortlisted alternatives. The rankings should therefore be read as structured comparative evidence for early-stage shortlisting, not as a definitive ranking under site-specific operating, regulatory, or market conditions.

3.2.1. Data harmonisation and residual comparability constraints

The seven configurations were compiled from independent literature sources rather than from a single experimental campaign, and therefore differ in process scale, geographical context, feedstock composition, nutrient concentration, cost year, electricity and reagent assumptions, system boundaries, and recovered product form. Normalising all indicators per unit of recovered nutrient provides a common functional basis but does not eliminate this cross-study heterogeneity; the harmonisation was consequently designed as a transparent screening step, not as a meta-analytical re-estimation of technology performance. The main harmonisation decisions are summarised in Table 1, and the corresponding computation of each indicator is described in Appendix B.2. Because the model uses point estimates, configurations sourced from particularly favourable operating contexts may rank higher than under median conditions. A detailed discussion of the residual comparability constraints and their possible ranking effects is provided in Appendix B.2.

3.2.2. Criteria and cleaner production orientation

The evaluation uses the three quantitative criteria defined above, with their units and optimisation directions summarised in Table 2. TC (€ kg^{-1} nutrient) captures the economic burden of each route and is

Table 1
Data harmonisation procedure and residual comparability limitations.

Harmonisation dimension	Source-study heterogeneity	Harmonisation applied in this study	Residual limitation and potential ranking effect
Scale and maturity	Pilot, demonstration, or near-market systems reported at different capacities and technology readiness levels	Indicator values expressed per kg of recovered nutrient, providing a common functional unit independent of system size	Unit costs remain scale-dependent; pilot-scale systems may show higher TC, biasing the ranking against less mature configurations
Feedstock and nutrient concentration	WWTP digestate, WWTP effluent, sidestreams, dewatering liquor, and pig-slurry digestate at varying nutrient concentrations	Target stream and recovered nutrient identified and reported for each alternative	Dilute streams increase energy and reagent demand per kg recovered; concentrated sidestreams may show lower TC regardless of intrinsic process efficiency
Economic boundary	Heterogeneous reporting of CAPEX, OPEX, lifespan, reagent consumption, and energy price assumptions	TC computed as annualised CAPEX plus annual OPEX, divided by annual recovered nutrient mass	Differences in cost year, electricity price, and reagent cost are not fully removed; electrochemical routes are particularly sensitive to electricity price assumptions
Environmental boundary	Source studies do not report identical life-cycle boundaries or environmental impact categories	EA expressed as potential avoided GHG emissions from substitution of conventional mineral fertilisers only (cradle-to-gate)	EA is a climate-substitution proxy only; transport, field application, eutrophication, toxicity, and other LCIA categories are excluded. The environmental ranking may change under a full LCA (see Section 3.2.2)
Recovered product form	Ammonium sulphate, struvite, hydroxyapatite, ammonium salts, and nitrogen-rich concentrates with differing purity and nutrient density	Products linked to potential substitution of conventional N and/or P fertilisers using established carbon-footprint reference values	Product purity, nutrient density, contaminant content, agronomic value, regulatory acceptance, and market uptake are not modelled; marketable products may be undervalued by the screening criteria
Nutrient basis	Some technologies recover nitrogen only; others recover both nitrogen and phosphorus from the same stream	All criteria are expressed per kg of recovered nutrient using an equal-mass N+P denominator in the base case; N-only routes therefore reduce to per-kg-N metrics	The equal-mass assumption may understate the strategic value of phosphorus recovery. A weighted denominator $m_N + w_P m_P$ could be defined from the reported nutrient masses, but a full nutrient-specific PROMETHEE re-analysis would also require N- and P-specific substitution credits for EA and nutrient-specific recovery efficiencies for RE (see Section 3.2.3)
Input-data uncertainty	Most source studies report point estimates rather than uncertainty ranges, confidence intervals, or harmonised scenarios	The harmonised performance matrix uses these point estimates; no formal uncertainty propagation is performed due to inconsistent reporting	Ranking stability reflects robustness to preference-model assumptions, not full robustness to input-data uncertainty; rankings may change if uncertain TC, EA, or RE values are varied

CAPEX = capital expenditure; OPEX = operating expenditure; GHG = greenhouse gas; LCIA = life-cycle impact assessment; LCA = life-cycle assessment; w_P = phosphorus weighting factor relative to nitrogen ($w_N = 1$). TC, EA, and RE as defined in Section 3.2.2.

Table 2
PROMETHEE criteria used in the case study.

Source	Technology	VN	TC	EA	RE
Alrbai et al. (2024)	Air stripping	N	1.780	2.670	90
Brienza et al. (2021)	Air stripping (side-stream)	N	3.780	2.670	57
Sánchez et al. (2024)	Chemical precipitation	N+P	39.740	2.920	90
Molinos-Senante et al. (2011)	Chemical precipitation	N+P	59.360	3.300	88
Huang et al. (2020)	Ion exchange (regen.)	N+P	5.630	2.610	85
Koskue et al. (2022)	Electrochemical	N	2.660	1.910	79
Morrissey et al. (2022)	Electrochemical	N+P	5.520	3.300	90

VN: valuable nutrient recovered (N = nitrogen; P = phosphorus; N+P = combined).
TC: total cost of nutrient recovered (€ kg^{-1} (N+P)*). Minimised.
EA: avoided greenhouse gas emissions (kg CO_2e kg^{-1} nutrient (N+P)* recovered). Potential climate-substitution benefit only; see Section 3.2.2 and Supplementary Appendix B.4 for scope limitations. Maximised.
RE: nutrient recovery efficiency (% of (N+P)*). Maximised.
*For technologies recovering only N ($P = 0$), indicators reduce to per-N metrics.

minimised; EA (kg CO_2e kg^{-1} nutrient) represents the potential climate-substitution benefit of displacing synthetic fertiliser production and is maximised, being interpreted strictly as a climate-substitution proxy rather than a complete environmental performance indicator, since transport, field application, eutrophication, and other life-cycle impact categories are excluded (scope limitations in Appendix B.4); and RE (%) measures the fraction of influent nutrient load captured in a reusable product and is maximised. TC is computed as a harmonised unit cost following the annualisation procedure described above.

The omitted dimensions — product purity, contaminant content, regulatory compliance, operational reliability, market acceptance, fertiliser value, and energy or reagent price exposure — are not treated as secondary, but as insufficiently harmonised across the available literature for inclusion in the quantitative PROMETHEE matrix; their implications for practical technology choice are detailed in Appendix B.3. Their exclusion may alter the relative standing of technologies that appear favourable under the TC–EA–RE screening set in site-specific appraisals.

3.2.3. Normalisation by recovered nutrients and the N+P aggregation

All criteria are expressed per unit of total recovered nutrients (N+P), providing a unified functional basis for comparing technologies with different recovery scopes. This convention assigns equal mass to 1 kg

of recovered nitrogen and 1 kg of recovered phosphorus in the denominator; it facilitates comparison but is not intended to imply equivalence between N and P, which differ in resource scarcity, economic value, fertiliser function, production burden, and policy relevance. Under this convention, N-only technologies reduce to per-kg-N metrics, whereas dual-nutrient technologies are evaluated per kg of total recovered N+P, which may under-represent the strategic relevance of phosphorus recovery where P scarcity, critical raw material status, or circular phosphorus management are central objectives. A more general nutrient-weighted denominator $m_N + w_P m_P$ (with nitrogen as reference, $w_N = 1$) could be defined from the reported nutrient masses; the equal-mass base case corresponds to $w_P = 1$. The detailed rationale, the nutrient-weighted formulation, and the reasons why a full nutrient-specific PROMETHEE re-analysis was not implemented are provided in Appendix B.5. Recovered products are interpreted as potential — not automatic — substitutes for conventional mineral fertilisers, conditional on product quality, regulatory compliance under Regulation (EU) 2019/1009 (European Parliament and Council of the European Union, 2019), agronomic performance, logistics, and market uptake, which are not modelled here and are discussed in Appendix B.6. The harmonised performance matrix should accordingly be read as a transparent and reproducible dataset for MCDM screening that does not replace site-specific assessment of economic, technical, agronomic, regulatory, and market feasibility.

3.3. Preference modelling under alternative implementation perspectives

The PROMETHEE II ranking depends not only on criterion weights but also on how pairwise performance differences are translated into preference intensities through the choice of preference function. This choice has substantive meaning: a unit-cost difference of €1 kg^{-1} may be decisive under a tight WWTP procurement budget yet negligible if it falls within the variability of local energy tariffs, reagent prices, scale effects, or feedstock composition, and the same applies to modest differences in avoided emissions or recovery efficiency drawn from heterogeneous pilot- or near-market studies. Making these judgements explicit, and testing their influence on the ranking, is therefore part of the transparency requirement for cleaner production decision-making.

Three preference-function scenarios (PF1–PF3) are specified (Table 3), combining the standard preference functions — whose behavioural meaning is summarised in Appendix A — across the three criteria to represent interpretable WWTP procurement contexts: cost-driven (PF1), cost-tolerant with proportional valuation of climate and efficiency gains (PF2), and a smooth Gaussian valuation of incremental climate benefits (PF3). No single scenario is asserted as uniquely correct; PF2 is used as the reference configuration, while PF1 and PF3 represent analytically useful departures from that baseline.

The threshold values are not statistical confidence intervals but *decision-relevance parameters*: each defines the minimum performance difference considered large enough to influence an implementation-oriented comparison. The values $q_1 \in \{0.5, 1.0, 1.5\}$ €kg^{-1}, $p_2, \sigma_2 \in \{0.2, 0.3, 0.4\}$ kg CO_2e kg^{-1}, and $p_3 \in \{5, 10, 15\}$ percentage points represent strict, reference, and more tolerant interpretations of decision-relevant differences in TC, EA, and RE, respectively. Their numerical order of magnitude is anchored in the observed spread of criterion values (Table 2) and in plausible site-specific operational variability; the detailed percentage-of-range justification is reported in Appendix B.7.

3.4. Alternative stakeholder priorities and robustness assessment

The weighting vector resolves trade-offs between total cost, avoided emissions (climate substitution benefit), and recovery efficiency when no technology dominates on all criteria. Five weighting profiles $w = (w_{TC}, w_{EA}, w_{RE})$, with non-negative components summing to one, are examined (Table 4). These are not preferences elicited from a specific decision-maker but stylised institutional perspectives — balanced public-utility (W1), cost-driven operator (W2), climate-driven operator or regulator (W3), efficiency-driven circularity (W4), and joint climate–circularity (W5) — designed to test whether the ranking is stable under plausible WWTP priorities; their institutional interpretation is given in the table.

For each combination of preference-function scenario, weighting profile, and threshold setting, PROMETHEE II net flows $\phi(a_i)$ and the induced complete ranking are computed. The robustness design combines the three preference-function scenarios (PF1–PF3), the five weighting profiles (W1–W5), and a full factorial grid of threshold settings:

$$q_1 \in \{0.5, 1.0, 1.5\}\ e\ \mathrm{kg}^{-1}, \qquad \theta_2 \in \{0.2, 0.3, 0.4\}\ \mathrm{kg\ CO_2e\ kg^{-1}},$$
$$p_3 \in \{5, 10, 15\}\ \text{percentage points},$$

where θ_2 denotes the avoided-emissions preference parameter, specified as p_2 under the V-shape function and as σ_2 under the Gaussian function. This yields $3^3 = 27$ threshold combinations and, in total, $3 \times 5 \times 27 = 405$ PROMETHEE II runs. The rationale for adopting a design more demanding than a weight-only sensitivity analysis is detailed in Appendix B.7; as discussed in Section 4, the analysis characterises model-parameter robustness conditional on the harmonised input data and does not propagate statistical uncertainty in the input performance values.

3.5. Reference ranking and robustness of technology priorities

Results are reported in two stages: a single reference execution establishes the pattern of net flows under a balanced perspective, after which the evaluation is repeated across the full scenario space to identify stable and sensitive positions. Throughout, results are interpreted as evidence for early-stage screening and shortlisting, not as definitive technology selection; additional dimensions such as product purity, contaminant content, regulatory compliance, and operational reliability may alter the relative standing of individual alternatives and are discussed in Section 4.

Reference scenario. The reference configuration combines PF2 with balanced weighting W1 and parameters $(q_1, p_2, p_3) = (1.0, 0.3, 10)$; leaving, entering, and net flows are reported in Table 5. The flow plane (Fig. 2) and the net-flow gaps (Fig. 3) reveal a three-group structure — {Morrissey et al. (2022), Alrbai et al. (2024)}, {Molinos-Senante et al. (2011), Sánchez et al. (2024)}, and {Huang et al. (2020), Koskue et al. (2022), Brienza et al. (2021)} — which is more informative for screening than a strict reading of the seven individual positions.

The electrochemical configuration of Morrissey et al. (2022) ranks first ($\phi = 0.3722$), combining the highest EA (3.30 kg CO_2e kg^{-1}), 90% recovery efficiency, and a unit cost (€5.52 kg^{-1}) competitive with all alternatives except air stripping (Alrbai et al., 2024); its standing could nonetheless change once product purity, chemical residues, and regulatory acceptability under the EU Fertilising Products Regulation (European Parliament and Council of the European Union, 2019) are considered, none of which is captured here. Air stripping (Alrbai et al., 2024) ranks second ($\phi = 0.3370$) on cost grounds (€1.78 kg^{-1}, the lowest value), but this advantage depends on a concentrated WWTP-digestate feedstock that is not universally available and is therefore strongly context-dependent. The two chemical precipitation alternatives occupy intermediate positions with near-zero net flows ($\phi = 0.0333$ and 0.0204): although struvite precipitation enables simultaneous N and P recovery, its high unit costs (€39–59 kg^{-1}) constrain its competitiveness when economic feasibility is weighed jointly with climate benefit and efficiency. Ion exchange (Huang et al., 2020) and the Koskue electrochemical route (Koskue et al., 2022) rank fifth and sixth with negative net flows, the latter recording the lowest EA in the dataset, suggesting that electricity-related burdens erode part of its substitution benefit; side-stream air stripping (Brienza et al., 2021)

Table 3
Preference-function scenarios used in the case study.

Scenario	TC (j = 1, minimise)[a]	EA (j = 2, maximise)	RE (j = 3, maximise)	Decision-maker interpretation
PF1	Usual	V-shape (p_2)	V-shape (p_3)	Any cost reduction is decisive; climate substitution benefits and recovery-efficiency gains are valued proportionally.
PF2	U-shape (q_1)	V-shape (p_2)	V-shape (p_3)	Small cost differences are disregarded; climate substitution benefits and recovery-efficiency gains are valued proportionally.
PF3	U-shape (q_1)	Gaussian (σ_2)	V-shape (p_3)	Small cost differences are disregarded; incremental climate benefits are valued smoothly; efficiency gains are valued proportionally.

[a] The minimisation criterion is handled within the PROMETHEE framework by applying preference functions to sign-adjusted differences (Section 2.2).

Table 4
Weighting profiles used in the sensitivity analysis.

Profile	TC	EA	RE	Institutional interpretation
W1 (balanced)	1/3	1/3	1/3	Public-utility perspective with equal emphasis on cost, climate substitution benefit, and recovery efficiency.
W2 (cost-driven)	0.60	0.20	0.20	Budget-constrained implementation, prioritising affordability and near-term deployability.
W3 (climate-driven)	0.20	0.60	0.20	Climate-oriented prioritisation, reflecting carbon pricing, green procurement, or decarbonisation reporting.
W4 (efficiency-driven)	0.20	0.20	0.60	Resource-circularity perspective, prioritising nutrient recirculation and reduced dependence on primary fertiliser inputs.
W5 (climate–circularity)	0.20	0.40	0.40	Integrated cleaner production perspective with joint emphasis on climate mitigation and circular nutrient recovery.

TC = total cost; EA = avoided emissions, interpreted as climate substitution benefit; RE = recovery efficiency. Weights satisfy $w_{TC} + w_{EA} + w_{RE} = 1$.

Table 5
PROMETHEE II flows and ranking for the reference scenario PF2+W1 ($q_1 = 1.0$, $p_2 = 0.3$, $p_3 = 10$).

Source	Technology	ϕ^+	ϕ^-	ϕ	Rank
Morrissey et al. (2022)	Electrochemical	0.5389	0.1667	0.3722	1
Alrbai et al. (2024)	Air stripping	0.4944	0.1574	0.3370	2
Molinos-Senante et al. (2011)	Chemical precipitation	0.4000	0.3667	0.0333	3
Sánchez et al. (2024)	Chemical precipitation	0.4093	0.3889	0.0204	4
Huang et al. (2020)	Ion exchange (regen.)	0.2556	0.4556	−0.2000	5
Koskue et al. (2022)	Electrochemical	0.3333	0.5833	−0.2500	6
Brienza et al. (2021)	Air stripping (side-stream)	0.2889	0.6019	−0.3130	7

ranks last ($\phi = -0.3130$), combining elevated cost with the lowest recovery efficiency (57%), confirming that feedstock concentration and operating context, not process route alone, determine cleaner production performance.

Robustness across decision-maker views. Table 6 and Fig. 4 summarise rank stability across the 405 runs; as established above, the reported rank frequencies are conditional on the harmonised point estimates and do not bound the full uncertainty space of the input data. The rank acceptability profiles in Fig. 4 reveal differences in positional stability not captured by mean rank or Top-3 frequency alone: ion exchange (Huang et al., 2020) holds a stable but unfavourable rank 5 in 78% of runs; (Molinos-Senante et al., 2011) chemical precipitation shows the most dispersed distribution, indicating sensitivity to the weighting–preference combination; and Koskue et al. (2022) electrochemical shows a bimodal pattern at ranks 3 and 6–7, occupying structurally different positions under efficiency- versus cost-oriented weights. These patterns reinforce the value of reporting full rank acceptability profiles rather than summary statistics alone.

The Morrissey electrochemical configuration is the most robustly preferred technology, ranking first in 65.2% of runs and within the top three in all 405 runs (Top-3 frequency = 1.000) across every weighting profile and preference-function scenario, indicating that its position is not conditional on a specific stakeholder priority. Air stripping (Alrbai et al., 2024) ranks first in the remaining 34.8% of runs, predominantly under cost-weighted profiles, and its Top-3 frequency of 0.941 confirms it as a competitive option for budget-constrained screening, subject to concentrated-feedstock availability. The two chemical precipitation alternatives never rank first and reach the top three in only 48.1% and 37.8% of runs: while struvite precipitation is most clearly associated with simultaneous N and P recovery — of strategic relevance given the critical-material status of phosphorus (European Parliament and Council, 2024) — its cost profile makes it non-competitive under economic-weight scenarios. Ion exchange (Huang et al., 2020) and side-stream air stripping (Brienza et al., 2021) do not reach the top three under any profile, although this reflects the specific configurations and retained criteria assessed rather than a general dismissal of these technology families.

Taken together, the robustness results point to a two-tier screening outcome, valid within the scope of the three modelled criteria and the harmonised data: they identify candidates for further feasibility assessment, not technologies that are unconditionally superior. For WWTPs with access to concentrated digestate streams and operating under strong budget constraints, air stripping is the economically strongest option in the present comparison, subject to site-specific feasibility assessment. For WWTPs where climate performance and nutrient recirculation are jointly weighted — as increasingly required under green procurement and circular economy reporting (European Commission, 2020) — the Morrissey electrochemical configuration is the most robust candidate across the scenario space. The intermediate position of struvite precipitation, despite its dual-nutrient capability, identifies

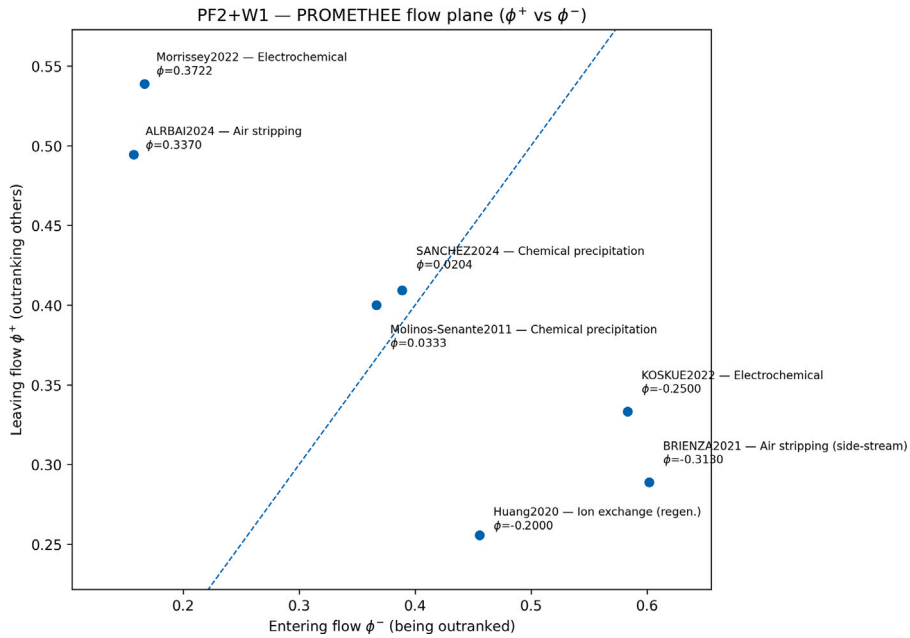

Fig. 2. PROMETHEE flow plane for PF2+W1. Each point represents a technology in the (ϕ^-, ϕ^+) plane; the dashed diagonal $y = x$ separates alternatives with $\phi > 0$ (above) from those with $\phi < 0$ (below).

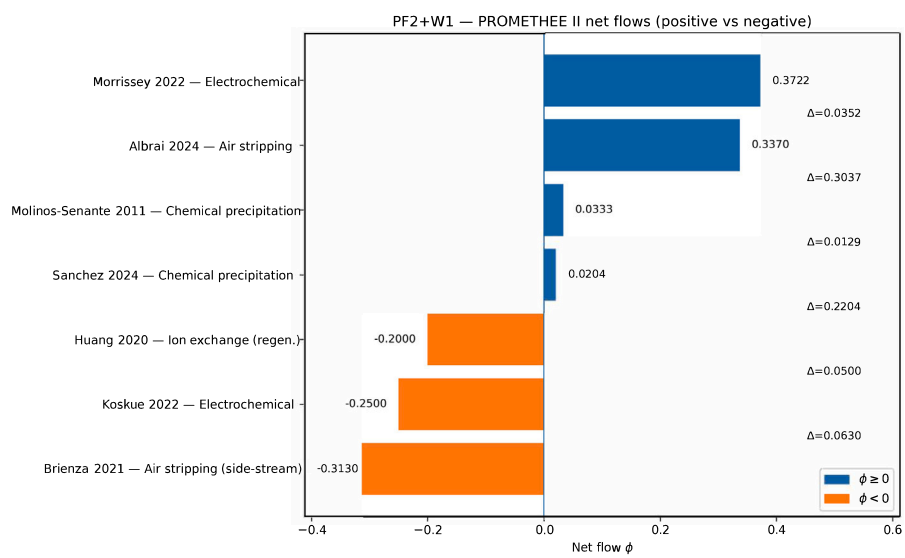

Fig. 3. PROMETHEE II net flows (ϕ) for PF2+W1, ordered from best to worst. Bars are coloured by the sign of ϕ; gaps between consecutive ranks are shown as brackets with Δ.

scale-up and chemical-cost reduction as the critical engineering levers for this route to become competitive under broader implementation conditions.

4. Discussion

This section interprets the PROMETHEE II results for cleaner production, circular nutrient recovery, and WWTP implementation. The aim is not to restate the ranking, but to clarify what the stability and sensitivity patterns imply for technology shortlisting, investment prioritisation, and the transition from pollutant-removal-oriented towards resource-recovery-oriented wastewater treatment.

4.1. Purpose and framing

The results are read as cleaner-production-oriented technology shortlisting: the relevant question is not whether a technology can recover nutrients, but whether it does so in a way that reduces dependence on primary fertiliser production, improves resource efficiency, and remains feasible under WWTP operating constraints (Chojnacka, 2023; Guven et al., 2023; Marín et al., 2024). Robustness here refers specifically to stability with respect to modelling assumptions within the PROMETHEE II framework, and should not be read as robustness to uncertainty in the underlying performance data, since the input matrix consists of harmonised point estimates from heterogeneous sources. Rank differences are therefore not interpreted as intrinsic technological properties. Instead, the rankings identify candidates for further feasibility assessment rather than establishing definitive superiority. Product purity, contaminant content, regulatory compliance, agronomic value, market acceptance, operational reliability, and energy or reagent price exposure remain outside the matrix and may alter relative attractiveness in site-specific appraisals. The Top-1 and Top-3 frequencies carry

Table 6
Robustness summary across 405 PROMETHEE II sensitivity runs.

Source	Technology	Mean rank	Median	Top-1 freq.	Top-3 freq.	IQR(rank)
Morrissey et al. (2022)	Electrochemical	1.393	1	0.652	1.000	1
Alrbai et al. (2024)	Air stripping	1.931	2	0.348	0.941	1
Molinos-Senante et al. (2011)	Chemical precipitation	3.899	4	0.000	0.481	1
Sánchez et al. (2024)	Chemical precipitation	3.948	4	0.000	0.378	1
Huang et al. (2020)	Ion exchange (regen.)	5.232	5	0.000	0.000	0
Koskue et al. (2022)	Electrochemical	5.760	6	0.000	0.200	1
Brienza et al. (2021)	Air stripping (side-stream)	5.837	6	0.000	0.000	2

Top-1 frequency: share of runs where the alternative ranks first. Top-3 frequency: share of runs where the alternative ranks among the top three. IQR: interquartile range of ranks across runs. Results are conditional on the modelled criteria and harmonised performance data; see Section 4 for limitations.

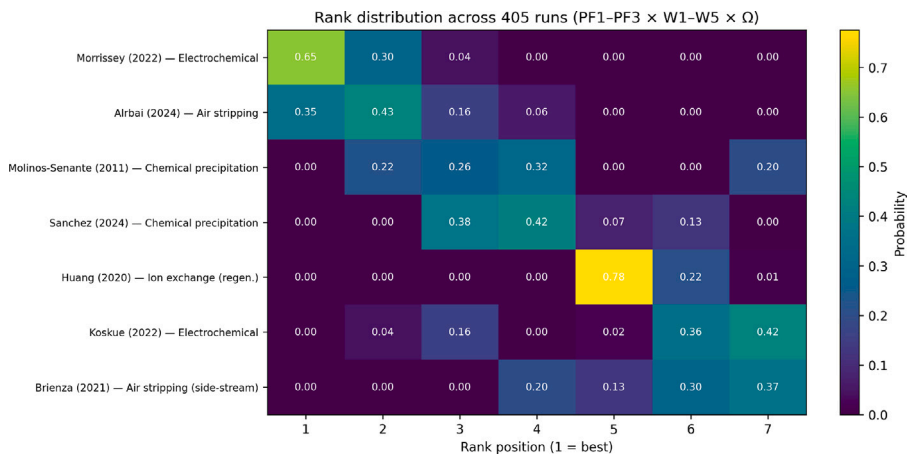

Fig. 4. Rank acceptability profiles across 405 PROMETHEE II runs (PF1–PF3 × W1–W5 × Ω). Each cell reports the empirical probability that a technology attains a given rank position (1 = best).

different decision meanings: the former is relevant for single-option selection, whereas the latter is relevant for early-stage shortlisting.

4.2. General interpretation of comparative results

No single route performs best across all dimensions; the screening instead yields a structured outcome — two leading alternatives, two intermediate alternatives, and three lower-ranked configurations — with the largest separation falling between the leading pair and the rest rather than between the first- and second-ranked technologies. The two leaders embody distinct implementation logics. The electrochemical struvite configuration (Morrissey et al., 2022) leads under the balanced reference scenario and remains within the Top-3 across all 405 runs, reflecting a balanced profile that combines the highest climate-substitution benefit in the dataset, a high recovery efficiency, and a competitive unit cost; it is thus aligned with an integrated nutrient-circularity perspective offering dual N+P recovery. Air stripping on digestate (Alrbai et al., 2024) is the strongest low-cost option, ranking first mainly under cost-weighted profiles and remaining highly competitive on Top-3 frequency; it is aligned with a targeted, near-term circular-nitrogen strategy where concentrated streams are available. The results therefore support a differentiated shortlisting logic conditioned by feedstock availability, stakeholder priorities, and the intended scope of recovery, not a universal recommendation. The intermediate position of chemical precipitation shows that dual-nutrient credentials alone do not guarantee a favourable multi-criteria position once cost is weighed jointly with climate-substitution benefit and recovery efficiency, while the lower-ranked alternatives reflect the specific configurations and source-study assumptions rather than general unsuitability.

4.3. Technology-specific implications

Electrochemical struvite recovery. The configuration of Morrissey et al. (2022) is the most robustly preferred alternative, achieving the joint dataset maximum for EA and RE at a unit cost close to the lower-cost non-stripping routes; in cleaner production terms, it is a strong candidate for contexts in which nutrient circularity and climate substitution are jointly prioritised. This holds only within the screening model: electrochemical routes may require verification of product purity, chemical residues, electrode-related issues, and regulatory acceptability under Regulation (EU) 2019/1009 (European Parliament and Council of the European Union, 2019), and their implementation case depends on electricity demand, grid carbon intensity, reagent consumption, and integration with existing WWTP energy and material flows.

Air stripping on digestate. Air stripping on digestate (Alrbai et al., 2024) is the lowest-cost route and performs strongly under cost-priority profiles, offering early circular nitrogen recovery and potential climate substitution under favourable economics. Its main limitation is transferability: the favourable performance is tied to a concentrated digestate stream, and the contrast with the more dilute side-stream variant (Brienza et al., 2021) shows that the process label alone does not determine performance. It is therefore a credible shortlisting candidate only where suitable high-strength streams exist and the recovered ammonium product can meet regulatory and market requirements.

Chemical precipitation. The two precipitation routes (Molinos-Senante et al., 2011; Sánchez et al., 2024) occupy intermediate positions. Their strength is strategic rather than economic: they recover phosphorus alongside nitrogen, and phosphorus has increasing policy relevance as

a critical raw material under EU legislation (European Parliament and Council, 2024). However, their high unit costs substantially weaken their screening position, especially under cost-weighted profiles, illustrating that a route attractive on circular-economy grounds may still screen poorly when the economic burden is high.

Ion exchange with regeneration. Ion exchange (Huang et al., 2020) holds a stable but non-leading position across the runs, indicating that its lower screening performance is a robust feature of the present comparison rather than an artefact of a single parameter setting. Its moderate cost and recovery efficiency do not offset a weaker climate-substitution benefit, and regeneration chemical requirements may further constrain its environmental profile. This is not a general dismissal of the family; a more conclusive assessment requires long-term evidence on media durability, regeneration stability, chemical consumption, and recovered-product marketability under full-scale WWTP conditions.

Electrochemical nitrogen recovery. The configuration of Koskue et al. (2022) is among the least competitive options here, chiefly because its high electricity demand yields the lowest climate-substitution benefit in the dataset. This cautions against treating electrochemical systems as a homogeneous category, since performance depends strongly on process design, electricity intensity, and the carbon intensity of the electricity supply (Koskue et al., 2022; Nagy et al., 2023). Such configurations may become more attractive under decarbonised electricity or lower-demand designs; the result is best read as an indication of context sensitivity, not as a rejection of electrochemical nitrogen recovery as a technology family.

Side-stream air stripping. The configuration of Brienza et al. (2021) shows the weakest screening performance, combining the lowest recovery efficiency in the dataset with an elevated unit cost relative to the leading air-stripping route, consistent with the higher cost and energy burden of dilute feedstocks. Its rank should still be read cautiously: recovered-product quality and conformity with the EU Fertilising Products Regulation (European Parliament and Council of the European Union, 2019) are not captured by the three-criterion screening set and may become decisive in a subsequent feasibility appraisal.

4.4. Implementation relevance and policy alignment

The robustness results support a sequenced rather than uniform deployment strategy. Lower-cost nitrogen recovery can deliver earlier resource-efficiency and climate-substitution gains in suitable WWTPs, while more complex multi-nutrient routes require further optimisation, scale-up, and regulatory and market validation. The intermediate position of struvite precipitation reinforces the need for cost-reduction pathways and stronger valuation of circular phosphorus benefits. Aligning investment support, green procurement criteria, and regulatory incentives with these differentiated maturity and performance profiles would improve the coherence of WWTP modernisation strategies.

More broadly, the findings support a shift in WWTP decision-making from a narrow pollutant-removal logic towards a resource-recovery logic, under which technologies are judged not only by their ability to remove nutrients but by their capacity to retain nutrients in productive use, offset primary fertiliser demand, reduce climate burdens, and remain feasible under operational constraints. This is the cleaner production contribution of the proposed framework: it translates heterogeneous techno-economic evidence into a transparent and reproducible basis for early-stage circular-resource-recovery decisions.

4.5. Research and innovation priorities

The results map onto clear technical priorities. For electrochemical struvite recovery, these include reducing specific electricity demand, extending electrode service life, lowering reagent requirements, and strengthening coupling with low-carbon or renewable electricity (Nagy et al., 2023). For air stripping, the main priorities are heat integration, reagent recovery, and improved transferability to feedstocks with lower ammonium concentration. For chemical precipitation, they include quantifying scale economies, optimising chemical dosing, and generating stronger evidence on recovered struvite value under different regulatory and commodity-market conditions. For ion exchange, long-term evidence is needed on media stability, regeneration performance, chemical consumption, and product marketability under extended pilot and full-scale conditions.

The results also reinforce the need for richer comparative datasets incorporating uncertainty ranges for cost, climate substitution benefit, and recovery efficiency; nutrient-specific N and P recovery indicators; product purity and contaminant data; regulatory conformity; agronomic performance; operational reliability; and multi-impact life-cycle indicators. Such datasets would allow the PROMETHEE II framework to evolve from literature-based screening towards a more comprehensive, site-specific decision-support tool. Overall, the contribution of PROMETHEE II in this context is not the production of a fixed ranking but the clarification of how technology priorities shift under different decision assumptions, converting heterogeneous evidence into cleaner production guidance for phased deployment, innovation targeting, and regulatory alignment in nutrient recovery from wastewater.

5. Conclusions

This study contributes to cleaner production in wastewater treatment by providing a transparent and implementation-oriented framework for the early-stage screening of nutrient recovery technologies for bio-based fertiliser production. Rather than relying on a single performance indicator or on a fixed ranking, the analysis evaluates alternative recovery routes jointly in terms of total cost, climate substitution benefit, and recovery efficiency per unit of nutrient recovered. In doing so, it supports a more explicit comparison of the economic, climate-related, and resource-efficiency trade-offs that shape circular nutrient recovery decisions in wastewater treatment plants (WWTPs) (Chojnacka, 2023; Guven et al., 2023; Álvarez Salas et al., 2024; Marín et al., 2024).

The results do not identify a universally superior technology. They show, instead, which configurations are most robust within the assessed dataset, the three retained criteria, and the PROMETHEE II modelling assumptions. The electrochemical struvite recovery configuration reported by Morrissey et al. (2022) is the most stable high-performing alternative, remaining within the Top-3 in all 405 sensitivity runs and ranking first in 65.2% of them. Its performance reflects a favourable balance between high recovery efficiency, strong climate substitution benefit, and competitive cost within the harmonised comparison. Air stripping on digestate (Alrbai et al., 2024) emerges as the main competing route, ranking first in 34.8% of runs and showing particular strength under cost-oriented decision profiles. Its relevance is therefore especially clear for WWTPs with access to concentrated digestate streams and strong affordability constraints.

From a cleaner production perspective, these findings support a differentiated shortlisting logic rather than a single technology recommendation. Lower-cost nitrogen recovery routes may offer near-term implementation value where suitable high-strength streams are available, while more integrated multi-nutrient configurations warrant further strategic assessment where broader nutrient circularity and climate substitution objectives are jointly prioritised. The intermediate position of chemical precipitation, despite its relevance for phosphorus recovery, further shows that circular-economy credentials alone do not guarantee a favourable implementation-screening position when economic feasibility is assessed jointly with environmental and technical criteria.

Methodologically, the study demonstrates that combining preference-function scenarios, threshold grids, and stakeholder weighting profiles within a full factorial design generates more informative

rank acceptability evidence than a single-scenario ranking. This structure makes explicit whether an alternative remains competitive across changes in stakeholder priorities and preference-model assumptions, or whether its apparent attractiveness depends on narrower modelling conditions. The approach is transferable to other cleaner production technology-screening problems where evidence is heterogeneous, stakeholder priorities differ, and small reported performance differences may not represent genuine operational advantages.

Several limitations therefore remain. The performance matrix is based on harmonised point estimates from independent literature sources that differ in scale, system boundaries, feedstock characteristics, electricity and reagent assumptions, and recovered product forms. In addition, the three-criterion screening set does not explicitly include product purity, contaminant risks, regulatory compliance, agronomic performance, fertiliser value, market acceptance, operational reliability, or sensitivity to energy and reagent price fluctuations. The avoided-emissions criterion should also be read strictly as a potential climate substitution benefit, not as a complete environmental performance indicator. Final technology selection would therefore require site-specific techno-economic assessment, product-quality verification, regulatory appraisal, agronomic testing, and full multi-impact life-cycle assessment of shortlisted alternatives.

Future research should extend the framework in three directions. First, comparative datasets should report uncertainty ranges for cost, climate substitution benefit, and recovery efficiency, allowing input-data uncertainty to be propagated through the MCDA model. Second, nutrient-specific indicators for nitrogen and phosphorus recovery should be developed, including nutrient-specific substitution credits and recovery efficiencies, so that the strategic value of phosphorus recovery can be assessed more explicitly. Third, additional implementation criteria should be incorporated where comparable evidence becomes available, particularly product quality, contaminant content, regulatory conformity, operational reliability, marketability, and broader life-cycle impacts. Such developments would allow the present PROMETHEE II screening framework to evolve into a more comprehensive decision-support tool for site-specific WWTP upgrading and circular resource recovery planning.

CRediT authorship contribution statement

Isabel González-García: Resources, Funding acquisition, Data curation. **Rocío de Andrés Calle:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Methodology, Investigation, Formal analysis, Conceptualization. **Berta Riaño:** Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. The PROMETHEE II method

This appendix documents the PROMETHEE II method as applied in this study, in four parts: the definition of performance differences and preference functions (A.1); the standard preference functions available within the PROMETHEE family and their behavioural meaning (A.2); the aggregation, outranking-flow, and rank-acceptability formulation used to derive the ranking (A.3); and the rationale for adopting PROMETHEE II under heterogeneous evidence (A.4).

A.1. Performance differences and preference functions

For each criterion j and ordered pair of alternatives (a_i, a_k), the performance difference is defined so that a positive value indicates an advantage of a_i over a_k, after accounting for whether the criterion is maximised or minimised. For maximisation criteria — avoided emissions and recovery efficiency — this is

$$d_j(a_i, a_k) = f_j(a_i) - f_j(a_k), \tag{A.1}$$

and for the minimisation criterion — total cost — it is

$$d_j(a_i, a_k) = f_j(a_k) - f_j(a_i), \tag{A.2}$$

where $f_j(a)$ denotes the performance of alternative a on criterion j. A preference function $P_j : \mathbb{R} \to [0, 1]$ maps this difference into a criterion-level preference degree

$$P_j\big(d_j(a_i, a_k)\big) \in [0, 1], \tag{A.3}$$

where values near zero indicate indifference and values near one indicate strict preference. The specific functional forms that P_j may take are summarised in Appendix A.2.

A.2. Standard preference functions and their behavioural meaning

For transparency and reproducibility, this subsection summarises the standard preference functions available within the PROMETHEE family of methods and clarifies the decision attitudes implicit in each specification. In PROMETHEE, the preference function is not a merely technical choice: it determines how observed performance differences are translated into preference intensities, that is, whether even very small advantages are treated as decision-relevant, whether minor deviations are regarded as negligible, or whether preference strengthens progressively as the size of the difference increases.

The *usual* function reflects a highly decisive attitude. Any strictly positive difference is sufficient to generate full preference, so no indifference region is recognised. This specification is appropriate when even small improvements are considered operationally relevant. By contrast, the *U-shape* function introduces an indifference threshold q, below which differences are treated as negligible. Its use therefore implies tolerance towards minor deviations, which may reflect normal variability, measurement uncertainty, or limited practical significance.

The *V-shape* function assumes that preference increases proportionally with the observed difference until full preference is reached at threshold p. This specification is suitable when larger gains should count progressively more strongly than smaller ones. The *level* function adds an intermediate region between indifference and strict preference, thereby distinguishing weak preference from strong preference. It is especially useful when the decision maker recognises that some differences are noticeable but not yet decisive.

The *V-shape with indifference* function combines these two ideas. Differences below q are ignored, but once that threshold is exceeded, preference increases gradually until full preference is reached at p. This specification is appropriate when minor deviations should be discounted but larger advantages should be recognised progressively. Finally, the *Gaussian* function represents preference as a smooth and continuous process without abrupt cut-offs. Rather than imposing fixed step changes, it allows the strength of preference to increase gradually according to the spread parameter σ, which is useful when the decision maker wishes to avoid rigid threshold behaviour.

The choice among these functions therefore affects the behavioural meaning of the PROMETHEE model. Even when the underlying performance matrix remains unchanged, different preference functions may lead to different rankings because they embody different interpretations of what constitutes a meaningful advantage. In the present study, these behavioural differences are operationalised through alternative

Table A.1
Standard PROMETHEE preference functions, behavioural interpretation, and mathematical expressions.

Function	Formula $P_j(d_j)$	Implicit decision attitude	Typical application
Usual	$P_j(d_j) = \begin{cases} 0, & d_j \le 0 \\ 1, & d_j > 0 \end{cases}$	Any improvement, however small, is treated as decisive.	Criteria for which even marginal improvements are considered relevant.
U-shape	$P_j(d_j) = \begin{cases} 0, & d_j \le q \\ 1, & d_j > q \end{cases}$	Small differences are ignored; only gaps beyond q justify strict preference.	Costs or performance values subject to normal variability.
V-shape	$P_j(d_j) = \begin{cases} 0, & d_j \le 0 \\ d_j/p, & 0 < d_j < p \\ 1, & d_j \ge p \end{cases}$	Preference increases proportionally with the magnitude of the difference.	Environmental gains or efficiency improvements valued progressively.
Level	$P_j(d_j) = \begin{cases} 0, & d_j \le q \\ 0.5, & q < d_j < p \\ 1, & d_j \ge p \end{cases}$	Distinguishes indifference, weak preference, and strong preference.	Semi-quantitative or class-based performance comparisons.
V-shape with indifference	$P_j(d_j) = \begin{cases} 0, & d_j \le q \\ (d_j - q)/(p - q), & q < d_j < p \\ 1, & d_j \ge p \end{cases}$	Ignores very small deviations and strengthens preference progressively for larger ones.	Trade-offs where caution towards minor differences and decisiveness for larger gaps coexist.
Gaussian	$P_j(d_j) = \begin{cases} 0, & d_j \le 0 \\ 1 - \exp\left(-\frac{d_j^2}{2\sigma^2}\right), & d_j > 0 \end{cases}$	Preference increases smoothly, without abrupt threshold effects.	Indicators for which gradual judgement is preferred to rigid cut-offs.

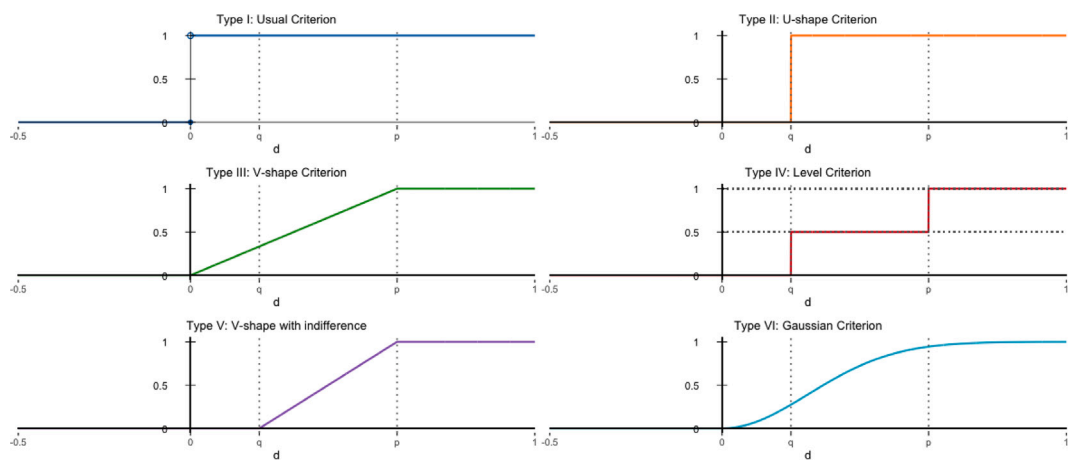

Fig. A.1. Graphical representation of the standard PROMETHEE preference functions.

preference-function scenarios in order to test whether the prioritisation of nutrient recovery technologies remains stable under different interpretations of performance differences.

Table A.1 summarises the standard PROMETHEE preference functions, their mathematical expressions, implicit decision attitudes, and typical fields of application. Fig. A.1 provides a graphical representation of their behaviour.

A.3. Aggregation, outranking flows, and rank acceptability profiles

Criterion-specific preference degrees are aggregated through the global preference index

$$\pi(a_i, a_k) = \sum_{j=1}^{n} w_j \, P_j\big(d_j(a_i, a_k)\big), \tag{A.4}$$

where w_j is the weight assigned to criterion j, with $w_j \ge 0$ and $\sum_{j=1}^{n} w_j = 1$ (Behzadian et al., 2010). These weights operationalise stakeholder priorities: a profile emphasising avoided emissions may reflect a climate-oriented regulator's perspective, whereas a profile emphasising cost may reflect a budget-constrained utility operator's constraints. Because positive values of d_j consistently indicate an advantage for a_i across both maximisation and minimisation criteria, positive contributions to $\pi(a_i, a_k)$ unambiguously support the relative superiority of a_i regardless of criterion direction.

PROMETHEE II then derives a complete ranking through the positive and negative outranking flows

$$\phi^+(a_i) = \frac{1}{m-1} \sum_{k \ne i} \pi(a_i, a_k), \qquad \phi^-(a_i) = \frac{1}{m-1} \sum_{k \ne i} \pi(a_k, a_i), \tag{A.5}$$

and the net flow

$$\phi(a_i) = \phi^+(a_i) - \phi^-(a_i), \tag{A.6}$$

where m is the number of alternatives. Alternatives are ranked in decreasing order of $\phi(a_i)$.

A.3.1. Rationale for rank acceptability profiles

Because the relative weighting of economic, environmental, and technical objectives is genuinely contested among WWTP stakeholders, a ranking derived from a single weighting profile carries limited authority. Rank acceptability profiles address this limitation by recording how frequently each alternative attains each rank across the full scenario space. In this study, $S = 405$ scenarios combine three preference-function scenarios, five weighting profiles, and twenty-seven threshold parameter combinations. A technology whose ranking is stable across this space is one whose relative advantage does not depend on a narrow modelling assumption and therefore provides a more defensible basis for early-stage implementation shortlisting. Conversely, a technology whose ranking is highly sensitive to these choices reveals a genuine trade-off between objectives that investment decisions and regulatory frameworks must address explicitly.

Formally, the rank acceptability of alternative a_i at rank q is defined across all S scenarios as

$$A_{iq} = \frac{1}{S}\sum_{s=1}^{S}\mathbf{1}\{r_s(a_i) = q\}, \tag{A.7}$$

where $r_s(a_i)$ is the rank of a_i in scenario s and $\mathbf{1}\{\cdot\}$ is the indicator function.

A.4. Rationale for the adoption of PROMETHEE II under heterogeneous evidence

Three structural properties motivate the adoption of PROMETHEE II in the present comparison. Its pairwise comparison structure evaluates performance differences criterion by criterion before aggregation, thereby limiting the implicit substitution rates embedded in composite scoring methods. Its preference-threshold mechanism allows the analyst to specify the minimum performance gap considered decision-relevant, which is especially useful when the evidence base differs in system boundaries, allocation conventions, and scope. Treating marginal differences as decisive could otherwise distort technology rankings, particularly when performance values are derived from heterogeneous literature sources. Its net outranking flow produces a complete ranking directly usable for shortlisting. Taken together, these properties make PROMETHEE II well suited to an evidence base that is heterogeneous by construction and to a decision problem in which stakeholders may legitimately weight economic, environmental, and technical objectives differently (Behzadian et al., 2010; Taherdoost and Madanchian, 2023).

Appendix B. Detailed case-study documentation

This appendix collects the detailed material supporting the comparative screening in Section 3: the route-specific cleaner-production interpretations (B.1), the residual comparability constraints (B.2), the implications of the omitted criteria (B.3), the environmental-scope limitations of the avoided-emissions criterion (B.4), the rationale for the N+P aggregation and the nutrient-weighted denominator (B.5), the product-substitution interpretation (B.6), and the justification of the robustness design (B.7). The policy rationale for the criterion set is summarised first.

Policy rationale for the TC–EA–RE criterion set. The three criteria reflect the principal dimensions along which cleaner production performance is evaluated under current EU policy frameworks. The Farm to Fork Strategy targets a reduction in fertiliser use of at least 20% by 2030 (European Commission, 2020), directly incentivising NR as a substitution pathway. The Critical Raw Materials Act classifies phosphorus among the EU's critical raw materials (European Parliament and Council, 2024), assigning additional strategic value to phosphorus recovery routes beyond their immediate economic performance. The Haber–Bosch process — the backbone of synthetic nitrogen fertiliser production — accounts for approximately 1%–2% of total global energy consumption (Erisman et al., 2008), providing a clear decarbonisation rationale for displacing it with recovered nutrients. Together, these frameworks define a policy landscape in which the TC–EA–RE criterion set is not an arbitrary methodological choice but a direct operationalisation of the dimensions that regulators and operators are increasingly required to report and optimise jointly.

B.1. Route-specific cleaner-production interpretations

The descriptions below emphasise the aspects most directly relevant to cleaner production performance: energy demand, process chemical consumption, and nutrient recirculation potential. The technical specifications referenced throughout are reported in Supplementary Table B.2.

Air stripping. Air stripping recovers ammoniacal nitrogen by shifting the NH_4^+/NH_3 equilibrium and transferring NH_3 to the gas phase for scrubbing, typically yielding ammonium sulphate (AS). Its cleaner production profile is shaped primarily by the thermal energy demand for heating the feedstock to operating temperature, the acid consumption in the scrubbing stage, and the displacement potential of the AS product relative to synthetic nitrogen fertilisers. Performance is highly sensitive to influent ammonium concentration and feedstock temperature: the variant treating WWTP digestate (Alrbai et al., 2024) operates on a concentrated stream and achieves a recovery efficiency of 90%, whereas the side-stream configuration treating dilute pig slurry digestate (Brienza et al., 2021) achieves only 57%, with a corresponding increase in unit cost. This concentration sensitivity is central to interpreting the screening results: the apparent cost advantage of air stripping over competing routes depends directly on feedstock characteristics and may not transfer across sites.

Chemical precipitation. Chemical precipitation recovers phosphorus as struvite ($MgNH_4PO_4{\cdot}6H_2O$), with partial co-recovery of ammonium depending on stream composition and Mg dosing. From a cleaner production perspective, this route is distinguished by its simultaneous recovery of nitrogen and phosphorus, its lower direct electricity requirements relative to electrochemical alternatives, and the agronomic value of slow-release struvite as a potential substitute for mined phosphate fertilisers. However, the two alternatives assessed here differ substantially in unit cost (€59.36 vs €39.74 kg^{-1} recovered nutrient (Molinos-Senante et al., 2011; Sánchez et al., 2024)), reflecting differences in plant scale and chemical dosing rather than fundamental process limitations. This spread underscores that process route alone does not determine economic performance; scale and operating context are equally decisive.

Ion exchange with regeneration. Ion exchange captures ammonium selectively from wastewater via specialised media, followed by regeneration steps that recover ammonium salts and hydroxyapatite (HAP). It achieves a moderate unit cost (€5.63 kg^{-1}) and recovery efficiency (85%) (Huang et al., 2020), but its cleaner production profile is partially offset by the chemical burden of the regeneration cycle and the energy required for repeated cycling. The recovery of HAP alongside ammonium salts introduces partial material circularity, distinguishing it from single-nutrient routes; whether this broader recovery scope translates into competitive overall performance is one of the questions the screening is designed to address.

Electrochemical treatment. The two electrochemical alternatives recover nutrients through concentration and controlled crystallisation. They are distinguished by high recovery efficiencies (79%–90%) and substitution potential, but are associated with substantially higher electricity consumption per unit of nutrient recovered than precipitation or stripping. This dependence is directly visible in the criteria: the configuration of Morrissey et al. (2022) achieves the highest avoided emissions (EA = 3.30 kg CO_2e kg^{-1}) alongside a relatively low unit cost (€5.52 kg^{-1}), whereas the configuration of Koskue et al. (2022) shows the lowest avoided-emissions value in the dataset (EA = 1.91 kg CO_2e kg^{-1}), reflecting higher net electricity consumption relative to the displacement credit. This within-route variation illustrates why treating "electrochemical" as a single generic option would misrepresent the comparative landscape.

B.2. Residual comparability constraints and their ranking effects

The harmonisation procedure underlying Table 1 was applied as follows: economic data were converted into a unit cost by annualising reported capital costs over the stated lifespan, adding annual operating costs, and dividing by the annual mass of recovered nutrient; environmental data were expressed as a potential avoided greenhouse gas benefit per kg recovered using a common substitution logic against

Table B.2
Performance matrix and technical specifications of the evaluated NR alternatives.

Source	Technology	Effluent	BBF	AP	VN	NR	Life
Alrbai et al. (2024)	Air stripping	WWTP digestate	AS	856	N	181,472	15
Brienza et al. (2021)	Air stripping (side-stream)	Pig slurry digestate	AS	3545	N	751,540	10
Sánchez et al. (2024)	Chemical precipitation	WWTP digestate	Str	80	N P	4560 10,080	19
Molinos-Senante et al. (2011)	Chemical precipitation	WWTP effluent/sludge	Str	5	N P	1060 630	20
Huang et al. (2020)	Ion exchange (regen.)	WWTP sidestream (solids-free)	AS/AN[e] HAP	98	N P	20,776 629	40
Koskue et al. (2022)	Electrochemical	Dewatering liquor (pig slurry)	N-conc.	–	N	34,675	25
Morrissey et al. (2022)	Electrochemical	WWTP digestate	Str	256	N P	54,272 32,256	40

Column definitions and units.
Effluent: origin stream where the technology is applied.
BBF: bio-based fertiliser product recovered (–) when not reported as a discrete product.
AP ($t\,y^{-1}$): annual production of BBF.
VN: valuable nutrient recovered (N = nitrogen; P = phosphorus).
NR ($kg\,y^{-1}$): mass of nutrient recovered per year (as N or P, consistent with VN).
[e] Depending on the configuration, the recovered product can be reported as ammonium sulphate (AS) or ammonium nitrate (AN).
Abbreviations: WWTP = wastewater treatment plant; AS = ammonium sulphate; AN = ammonium nitrate; Str = struvite; HAP = hydroxyapatite; N-conc. = N-rich concentrate.

conventional fertiliser production; and recovery efficiency was retained as reported or reconstructed from influent load and recovered mass.

Despite the harmonisation summarised in Table 1, several residual sources of non-comparability remain and may influence the PROMETHEE ranking systematically. Scale effects may favour technologies reported at larger or more mature installations: the air stripping configuration of Alrbai et al. (2024) represents a near-market system, whereas several other configurations were reported at pilot or demonstration scale, which typically exhibits higher unit costs independently of process efficiency. Feedstock concentration is particularly consequential for air stripping and precipitation routes, because dilute streams increase the cost and energy burden per kg of nutrient recovered; configurations tested on concentrated digestate sidestreams will therefore tend to show lower unit costs than those applied to dilute effluents, even where the underlying process is similar. Electricity-mix and electricity-price assumptions may affect electrochemical configurations disproportionately, while reagent prices and dosing requirements may influence precipitation and stripping systems in different directions depending on the local cost context. Product form also matters: ammonium sulphate, struvite, hydroxyapatite, and nitrogen-rich concentrates differ in nutrient density, agronomic function, and market value, which may affect the relative performance of configurations producing different output streams. Because the model uses point estimates as input values, configurations sourced from particularly favourable operating contexts may rank higher than they would under median operating conditions. The rankings should accordingly be interpreted as comparative evidence for early-stage shortlisting under harmonised literature data, not as a definitive statement of intrinsic technology superiority.

B.3. Implications of the omitted criteria for practical technology choice

The exclusion of additional feasibility dimensions may affect the practical interpretation of the ranking. Product purity and contaminant content may be decisive for determining whether a recovered material can be used as a fertiliser product rather than requiring further treatment or disposal, particularly for technologies producing chemically complex outputs or products whose acceptance depends on compliance with fertilising-product regulations, including Regulation (EU) 2019/1009 (European Parliament and Council of the European Union, 2019). Operational reliability, sensitivity to reagent supply, electricity-price exposure, and maintenance requirements may alter the relative attractiveness of technologies that appear favourable under the TC–EA–RE screening set, especially for routes requiring stable feed composition, chemical dosing, membrane or electrode performance, or frequent regeneration. Market acceptance and fertiliser value may also modify the effective substitution potential of recovered products, since a technically recoverable nutrient stream does not necessarily translate into an agronomically accepted or commercially viable fertiliser. These dimensions are not treated as secondary in importance, but as insufficiently harmonised across the available literature for inclusion in the quantitative PROMETHEE matrix; introducing them through subjective scores would have added a modelling layer that could not be validated with the available evidence. They are therefore retained as explicit limitations and as key elements for subsequent feasibility assessment.

B.4. Environmental-scope limitations of the avoided-emissions criterion

Whereas Appendix B.3 concerns the implementation dimensions omitted from the criterion set as a whole, this section addresses specifically the environmental scope of the single criterion that is retained, namely avoided emissions. The avoided-emissions criterion (EA) is interpreted strictly as a potential climate-substitution benefit associated with the assumed displacement of conventional mineral fertiliser production, and not as a complete environmental performance indicator. It is computed on a cradle-to-gate basis against established carbon-footprint reference values for conventional N and P fertilisers. Because transport and field-application stages, direct field emissions, eutrophication potential, acidification, toxicity, and other life-cycle impact categories are excluded, EA does not replace a full life-cycle assessment, and the environmental ordering of technologies may change when a broader set of impact categories is considered. The criterion therefore captures one environmentally relevant dimension — climate substitution — that is consistently reportable across the source studies, while the remaining impact categories are identified as part of the subsequent full-LCA stage of the two-stage appraisal.

B.5. Rationale for the N+P aggregation and the nutrient-weighted denominator

The equal-mass N+P denominator is adopted as a transparent and reproducible baseline for cross-technology screening. Under this convention, N-only technologies reduce to per-kg-N metrics, whereas dual-nutrient technologies are evaluated per kg of total recovered N+P. This provides a common reporting basis, but it may under-represent the strategic relevance of phosphorus recovery in contexts where P scarcity,

critical raw material status, or circular phosphorus management are central decision objectives.

A more general nutrient-specific denominator can be written as $w_N m_N + w_P m_P$, where m_N and m_P denote the recovered masses of nitrogen and phosphorus and w_N and w_P their relative weights. Since only relative weights matter, nitrogen may be used as the reference nutrient by setting $w_N = 1$, yielding $m_N + w_P m_P$. In this formulation, w_P is the value assigned to 1 kg of recovered phosphorus expressed in nitrogen-equivalent recovered-nutrient units, and the equal-mass base case corresponds to $w_P = 1$. Conceptually, increasing w_P would increase the weighted denominator of dual-nutrient technologies while leaving N-only routes unaffected (since $m_P = 0$ for those alternatives), and would therefore be expected to favour phosphorus-recovering configurations in P-oriented decision contexts.

A full PROMETHEE re-analysis under nutrient-specific weighting would, however, require more than the recovered N and P mass flows. For TC, the annual cost could in principle be renormalised using the weighted denominator, since the total annual cost is unchanged. By contrast, EA would require nutrient-specific substitution credits, because the avoided emissions of replacing conventional nitrogen and phosphorus fertilisers are not determined by mass alone, and RE is reported as a process-level metric that cannot be consistently decomposed into separate N- and P-specific recovery efficiencies for all alternatives. Reweighting only the cost criterion, while leaving the environmental and technical criteria on the equal-mass basis, would introduce a modelling asymmetry and could give a misleading impression of robustness. The rankings are therefore reported under the equal-mass N+P convention, which is appropriate for a first-stage harmonised screening exercise; applications focused specifically on phosphorus recovery, critical raw material substitution, or nutrient-specific policy targets should complement the present framework with site-specific nutrient-flow data, nutrient-specific substitution credits, and nutrient-specific recovery efficiencies.

B.6. Product-substitution interpretation

Recovered products are interpreted as potential substitutes for conventional mineral fertilisers: ammonium sulphate for nitrogen-based products, and monoammonium phosphate (MAP), diammonium phosphate (DAP), or calcium phosphates including hydroxyapatite for phosphorus-based products. This interpretation links nutrient recovery to a measurable cleaner-production benefit, whereby each kilogram of recovered nutrient may offset demand for primary fertiliser production. Substitution should nonetheless be understood as potential rather than automatic: its realisation depends on product quality, regulatory compliance under Regulation (EU) 2019/1009 (European Parliament and Council of the European Union, 2019), agronomic performance, logistics, farmer acceptance, and market uptake, which are not explicitly modelled here. The harmonised performance matrix should therefore be interpreted as a transparent and reproducible dataset for MCDM-based screening that does not replace site-specific assessment of economic, technical, agronomic, regulatory, and market feasibility.

B.7. Justification of the robustness design

The robustness design varies three dimensions of analytical variation rather than weights alone: the preference-function specification, the stakeholder weighting profile, and the performance-threshold setting. For each criterion, three threshold settings — a stricter, a reference, and a more tolerant specification — represent alternative assumptions about the minimum performance difference that should be treated as meaningful in the pairwise comparisons. These threshold ranges are anchored jointly in the observed spread of criterion values across the seven alternatives and in plausible site-specific operational variability; they should not be read as statistical uncertainty bounds, worst-case scenarios, or universal threshold values, but as a plausible screening envelope for testing whether the ranking depends on strict or more tolerant interpretations of performance differences.

The detailed percentage-of-range justification is as follows. For total cost, among the five alternatives with TC below €6 kg^{-1} — the cost-competitive subset — pairwise cost differences range from approximately €0.1 to €3.9 kg^{-1}, so $q_1 \in \{0.5, 1.0, 1.5\}$ €kg^{-1} corresponds to about 13, 26, and 38 per cent of this competitive range. These values are further anchored in operational variability from electricity prices, reagent prices, scale effects, and operating conditions; recent Eurostat values for medium-sized non-household users range from approximately €0.08 to €0.27 kWh^{-1} (EU average ≈ €0.19 kWh^{-1}) (Eurostat, 2025), which for energy-intensive routes such as electrochemical treatment translates into material differences in unit cost. For avoided emissions, the observed EA range is 1.39 kg CO_2e kg^{-1} (1.91–3.30), so $p_2 \in \{0.2, 0.3, 0.4\}$ kg CO_2e kg^{-1} corresponds to 14, 22, and 29 per cent of this range; the reference value $p_2 = 0.3$ avoids treating very small climate-benefit differences as decisive while preserving discrimination among meaningfully different alternatives. The Gaussian spread $\sigma_2 \in \{0.2, 0.3, 0.4\}$ kg CO_2e kg^{-1} is varied over the same numerical range as p_2 to keep the scale of climate-benefit discrimination comparable, which does not imply behavioural equivalence between the Gaussian and V-shape specifications. For recovery efficiency, the observed range is 33 percentage points (57%–90%), so $p_3 \in \{5, 10, 15\}$ percentage points corresponds to 15, 30, and 45 per cent of this range, representing strict, reference, and conservative interpretations of a decision-relevant difference in nutrient capture.

The three threshold levels for the three criteria yield $3^3 = 27$ threshold combinations, which are crossed with the three preference-function scenarios (PF1–PF3) and the five weighting profiles (W1–W5):

$$3 \text{ preference-function scenarios} \times 5 \text{ weighting profiles} \times 27 \text{ threshold combinations} = 405 \text{ PROMETHEE II runs.}$$

This design is deliberately more demanding than a weight-only sensitivity analysis because ranking changes in literature-based screening may arise not only from different criterion weights but also from different assumptions about whether small differences in cost, climate-substitution benefit, or recovery efficiency are decision-relevant. The resulting rank acceptability profiles indicate robustness within the preference-model space defined by these three dimensions, while remaining conditional on the harmonised input data. They provide model-parameter robustness and do not propagate statistical uncertainty in the input performance values, because the source studies differ in scale, system boundary, and operating conditions in ways that cannot be reduced to a single parametric uncertainty distribution. Input-data uncertainty propagation is identified as a relevant future extension once comparable uncertainty ranges become available across the source studies.

Data availability

Data will be made available on request.

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