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Full length article

Mapping spatial supply-demand patterns of resource recovery from biowaste to advance biocycle economies in India

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ABSTRACT

Recovering energy and nutrients from biowaste can supply essential resources and reduce environmental impacts. To identify pathways to close resource cycles in India, this study maps the spatial distribution of energy and nutrient recovery potentials from human excrements, the organic fraction of municipal solid waste, manure, and crop residues, comparing them with projected demands in 2030. Full recovery without displacing existing uses of biowaste could cover 17 % of residential energy needs and 22 %, 23 %, and 80 % of national nitrogen, phosphorus, and potassium fertiliser demand, respectively. Most energy and nutrients could be recycled within 25 km and within subdistricts, supporting the economic viability of decentralised biological treatment such as anaerobic digestion. However, in regions with a high nutrient surplus or requiring longer transport, advanced recovery technologies producing concentrated mineral recycling fertilisers are needed to enhance financial feasibility. Our spatially explicit approach informs differentiated strategies for scalable, locally adapted biocycle economy development.

1. Introduction

Environmentally sound and safe waste management and sanitation still remain inaccessible to many in developing countries. Yet, biodegradable materials in waste and wastewater (biowaste) contain energy and nutrients, making their management a valuable opportunity for resource recovery (Trimmer et al., 2017; Wainaina et al., 2020; Lohri et al., 2017). Consequently, waste management and sanitation can help close biological resource cycles and support Sustainable Development Goals (SDGs), particularly in sanitation (SDG6), energy (SDG7), and agriculture (SDG2). The need for sustainable practices is urgent in developing countries, where treatment, safety, and disposal are often inadequate (Lohri et al., 2017).

India, like other developing countries, produces substantial urban and agricultural biowaste due to a large and growing population and significant agrarian sector (Franco et al., 2017; World Bank, 2021). Much urban biowaste, including the organic fraction of municipal solid waste (OFMSW) and human excrements, remains untreated and poorly utilised. While municipal solid waste (MSW) is collected and recyclables are often segregated, the residual MSW is typically disposed of untreated, with over half of its mass being biodegradable (Kumar et al., 2017; Breitenmoser et al., 2019; CPCB 2022). Furthermore, only 27 % of household wastewater was safely treated in 2020, posing public health risks (WHO 2021). In contrast, agricultural biowaste is commonly utilised as animal feed or bedding (crop residues) or organic fertiliser (crop residues and manure) (Gross et al., 2021; Hiloidhari et al., 2014), but unused crop residues are often burned or dumped near fields, contributing to air pollution and greenhouse gas emissions (Gadde et al., 2009; Sfez et al., 2017).

Various technologies exist to recover energy, feed and fertiliser (Lohri et al., 2017), and national policies, programmes and development agencies increasingly promote biowaste valorisation, including the *Swachh Bharat Mission* Urban 2.0 and the National Bioenergy Programme (Breitenmoser et al., 2019; CPHEEO, 2016; MNRE, 2022; Ministry of Housing and Urban Affairs, 2021). Among these technologies, anaerobic digestion (AD) has gained attention to enhance energy and fertiliser supply (Breitenmoser et al., 2019; Gross et al., 2021; Rao et al., 2010). AD is a microbial process that decomposes organic matter without oxygen, producing biogas for energy and digestate as fertiliser (Wellinger et al., 2013). While millions of small-scale digesters operate in rural India, urban AD of OFMSW and sanitation-derived biowaste faces barriers including limited source segregation, variable feedstock

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quality, weak fertiliser markets and poor cost recovery (Breitenmoser et al., 2019; Zhu et al., 2007). These constraints are reinforced by weak policy enforcement, insufficient waste and wastewater management fees, and low digestate market value, which often undermine financial viability (Zhu et al., 2007; Mittal et al., 2018).

On the demand side, renewable energy and fertilisers are critical resources. India's annual primary energy consumption has more than doubled in the past 20 years, from 17,000 to 38,000 petajoules per year (PJ yr^{-1}) (IEA 2021), and over 80 % of this energy was derived from fossil fuels and biomass in 2020 (IEA 2021). Enhancing the sustainability and reliability of electricity and cooking fuel supply is vital, as rapid expansion still primarily relies on non-renewable resources, and the electricity supply is prone to blackouts. Also, rural areas often depend on firewood or non-renewable fuels for cooking (World Bank, 2022; WHO, 2022). The energy potential from biowaste has been estimated at 2–3 % of India's total primary energy use or 8–10 % of the primary energy used for electricity generation (Wainaina et al., 2020; Breitenmoser et al., 2019; Rao et al., 2010). While waste-to-energy has received substantial policy and research attention, fertiliser potentials are less documented, despite strong relevance: over one-third of nitrogen and half of phosphorus and potassium fertilisers are imported, and production relies on fossil fuels and non-renewable mined phosphorus (Sharma, 2014; Cordell et al., 2009; Fowler et al., 2013). Human excrements alone could theoretically supply 11 %, 8 %, and 19 % of India's nitrogen, phosphorus, and potassium synthetic fertiliser demand, respectively (Trimmer et al., 2017).

To develop circular markets, policymakers, planners and development agencies need spatial data on potential supply-demand patterns for biowaste-derived products. Spatially explicit data are crucial for delineating the local market potential, identifying appropriate technologies, and estimating transport distances and costs (Trimmer et al., 2017; Fourcroy et al., 2024). Biowaste generation, its energy and nutrient contents, and demand for energy and fertilisers vary across India, owing to the spatial juxtaposition of urban cities and extensive agricultural areas. This study therefore estimates energy and fertiliser recovery potentials from four major biowaste types (human excrements, OFMSW, manure and crop residues) using AD as a promoted and available recovery technology. Results are mapped on a spatial raster and aggregated to multiple administrative levels, including subdistrict (*'Taluk'* or *'Tehsil')*, district, state, and national levels for 2011 and 2030. We also quantify residential energy use (electricity and cooking) and fertiliser application for crop production to calculate and map supply-demand patterns, and estimate transport distances for recovered products as a key cost factor shaped by nutrient density in the final product and, therefore, the nutrient recovery technology (Fourcroy et al., 2024; Trimmer and Guest, 2018). We specifically address the following questions:

- Which percentage of residential energy demand could be covered by AD of biowaste on different spatial levels (local to national) in 2030?
- Which percentage of the fertiliser demand could be covered by nutrient recovery from biowaste on different spatial levels (local to national) in 2030?
- How far must recovered fertiliser products be transported to the demand site?
- What are the implications of the results on the treatment and post-treatment for different biowaste types and a circular economy?

To our knowledge, this is the first study to jointly map energy and nutrient recovery potentials from multiple biowaste streams against spatially disaggregated residential energy and fertiliser demand in India. By combining multi-stream resource assessment with geospatial supply-demand matching, we provide data and maps to identify regions where biowaste recovery can support circular bioeconomies. The results can guide prioritisation of site-specific studies and interventions across waste, energy and agriculture to enhance resource recovery and reduce pollution.

2. Materials and methods

2.1. Study area

India's population reached 1.4 billion in 2024, growing at 1 % annually since 2014 (United Nations 2024). India currently comprises 36 states and union territories, subdivided into 785 districts, up from 640 districts in the 2011 census (the baseline year of this study) (Government of India, 2011). Districts are a suitable level for this study due to their role in managing public services including environment, health, sanitation, and agriculture (Government of India, 2009; Ministry of Panchayati Raj, 1994). At the local administrative level, subdistricts are also relevant, as they comprise towns and villages around an administrative centre that may collaboratively manage waste (Government of Karnataka, 2024).

Agroecological conditions shape crops, agricultural practices, biowaste generation, and fertiliser demand. Despite ongoing population growth and urbanisation, agriculture remained the primary source of income for 43 % of the workforce in 2019 (Franco et al., 2017; World Bank, 2021). The quantity, types, and utilisation of biowaste, as well as the energy sources used for cooking and fertilisers, vary across different contexts in India, impacting both the potential supply of biowaste and the demand for resources derived from it (Gross et al., 2021). For example, over 45 % of the rural population relied on firewood for cooking in 2021, whereas liquefied petroleum gas (LPG) and kerosene have largely replaced firewood in urban areas, where they are used by 89 % of households (NSSO, 2023).

2.2. Methodological approach

Recovery potentials and resource demand were assessed spatially at 1 km (Wainaina et al., 2020) resolution for India in 2011 and projected to the year 2030. We use 2011 as the baseline year because it is the most recent census year with comprehensive population and household energy data. The analysis included human excrements, OFMSW, manure and crop residues. The main steps are detailed in the following sections (Fig. 1).

2.3. Mapping of resource recovery potential and resource demand (steps 1 – 8)

Step 1: Total energy and nutrient potentials in 2011. We first calculated the total energy and nutrient potentials per capita, livestock unit, and cropland area in 2011. The total potential represents the energy and nutrients in the generated biowaste (TP_{Energy} and $TP_{Nutrients}$, respectively) on every km^2 in India in 2011. Annual values of TP_{Energy} and $TP_{Nutrients}$ were calculated as district- or state-level statistics, expressed as mean ± standard deviation (sd) per capita (cap) for human excrements and OFMSW, per livestock unit (lu) for manure and per cropland area (hectare, ha) for crop residues. Detailed formulae are provided in the supplementary information (SI) and are summarised here:

- *Human excrements (MJ cap^{-1} yr^{-1}, kg nitrogen, phosphorus and potassium cap^{-1} yr^{-1}):* TP_{Energy} and $TP_{Nutrients}$ in human excrements depend on the dietary energy and protein intake (Trimmer and Guest, 2018). We used state-level data on per capita calorie and protein consumption, differentiated for urban and rural households (NSSO, 2014a). Based on these values, we calculated urban and rural per-capita excretion factors for each state (formulae S1-S4, SI),
- *OFMSW (residential, commercial, and market waste in MSW) (MJ cap^{-1} yr^{-1}, kg nitrogen, phosphorus and potassium cap^{-1} yr^{-1}):* State-level data about the amount of MSW per capita and year were multiplied with data about biowaste content and its energy and nutrient potential

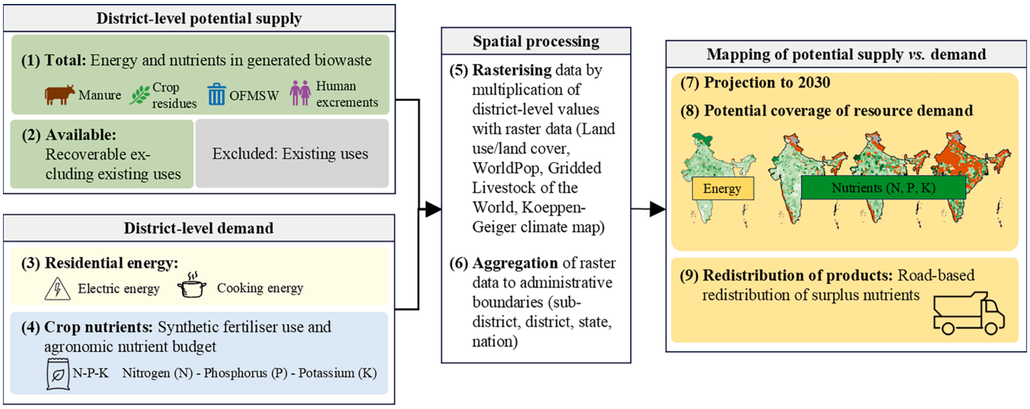

Fig. 1. Methodological approach.

from studies in India (Breitenmoser et al., 2018; Campuzano and González-Martínez, 2016) using formulae S5-S8 (SI).

- *Manure (MJ lu^{-1} yr^{-1}, kg nitrogen, phosphorus and potassium lu^{-1} yr^{-1}):* Excretion factors were estimated using formulae S9-S13 (SI) following the Tier 1 approach for livestock by the Intergovernmental Panel on Climate Change (IPCC, 2019). The assessment distinguished cattle, buffalo, sheep, goats, pigs and poultry and applied livestock-specific typical animal mass and volatile solids and nitrogen excretion rates per 1000 kg animal mass from Intergovernmental Panel on Climate Change (IPCC) Tier 1 livestock guidelines for Indian subcontinent (IPCC, 2019), while phosphorus and potassium excretion rates were obtained by combining these nitrogen excretion rates with manure nutrient ratios from the Food and Agriculture Organization (FAO) crop nutrient budget methodology (FAO, 2022a). (Table S3, SI).
- *Crop residues (MJ ha^{-1} yr^{-1}, kg nitrogen, phosphorus and potassium ha^{-1} yr^{-1}):* Crop residues were quantified from district-level crop production data for 40 crops (ICRISAT 2021) (Table S4, SI). TP_{Energy} and $TP_{Nutrients}$ were calculated from residue energy content and nutrient uptake per unit harvested crop (Ludemann et al., 2023) using formulae S14-S17 (SI). District-level crop data (ICRISAT 2021; ICRISAT 2024) were aggregated as five-year medians for 2009–2013 to account for interannual variability and represent baseline conditions around 2011. For 98 out of 640 districts, missing data were filled using median crop-residue yields from districts with the same state and climate zone. Climate zones were determined by overlaying the district boundaries with a gridded Köppen-Geiger climate map for India (Kottek et al., 2006) and assigning each district to the predominant climate class.

Step 2: Available energy and nutrient potentials in 2011. The available potential represents the technically achievable energy and nutrient potential from AD and post-treatment that does not conflict with existing biowaste uses (AP_{Energy} and $AP_{Nutrients}$, respectively). We calculated:

$$AP_{Energy} = TP_{Energy} \text{ x a\_energy x r\_energy x } \eta_{Final\ energy} \quad (1)$$

$$AP_{Nutrients} = TP_{Nutrients} \text{ x a\_nutrients x r\_nutrients x } \eta_{Post\text{-}treatment} \quad (2)$$

TP_{Energy} and $TP_{Nutrients}$ represent the total energy and nutrient potentials in human excrements and OFMSW, manure and crop residues from Step 1. The available fractions a_energy and a_nutrients represent the shares remain after subtracting existing uses, current resource recovery (including any energy already generated via AD) and collection losses, and were specified per biowaste type (Table S3). Existing nutrient uses mainly comprise manure recycling in crop-livestock systems and the small shares of OFMSW and human excrements already reused; existing energy uses include traditional crop residue combustion and biogas generation in household- and farm-scale digesters. For human excrements and OFMSW, we assumed identical availability for energy and nutrients (a_energy = a_nutrients = 0.95; range 0.80–1.00). For crop residues, we used crop- and state-specific available fractions from Hiloidhari et al. (Hiloidhari et al., 2014), which account for existing uses such as fodder and traditional fuels uses. For manure, only collectable stable manure was considered; manure excreted on pastures was excluded. We assumed 5 % of stable manure is already treated in existing digesters (a_energy = 0.95), and we did not treat manure as an additional surplus nutrient source (a_nutrients = 0.00), assuming nutrients are largely recycled within crop-livestock systems already (Table S3) (Breitenmoser et al., 2019). The factors r_energy and r_nutrients indicate the fractions retained in biogas and digestate following AD treatment and post-treatment. The conversion efficiency ($\eta_{Final\ energy}$) represents different biogas uses: direct cooking use for manure-based AD (typical for small-scale systems in India) and electricity generation for OFMSW, human excrements and crop residues (more likely with larger, grid-connected plants). Nutrient recovery efficiency ($\eta_{Post\text{-}treatment}$) was implemented as data distributions (Table S3) spanning reported performance of digestate use and upgrading options such as phosphorus precipitation, ammonia stripping, ion exchange and adsorption (Trimmer and Guest, 2018; Jensen et al., 2017). These parameters represent current and near-term recovery performance rather than a single fixed technology configuration.

Step 3: Calculate the residential energy demand per capita in each district in 2011. The residential energy demand E (MJ cap^{-1} yr^{-1}) was calculated as district-level statistics (mean ± sd) and included fuels for cooking and electricity:

$$E = \frac{\sum_{f=1}^{4} m_f \text{ x } LHV_f \text{ x } \eta_{Final\ energy}}{cap} + \frac{el}{cap} \quad (3)$$

Where, m_f is the mass of different fuels f (firewood, cow dung, LPG, kerosene in kg yr^{-1}) consumed in each district and year for cooking, based on the National Sample Survey Office (NSSO, 2014b), LHV_f is the lower heating value of the fuel f (MJ kg^{-1}, Table S3), $\eta_{Final\ energy}$ is the conversion to final energy (*c.f.* Formula 1), el the electricity consumed in the district (MJ yr^{-1}) and cap the number of inhabitants sampled in each district (NSSO, 2014b).

Step 4: Calculate the synthetic fertiliser demand and crop nutrient uptake per cropland area in each district in 2011. Median district-level synthetic fertiliser application data between 2009–2013 (NSSO, 2014a) were taken as proxy of farmers' fertiliser demand in 2011. From these records SynFert was derived - the median amount of nitrogen, phosphorus and potassium applied per hectare cropland and year in each district - which serves as the nutrient target to be replaced by biowaste-derived fertilisers. By contrast, the crop nutrient uptake C_i (formula 4, in kg nitrogen, phosphorus or potassium ha^{-1} yr^{-1}) quantifies the nutrients physically removed in harvested crops and enters the agronomical nutrient budget as an output term (formula 5). Hence, SynFert allows us to estimate the share of synthetic fertiliser that could be substituted by recovered nutrients, whereas SynFert and C_i are necessary to assess whether croplands have nutrient surplus or deficit. C_i was calculated as district-level statistics (mean ± sd):

$$C_i = \frac{\sum_{T=1}^{40} a_T \text{ x } (mp_T \text{ x } np_T) \text{ x } (R_T \text{ x } mp_T \text{ x } nr_{T,i})}{A} \qquad (4)$$

where a_T is the gross cropped area (total area sown once or several times per year in ha) of crop type T (40 crops were considered, Table S4) grown in the district (ICRISAT 2020), mp_T is the mass of the harvested crop products of crop T (kg ha^{-1} yr^{-1}) with $np_{T,i}$ the concentration of nutrient i (kg nitrogen, kg phosphorus and kg potassium kg^{-1} of crop product T), R_T is the residue ratio between crop products and crop residues, and $nr_{T,i}$ the nutrient concentration in crop residues (kg nitrogen, kg phosphorus and kg potassium kg^{-1}) (input values in Table S4 based on FAOSTAT (FAO, 2022a; Ludemann et al., 2023). No harvest data were available for 98 of 640 districts (2011 census). These gaps were filled using median per-hectare values from districts within the same state and Köppen-Geiger climate zone, consistent with the crop-residue gap-filling approach.

Step 5: Energy and nutrient supply and demand raster maps (2011). Annual per capita, per livestock unit and per hectare values from steps 1–4 were first derived at district level by linking these values to a district boundary shapefile (Table 1: Administrative boundaries). These district-level coefficients were then applied to the population, livestock and land-use rasters listed in Table 1, yielding maps of absolute quantities per pixel, for example megajoules of available energy or kilograms of nitrogen, phosphorus and potassium. Human population was represented using WorldPop gridded data. Grid cells with a population density ≥ 1400 inhabitants per km^2 were classified as urban and the remainder as rural. This density threshold was selected based on published urban density definitions (Zhou et al., 2019) and adjusted so that the aggregated urban and rural populations from the WorldPop grid matched the Indian national census within ca. 2 %. The output rasters, used for subsequent analysis and visualisation, were calculated at a 1 × 1 km resolution in Albers equal-area conic projection. Down-scaling from lower-resolution to higher-resolution rasters (e.g., the livestock population rasters had a resolution of ca. 10 km x 10 km, Table 1) assumed a homogenous density distribution within lower-resolution rasters.

Table 1
Data sources.

Dataset	Data type and resolution	Year of data
Human population	Raster, 3 ′ (ca. 100 m x 100 m at equator) (Tatem, 2017)	2011
	Raster, ca. 1 km x 1 km (Wang et al., 2022)	2030
Livestock (cattle, buffalo, sheep, goats, pigs and poultry)	Raster, 3 ″ (ca. 10 km x 10 km at the equator) (FAO, 2022b)	2015
	Statistics, district-level (ICRISAT 2020)	2012, 2019
Cropland areas extracted from land cover map (Buchhorn et al., 2020)	100 m x 100 m	2019
Administrative boundaries	Baseline: Vector (polygon) data at national-, state-, district- and subdistrict-level of 2011 (most recent national census) (GADM, 2018)	2011
	Projections for 2030: Vector (polygon) data at national-, state-, district- and subdistrict-level (Survey of India, 2023)	2023
Crop statistics (ICRISAT 2020)	Statistics, district-level	2009–2017
Synthetic fertiliser (ICRISAT 2020) demand	District	2009–2017
Household level data (NSSO, 2014b)	District and lower	2011
Roads (Open Street Map 2023)	Vector, including primary and secondary roads from OpenStreetMap	2023

Step 6: Aggregation to different administrative levels and comparison with statistical data (2011). Raster outputs from step 5 were summed within administrative boundaries to give total and available potentials at subdistrict, district, state and national scales (Table 1). Aggregation was performed twice: (i) with 2011 boundaries to benchmark against census data and (ii) using the current district boundaries for all 2030 results, assuming no boundary changes until then.

Step 7: Projection to 2030. For human population, gridded population projections for 2030 under the SSP2 'middle of the road' scenario were used (Wang et al., 2022). For crops and synthetic fertiliser use, district-level annual change rates were derived by comparing baseline conditions around 2011 (five-year medians for 2009–2013) with five-year medians centred on 2016 (2013–2017) and then extrapolated to 2030. For livestock, district-level annual change rates were derived from district statistics for 2012 and 2019 and then extrapolated to 2030, reflecting the available district time series used in this study. The resulting district totals were subsequently scaled to match national projections for India by FAO (Alexandratos and Bruinsma, 2012). Final energy demand in 2030 was estimated based on scenarios by the International Energy Agency (International Energy Agency 2021) and downscaled to districts in proportion to reported energy use.

Step 8: Potential coverage of resource demand per raster cell and administrative level. For each raster cell (result of step 5) and each administrative level (result of step 6), the potential coverage of residential energy demand was determined as a percentage of residential energy consumption. The potential coverage of synthetic fertiliser demand was determined as a percentage of its usage.

To identify areas with nutrient deficits or surpluses, an agronomic nutrient budget N_i (kg nitrogen, phosphorus or potassium yr^{-1}) was calculated for each raster cell and administrative level. This budget indicates where biowaste-derived fertilisers could help reduce nutrient deficits or replace synthetic fertiliser inputs. N_i was calculated as the difference between nutrient inputs and outputs for cropland areas on the raster cell, following Formula 5:

$$N_i = In_i - Out_i = SynFert_i + Man_i + CR_i\ (+\ Depo) + RecFert_i - C_i\ (-\ losses_i) \qquad (5)$$

where inputs (In_i) - separate for the nutrients i (nitrogen, phosphorus or potassium, in kg) - include synthetic fertilisers ($SynFert_i$), manure (Man_i), crop residues (CR_i), atmospheric deposition (Depo, only for nitrogen) and biowaste-derived recycling fertilisers ($RecFert_i$, e.g., compost or digestate). Outputs (Out_i) include crop nutrient uptake (C_i, formula 4) and losses from the plant-soil system (only for nitrogen). Nitrogen losses, including gaseous emissions and leaching through soil layers, can be substantial and were estimated as 50 % of nitrogen inputs to cropland (Pathak et al., 2010). Phosphorus and potassium surplus (i.e. $N_{Phosphorus} > 0$ or $N_{Potassium} > 0$) was assumed to accumulate in the soil (Pathak et al., 2024). All values are expressed for the raster cells in kg yr^{-1}. A negative N value indicates a nutrient deficit, $N = 0$ reflects a balanced budget, and a positive N value suggests excess nutrient inputs. While the agricultural nutrient budget accounts for key input and output flows, actual values vary with soil type, climate, and management practices.

2.4. *Redistribution of products (step 9)*

Road transport distances were estimated to characterise required redistribution of surplus nutrients rather than optimise logistics. An iterative allocation procedure was used to match the available nutrient potential from biowaste with demand across space. First, available biowaste-derived nutrients were allocated within each subdistrict to offset nutrient deficits ($N< 0$, formula 5) and substitute synthetic fertilisers. Any surplus was transferred to the nearest subdistrict with unmet demand (i.e., nutrient deficit, if any, plus synthetic fertiliser use), while ensuring the receiving subdistrict's nutrient balance did not exceed $N= 0$. Iteration prioritised supply hotspots and continued until either no surplus remained, or demand was met. For each subdistrict, we recorded nutrients used locally and exported. Distances were computed along the OpenStreetMap road network (Table 1) using centroid-to-centroid routing with the *dodgr* package in R. Intra-subdistrict distances were approximated by the maximum centroid-to-boundary distance.

Transport distances were estimated separately for nitrogen, phosphorus, and potassium to reflect their differing spatial supply-demand patterns and potential treatment routes (e.g. targeted recovery or blending), although products would typically be moved as mixed fertilisers (e.g. digestate). In the main part of this paper, biowaste-derived nutrients were assumed to substitute synthetic fertilisers irrespective of nutrient use efficiency (i.e., the capacity of plants to effectively use fertiliser nutrients), market competition and consumer preferences. Because these factors are highly dependent on the specific fertiliser product and context, transportation was also calculated for other substitution assumptions as described in the sensitivity analysis in the following section.

2.5. Uncertainty and sensitivity analysis

Many parameters in this paper have uncertainties, which were quantified using Monte Carlo analysis with Latin hypercube (LHC) sampling. LHC sampling generated distributions of 1000 values for uncertain parameters (Table S3), with most distributions assumed to be uniform. The simulation was conducted 1000 times to assess resource recovery potential, resource demand, and potential resource coverage. The mean values of these simulations, along with their derived standard deviations, are detailed in the results section.

As previously noted, it was assumed that all recovered plant nutrients would be utilised, regardless of the availability of biowaste-derived fertilisers, market competition, and consumer preferences. To evaluate the sensitivity of the transport distance calculations to this assumption, alternative calculations were performed assuming that only 25 % of the mineral fertilisers could be substituted with biowaste-derived fertilisers, with results detailed in the supplementary information.

3. Results and discussion

3.1. National resource recovery potential

By 2030, biowaste in India could provide substantial additional energy and plant nutrients without affecting existing uses. Our model suggests that full recovery from available biowaste would yield about 1539 petajoules (PJ) final energy per year (yr^{-1}) and annual nutrient potentials of about 5.8 million tons (Mt) nitrogen, 1.1 Mt phosphorus and 3.4 Mt potassium (Table 2, Fig. 2a and Fig. 3a,d,g). The associated uncertainty from the Monte Carlo simulation is on the order of ±40 % for energy and ±25–35 % for nutrients relative to the respective mean estimates. At the national scale, these available potentials correspond to about 17 % of the projected residential energy demand or 4 % of the projected final energy demand of all the sectors (International Energy Agency 2021). The associated national nutrient potentials are equivalent to 22 %, 23 % and 80 % of projected synthetic fertiliser demand for nitrogen, phosphorus and potassium, respectively, in 2030 (Figs. 2a and Fig. 3a,d,g).

Most of the energy potential is derived from agricultural biowastes. Collectable manure and unused crop residues together account for roughly 90 % of the available national energy potential (Fig. 2a and Table 2). Both biowastes already play a key role as organic fertilisers (Fig. 3a,d,g), but still a substantial share of crop residues is openly burned, causing air pollution and health impacts. Treating stable manure and the share of crop residues already used as organic fertilisers in AD would therefore mainly reroute existing organic fertiliser flows into cooking fuels and electricity, rather than adding new nutrient inputs. In contrast, urban biowaste streams are more important for nutrients than for energy. Human excrements and OFMSW contribute only about 10 % of the available national energy potential but more than half of the nutrient potential (Fig. 2a and Fig. 3a,d,g). If fully recovered, nutrients in human excrements alone could replace roughly 14 % of synthetic nitrogen and phosphorus fertiliser demand and around one-quarter of potassium demand, while supplying about 2 % of residential energy demand by 2030.

Previous studies support the differentiated pattern observed here. Global assessments by Trimmer et al. (Trimmer et al., 2017; Trimmer and Guest, 2018) show that nutrients recoverable from human excrements could offset around 10–15 % of projected synthetic fertiliser use by 2030, while contributing only about 1 % of household electricity demand. In Pakistan, Akram et al. (Akram et al., 2018) show that recycling human excrements and manure could fully replace synthetic potassium fertilisers and substantially reduce synthetic nitrogen and phosphorus fertiliser use. Taken together, recovery from urban biowaste primarily advances nutrient security and pollution control, while energy benefits from these sources are typically secondary.

3.2. Closing local resource cycles

Because recovery depends on proximity between biowaste and demand, we analyse subdistricts, which link urban sources with nearby agricultural demand in one planning unit. By 2030, the median available biowaste potential across subdistricts reaches 19 % (11–34 %, interquartile range) of residential energy demand, and 33 % (21–65 %), 37 %

Table 2
Projected amounts of biowaste and the available energy, nitrogen, phosphorus and potassium recovery potential in 2030. Energy values represent final energy: for manure, this refers to biogas used directly for cooking; for all other biowaste types, energy is expressed as electricity, assuming centralised conversion. t yr^{-1} = tonnes per year; PJ yr^{-1} = petajoules per year.

Biowaste	Amount (mio. t yr^{-1})		Energy (PJ yr^{-1})	Nitrogen (mio. t yr^{-1})	Phosphorus (mio. t yr^{-1})	Potassium (mio. t yr^{-1})
	Total	Available				
Manure	2090	560	747	[b]	[b]	[b]
Crop residues	1225	379	610	1.3	0.2	1.4
OFMSW	103	98	113	0.8	0.2	1.0
Human excrements	526[a]	499[a]	69	3.7	0.7	1.0
Total	**3944**	**1457**	**1539**	**5.8**	**1.1**	**3.4**

[a] Calculated as mass dewatered sludge based on phosphorus excretion, with an assumed total solids (TS) content of 0.25 kg TS per kg and a phosphorus concentration of 0.6 % of TS.

[b] all manure from stables was assumed to be utilised as organic fertiliser, resulting in no available nutrients being calculated.

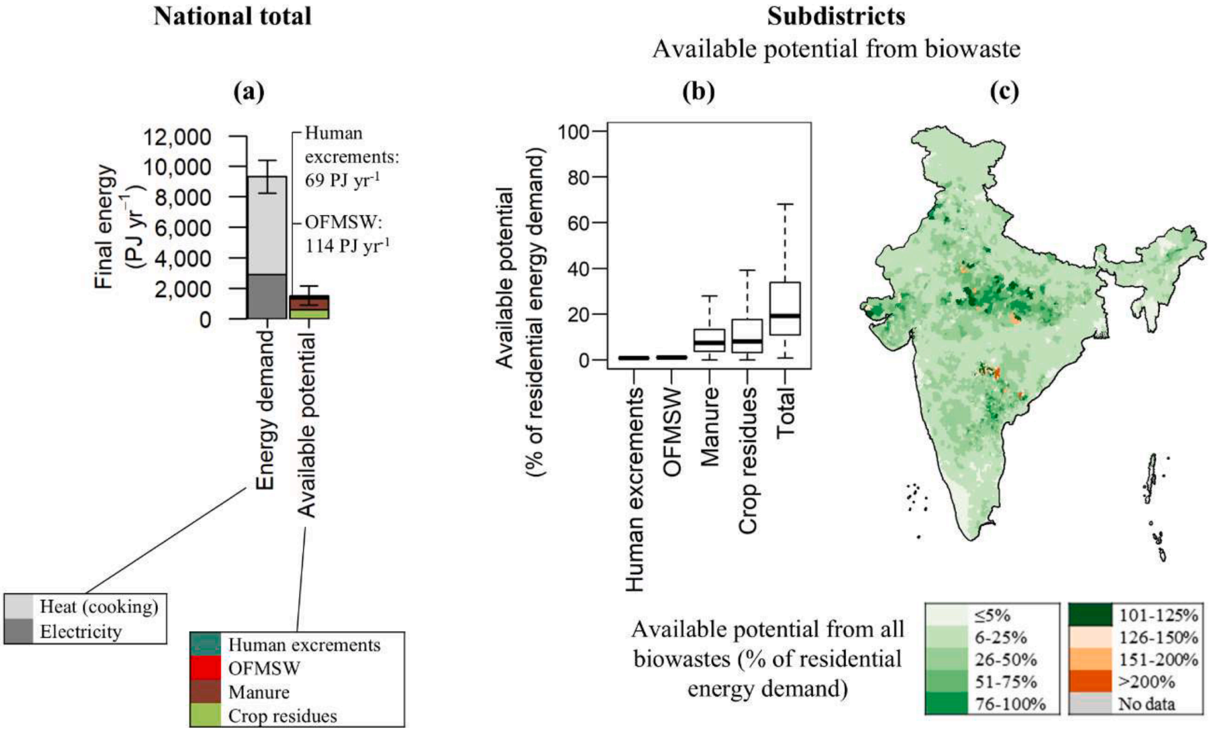

Fig. 2. National totals of residential energy demand and available energy potential from biowaste (a), boxplots showing the distribution of available energy potential from biowaste relative to residential energy demand across Indian subdistricts (b), and demand coverage map of the subdistricts (c).

(23–75 %), and 22 % (16–38 %) of synthetic nitrogen, phosphorus, and potassium fertiliser demand, respectively (Figs. 2b,c and Fig. 3e,f,h,i). This heterogeneity reflects spatial differences in climate, agricultural practices, waste generation, and socioeconomic conditions. In many subdistricts, urban sources (OFMSW, human excrements) are close to surrounding cropland, enabling local use of recovered energy and nutrients. Available nutrient potential exceeds projected demand in 18 % (nitrogen), 20 % (phosphorus), and 11 % (potassium) of subdistricts, indicating that recycling could remain predominantly local. This aligns with a district-level assessment from Pakistan, where most districts could recycle nutrients from manure and human excrements internally, while still requiring synthetic fertiliser inputs (Akram et al., 2018), and with a global city-level analysis showing short reuse distances in many Asian settings due to dense peri-urban agricultural demand (Trimmer and Guest, 2018).

Agricultural biowaste, including manure and crop residues, serves as both organic fertiliser and energy source for rural households and farms today (Hiloidhari et al., 2014). If all stable manure were treated in AD systems, it could cover >15 % of residential energy demand in half of the subdistricts by 2030 (Fig. 2b). However, only 10–40 % of installed household-scale AD plants remain operational after several years, mainly due to maintenance challenges and lacking repairs (Breitenmoser et al., 2019). Crop residues offer a median recovery potential of 8 % (3–18 %) of residential energy demand (Fig. 2b) and 10 % (5–16 %) of synthetic fertiliser demand by 2030 (Fig. 3b,e,h). Due to high fibre content and low moisture, crop residues are best suited to high-solids AD especially when co-digested with other biowaste, with low water demand being particularly relevant in arid regions (Satpathy and Pradhan, 2020).

Urban biowaste types are less utilised, although national policies and funding support the treatment of OFMSW and human excrements (e.g., as sewage sludge from wastewater treatment) through AD or composting (Breitenmoser et al., 2019). By 2030, resource recovery from OFMSW and human excrements could contribute only <2 % of the residential energy demand (Fig. 2b), but substantially to nutrient recovery, potentially covering 24 % (11–57 %), 23 % (13–66 %), and 11 % (5–27 %) of synthetic nitrogen, phosphorus, and potassium fertiliser demand, respectively (Fig. 3b,e,h). Realising this nutrient potential is mainly constrained by incomplete collection and treatment and by quality risks from poor segregation and contaminated sludge. In 2020, only 18 % of residential wastewater was collected centrally and <20 % of urban wastewater was properly treated (WHO 2021; CPCB 2021), highlighting that improved sanitation is a prerequisite for scalable nutrient recovery.

Fostering decentralised biowaste treatment and integrating nutrient recovery will be crucial. Digestate requires careful management to avoid contamination risks with pathogens, trace metals, and micropollutants (Sude et al., 2024). Where contamination risks are high or product standardisation is needed, advanced nutrient recovery technologies, such as struvite precipitation and ammonia stripping, offer safer alternatives with fertilisation properties comparable to synthetic products (Vaneeckhaute et al., 2017; Rizzioli et al., 2023). Larger towns and cities with a high density of urban biowaste are therefore promising entry points for piloting centralised nutrient recovery as part of new or upgraded resource recovery facilities.

3.3. *Transportation and implications for resource recovery*

The spatial distance between nutrient availability and agricultural demand shapes how readily biological resource cycles can be closed. International studies suggest that transporting digestate is economical only over 20–70 km (Tesfamariam et al., 2020). Our routing analysis shows that about two-thirds of available nitrogen, phosphorus and potassium can be matched to agricultural demand within 25 km, and a further 20–25 % within 25–50 km; <10 % require transportation beyond 50 km (Fig. 4). Even high-availability states such as Uttar Pradesh, Madhya Pradesh and Rajasthan could recycle most nutrients within 50 km. Notably, most recycling could occur within subdistricts, which typically combine urban and rural areas under one administrative unit (median 90 % recycled locally; 65–98 % interquartile range, data not shown). We assumed full substitution of synthetic fertilisers by biowaste-derived nutrients, which likely overestimates replacement.

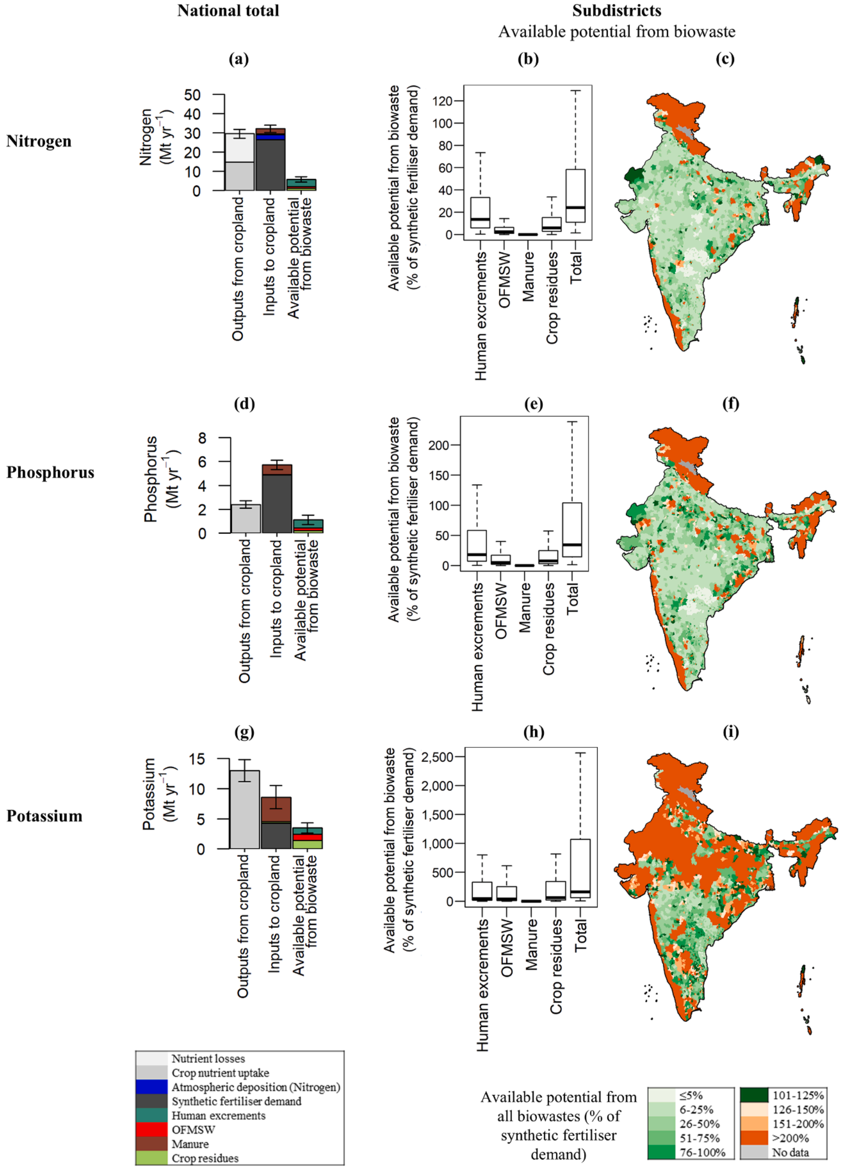

Fig. 3. National totals of nutrient outputs from cropland, nutrient inputs to cropland and available nutrient potential from biowaste (a,d,g), boxplots showing the distribution of available nutrient potential from biowaste relative to synthetic fertiliser demand across Indian subdistricts (b,e,h), and demand coverage maps of the subdistricts (c,f,i).

However, reducing substitution from 100 % to 25 % did not change results substantially (Fig. S1), indicating that local recycling with short transport remains viable under conservative assumptions. This is consistent with global city-level evidence that nutrient reuse distances are often relatively short in Asian cities because peri-urban cropland can absorb much of the recovered nutrients (Trimmer and Guest, 2018). In a city-level analysis (Trimmer and Guest, 2018), Beijing and Shanghai illustrate this pattern, with most recoverable nitrogen reusable within tens of kilometres, whereas very large and coastal agglomerations show markedly longer distances as coastlines constrain redistribution.

These generally short distances in India favour decentralised planning and treatment. In most regions, conventional technologies such as AD with dewatering and composting are sufficient to deliver biogas and organic fertilisers for nearby cropland. However, because these products are bulky and have relatively low nutrient and energy densities, transport costs rise quickly with distance and can exceed the value of displaced synthetic fertilisers. In subdistricts with nutrient surpluses or where exports beyond local recycling are required, nutrient-concentration steps may be warranted despite higher costs. Technologies such as struvite precipitation, ammonia stripping or membrane-based recovery can produce more concentrated, standardised mineral recycling fertilisers that are easier and cheaper to transport and integrate into fertiliser markets (Fourcroy et al., 2024; Trimmer and Guest, 2018; Vaneeckhaute et al., 2017; Rizzioli et al., 2023). Mineral recycling fertilisers can also reduce risks linked to organic fertilisers: while digestate and compost can improve soil structure and carbon storage, their nutrient content is variable, nutrients are not fully plant-available, and contaminants (e.g., plastics, trace metals) may occur (Nkoa, 2014). Mineral fertilisers therefore remain essential for precise nutrient supply and yield targets, and farmers often blend mineral and organic inputs.

These advanced recovery routes are economically viable only where waste and wastewater management fees, together with revenues from energy and fertiliser products (and, where relevant, carbon credits), cover investment and operation costs, and market risks. In India and similar low- and middle-income settings, further research and development and demonstration are therefore critical to adapt these technologies to local capacities and waste streams, reduce costs, and prove

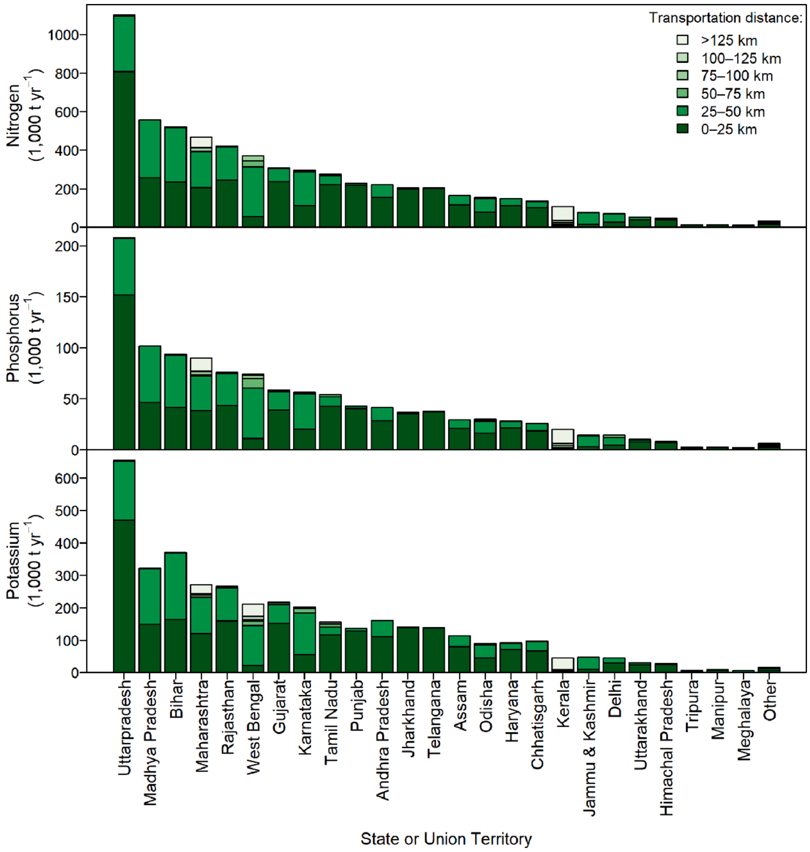

Fig. 4. State-wise available nitrogen, phosphorus, and potassium from biowaste recovery, classified by transportation distance for synthetic fertiliser substitution; percentages show shares usable within subdistrict (top 25 states shown, remaining states grouped under 'Other').

robust long-term performance and product quality under real operating conditions. Tailoring technology choice to local nutrient balances, fertiliser quality requirements, and transport logistics remains key.

3.4. Implications for policy, practice and future research

Our findings highlight that India should prioritise decentralised biowaste treatment, as short transport distances and spatial alignment with demand allow most subdistricts to manage biowaste locally (Fig. 4). Hence, despite the low nutrient density of digestate and compost, conventional post-treatment methods - such as dewatering and composting - are feasible in many regions. To reduce contamination risks and operational challenges, maintaining biowaste quality is essential. Planning should focus on controlled biowaste streams from farms, food industries, and markets, while progressively integrating more variable sources such as OFMSW through source-segregated, pollution-free collection.

Because agriculture also requires readily plant-available mineral fertilisers, investments in advanced nutrient recovery technologies, such as struvite precipitation or ammonia stripping, will be crucial in areas with a high nutrient excess, significant biowaste production or polluted waste streams. Scaling such technologies requires product standards, farmer-oriented product testing, and demonstration projects to build confidence and ensure agronomic effectiveness. Implementation-focused studies engaging stakeholders can foster product trust and viable business models. Financial sustainability should be tested through combinations of waste and wastewater management fees, product sales, and targeted subsidies.

Our analysis identifies subdistricts as practical governance units for regional biowaste management and closing biological resource cycles, combining urban and rural areas under one administrative framework. Effective site-specific planning must integrate legal, socio-cultural (e.g., product acceptance), agronomic, environmental, capacity and economic considerations (Lohri et al., 2017; Fourcroy et al., 2024). The geospatial approach developed in this study provides a foundation for identifying priority locations and tailoring solutions to local conditions through multi-criteria decision-making (Silva et al., 2014).

Finally, our spatially explicit approach can also support further treatment and recovery technologies, such as black soldier fly treatment, which produces both protein-rich animal feed from larvae and organic fertiliser (*frass*). The approach can be extended to support the planning and siting of such technologies by identifying regions with sufficient biowaste availability and local demand for recovered products in animal husbandry and for plant growth.

3.5. Limitations

This study integrates multi-sector annual data on waste, sanitation, agriculture and energy to map potentials for a biocycle economy in India. Several limitations of this spatial modelling approach should be considered when interpreting the results. First, constraints in data availability included the reliance on population data of 2011 for the baseline conditions (the latest published census in India) and gaps in agricultural data in several districts. These gaps were filled using global raster data - such as WorldPop (Tatem, 2017) and gridded livestock of the world (FAO, 2022b) - and input from similar regions in India. Remaining data gaps had to be filled using median values by state and climate zone, which may smooth local extremes. Second, the model did not account for the seasonal variation of biowaste availability and demand of energy and fertilisers, which must be considered in detailed planning. For example, livestock may be distant from stables during certain months, affecting the availability of biowaste. The reported values should therefore be interpreted as annual averages and upper bounds of available energy and nutrients. Third, we assume that biowaste is treated via AD with a range of reported conversion efficiencies and nutrient recovery rates. Site-specific factors such as feedstock contamination, process disturbances and infrastructure constraints are only captured through conservative assumptions on available fractions and recovery efficiencies. For instance, environmental factors such as low temperatures in northern and mountainous regions, which necessitate adaptations like extended retention times, insulation, or solar heating for AD systems, were not explicitly modelled (Gross et al., 2017; Buysman, 2009). Finally, the model does not simulate detailed plant siting, collection logistics or full techno-economic feasibility. The resulting spatial patterns thus indicate where resource recovery is promising, rather than predicting where plants should be built in practice.

The geospatial framework presented provides a robust starting point for more detailed, site-specific planning that explicitly considers technology choice, financing, governance and farmer behaviour. The approach is scalable and can be adapted to higher or lower spatial resolution depending on input data available. In future work, coupling this approach with spatio-temporal models (e.g., at the river basin scale with monthly resolution) could enhance the dynamic assessment of supply-demand patterns and infrastructure planning (Vaneeckhaute, 2021).

4. Conclusions

This spatial analysis reveals a strong geographic alignment between biowaste generation and resources demand across India. As a result, business models and technologies tailored to local markets - requiring minimal transport and non-polluted source segregation - will be essential to closing resource cycles. In most regions, short distances favour decentralised systems using conventional treatment and low-tech post-processing. In contrast, areas with nutrient surpluses, high biowaste volumes or polluted waste streams will require larger-scale infrastructure and advanced recovery technologies, such as mineral fertiliser production for regional distribution. These findings underscore the need for spatially differentiated strategies that match technological choices with local resource patterns and transport conditions.

CRediT authorship contribution statement

T. Gross: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **L. Breitenmoser:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Conceptualization. **S. Kumar:** Writing – review & editing, Project administration, Funding acquisition, Conceptualization. **C. Hugi:** Writing – review & editing, Validation, Project administration, Funding acquisition, Conceptualization. **A. Ehrensperger:** Writing – review & editing, Conceptualization.

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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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2026.108874.

Data availability

Data will be made available on request.

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