





## Technology evaluation and impact assessment of innovative wastewater treatment and resource recovery systems in Kanpur, India

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### ABSTRACT

Resource recovery from wastewater treatment plants is crucial for India's circular economy, as emphasized by the national draft water reuse norms 2024. This study evaluated resource recovery technologies using circularity and sustainability assessment methods to inform technology selection. A multiple-criteria decision analysis compared three innovative and two reference treatment trains in Kanpur, India, based on treatment performance, costs, and resource recovery potential. Quantitative microbial risk and life cycle assessments further evaluated health and environmental benefits and burdens. Innovative systems, such as Andicos (ultrafiltration + co-digestion) and SFD-MBR (slow-forming dynamic membrane bioreactor) had slightly lower performance indices ( $\Delta PI$ : 0.10–0.12) than the reference system MBR due to lower nutrient removal. The innovative systems generated 1.3 to 2 times more revenue from selling water, nutrients, and energy. Further, reusing nutrient-rich treated effluents for irrigation reduced eutrophication potential by 94%. Treatment trains with constructed wetland plus (CW+) achieved the highest faecal coliform (FC) removal, meeting reuse norms of <5 MPN/100 mL, potentially preventing up to 2,600 gastrointestinal infections annually among 4,000 farmers using the water for irrigation. This study highlights the potential environmental, health, and economic benefits of innovative wastewater treatment technologies for advancing resource recovery in India.

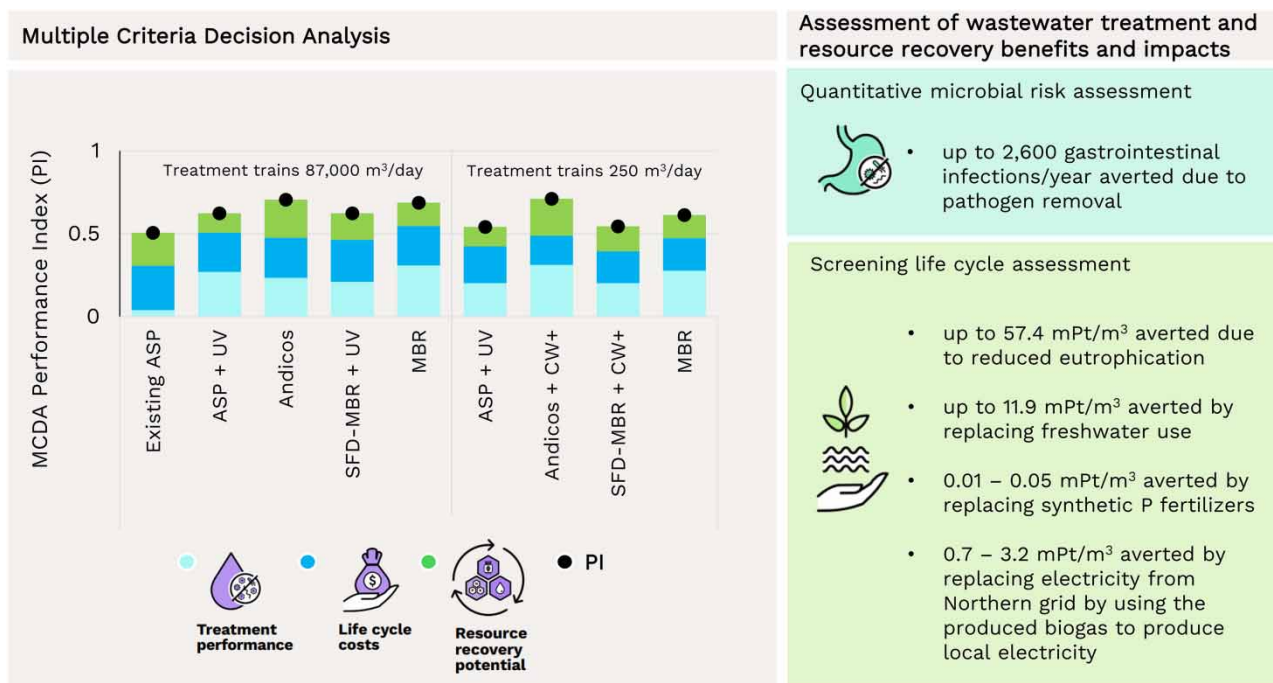
**Key words:** circular economy, multiple-criteria decision analysis, resource recovery, sustainability assessment, wastewater treatment

### HIGHLIGHTS

- Comparing wastewater treatment systems based on performance, costs, and recovery potential.
- Conventional systems (ASP and MBR) slightly excelled in TSS, BOD, COD, and nutrient removal.
- Innovative systems (Andicos and SFD-MBR) generated higher revenues from resource recovery.
- CW+ systems met water reuse norms for faecal coliforms.
- Water reuse offers greater environmental benefits than energy and nutrient recovery.

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## GRAPHICAL ABSTRACT



## INTRODUCTION

**Wastewater and the circular economy in India**

Recovering resources from wastewater, e.g., water for irrigation, bioenergy, or fertilizers, holds a significant potential to contribute to a circular economy (Smol *et al.* 2020). Circular waste management models are prominently addressed in the Sustainable Development Goals (SDGs), where water reuse (SDG 6), renewable energy (SDG 7), and nutrient recycling and reuse (SDG 12) are promoted to restore degraded soils (SDG 15), support sustainable agriculture and food security (SDG 2), and build resilient cities (SDG 11) (Otoo & Drechsel 2018).

Wastewater treatment plants are increasingly recognized as necessary alternative water and nutrient providers for Indian urban and peri-urban agriculture in India, supported by recent government programmes (NIUA 2024). The National Framework on Safe Reuse of Treated Water was launched in 2022 (NMCG 2022), and new water reuse norms were drafted in 2024, promoting safe agricultural water reuse practices (CPCB 2024). The new national draft water reuse norms 2024 no longer define nutrient thresholds (CPCB 2024; Table 1), unlike previous standards such as the sewage treatment plant (STP) effluent discharge standards (NGT 2019) and water reuse norms of 2012 (CPHEEO 2012). This shift could benefit the wastewater treatment sector in two ways: (i) nutrient removal processes are no longer required for the effluent reused in agriculture, which can reduce operational costs and (ii) additional revenue opportunities could arise if farmers are willing to pay for the nutrient-rich irrigation water, replacing synthetic fertilizers.

The increasing national demand for phosphorous (P) fertilizers, rising fertilizer prices, and growing water stress will likely drive greater interest in treated effluents (Kumar & Goyal 2020). India is the second largest consumer of P globally (Watts & Woodruff 2017). Reducing India's dependence on imported P is a critical step towards 'self-reliance' (Nanda *et al.* 2019). Gowd *et al.* (2022) calculated that chemical precipitation and P recovery from all Indian wastewater produced could avoid around 4% of the total P fertilizer imports, valued at up to 110 million USD/yr while also reducing greenhouse gas emissions by 663 kg CO<sub>2eq</sub>/ha of agricultural land through a shift to recovered fertilizer. Bassi *et al.* (2023) estimated that using all secondary treated wastewater available in 2021 (11,622 million m<sup>3</sup>) could meet up to 2% of India's irrigation demand and supply up to 6,000 tons of recovered nutrients.

Standard wastewater treatment technologies in India include sequential batch reactors, activated sludge processes (ASPs), membrane bioreactors (MBRs), up-flow anaerobic sludge blankets, and waste stabilization ponds (CPCB 2021; Bassi *et al.*

**Table 1** | Secondary treated STP effluent discharge standards and water reuse norms in India

		pH	BOD (mg/L)	TSS (mg/L)	COD (mg/L)	TN <sup>a</sup> (mg/L)	TP <sup>b</sup> (mg/L)	Faecal coliforms desirable (MPN/100 mL)	Faecal coliforms permissible (MPN/100 mL)
STP effluent discharge standards for Class I cities/other (NGT 2019)		6.5–9.0	20/30	30/50	100/150	15	1	230	1,000
Recommended norms for water reuse in agriculture 2012 (CPHEEO 2012)	Non-edible crops	–	20	30	30	10 <sup>c</sup>	2	–	230
	Edible crops – raw	–	10	0	–	10 <sup>c</sup>	5	–	0
	Edible crops – cooked	–	20	30	30	10 <sup>c</sup>	2	–	230
Draft norms for water reuse in agriculture 2024 (CPCB 2024)	Non-edible crops	6.5–8.5	≤ 6–10	AA <sup>d</sup>	AA <sup>d</sup>	AA <sup>d</sup>	AA <sup>d</sup>	–	100
	Edible crops – raw							–	0
	Edible crops – cooked							–	≤ 5

<sup>a</sup>Total nitrogen (TN) = Ammonical nitrogen (NH<sub>3</sub>-N) + nitrate nitrogen (NO<sub>3</sub>-N) + nitrite nitrogen (NO<sub>2</sub>-N) + organic nitrogen.

<sup>b</sup>Total phosphorus (TP) = Orthophosphate (PO<sub>4</sub>-P) + polyphosphates + organic phosphorus.

<sup>c</sup>Norms for both total Kjeldal nitrogen and nitrate are set at 0.010 kg N/m<sup>3</sup>.

<sup>d</sup>As arising.

2023). Energy recovery from sewage sludge through anaerobic digestion is limited to a few operational cases (Never 2016). Two-thirds of the installed wastewater treatment systems fail to meet the effluent discharge standards (MOEFCC 2017; NGT 2019; Table 1), hindering safe reuse and negatively impacting human health and the environment. Yet, the use of partially treated and untreated sewage, such as in Hyderabad, Telangana (Amerasinghe *et al.* 2013), is widespread in India given the lack of freshwater alternatives and the fertilizing properties of sewage (Kumar & Tortajada 2020). To ensure safe agricultural reuse, advanced treatment systems capable of removing pathogens and micropollutants are needed in India and globally (Christou *et al.* 2024).

The Pavitra Ganga Project, a joint EU-India project, has tested innovative wastewater treatment and resource recovery technologies in Kanpur, Uttar Pradesh. The research project evaluated the following technologies: (i) an anaerobic integrated permeate channel ultrafiltration membrane bioreactor followed by a co-digestion of sewage sludge with biowastes (Andicos) (Andicos 2024), (ii) a self-forming dynamic membrane bioreactor based on a micro-mesh filter with a cake-layer from activated sludge (SFD-MBR) (Vergine *et al.* 2019), and (iii) constructed wetland plus (CW+) adding adsorptive materials like activated carbon and zeolites to vertical flow wetlands for advanced removal of trace organic compounds and heavy metals, respectively (Ofiera *et al.* 2024).

### Technology evaluation and impact assessment

With the planned shift from sole wastewater treatment to resource recovery systems, technology evaluation requires decision support considering their circularity and sustainability performance (Renfrew *et al.* 2024). Multiple-criteria decision analysis (MCDA) is a widely used framework for integrating decision-relevant indicators in technology evaluations (Kalbar *et al.* 2012). MCDA is established for assessing wastewater treatment systems considering environmental, economic, financial, social, and technological criteria (e.g., Hadipour *et al.* 2016; Plakas *et al.* 2016). The indicators that are frequently used are capital expenditure per treated unit (CAPEX) (monetary unit/m<sup>3</sup>), operational and maintenance expenditure (OPEX) (monetary unit/m<sup>3</sup>), global warming potential (GWP) (kg CO<sub>2eq</sub>/m<sup>3</sup>), energy requirement (kWh/m<sup>3</sup>), land area requirement (m<sup>2</sup>/m<sup>3</sup>/year), noise, odour, public/cultural acceptance, creation of jobs, public health and safety, flexibility, and reliability of the technology (Renfrew *et al.* 2024).

These criteria reflect the goals of wastewater treatment technologies, which are to remove pathogens, pollutants, and nutrients to reduce the risks of infectious diseases, pollution, and eutrophication in freshwater and marine ecosystems (i.e., sustainability performance; Pikaar *et al.* 2022). However, when selecting a wastewater treatment and resource recovery technology, decision-makers must also consider its potential for recovering water, energy, and nutrients (i.e., circularity performance, Samberger *et al.* 2024). Hence, circularity indicators, such as resource recovery rates, should be better addressed in decision-support systems, such as MCDA, for technology selection.

On the other hand, several MCDAs have included sustainability indicators such as environmental impacts (e.g., GWP) of wastewater systems (e.g., Kalbar *et al.* 2012; Bertanza *et al.* 2017). Including sustainability indicators in the MCDA can lead to interdependencies between the indicators, i.e., energy consumption and energy recovery potential (kWh/m<sup>3</sup>) drive the operational costs (cost/m<sup>3</sup>) of the technology as well as its environmental impacts, e.g., GWP (Pennellini *et al.* 2023). These interdependencies can amplify the perceived advantage or disadvantage of a technology in MCDA, presenting a methodological weakness (Kalbar *et al.* 2012). Nevertheless, not accounting for the positive and negative impacts (externalities) in planning wastewater treatment and reuse projects has been highlighted as an important barrier to circular economy technology transitions (Lautze *et al.* 2014). For example, P removal in wastewater treatment plants can reduce the eutrophication of nearby aquatic ecosystems, a positive externality that should be accounted for (Rashid *et al.* 2023). On the other hand, the energy consumption of wastewater treatment plants contributes to GWP. This negative externality should also be considered when evaluating technologies. Life cycle assessment (LCA) can quantify the environmental burdens and benefits of wastewater treatment plants considering input (energy, chemicals, land use) and output indicators (emissions to water and soils) (Remy *et al.* 2015). Quantitative microbial risk assessment (QMRA) can be applied to quantify health externalities, i.e., how reducing faecal coliforms (FCs) diminishes the risk of gastrointestinal infections of the wastewater treatment plant workers or downstream water re-users (Fuhrimann *et al.* 2016). The avoided health and environmental burdens ultimately manifest as financial benefits, e.g., reduced healthcare costs, increased fish stock, and enhanced tourism, as shown by Otoo & Drechsel (2018) and Sampat *et al.* (2021). Comprehensive cost-benefit analyses are usually applied to monetize these externalities.

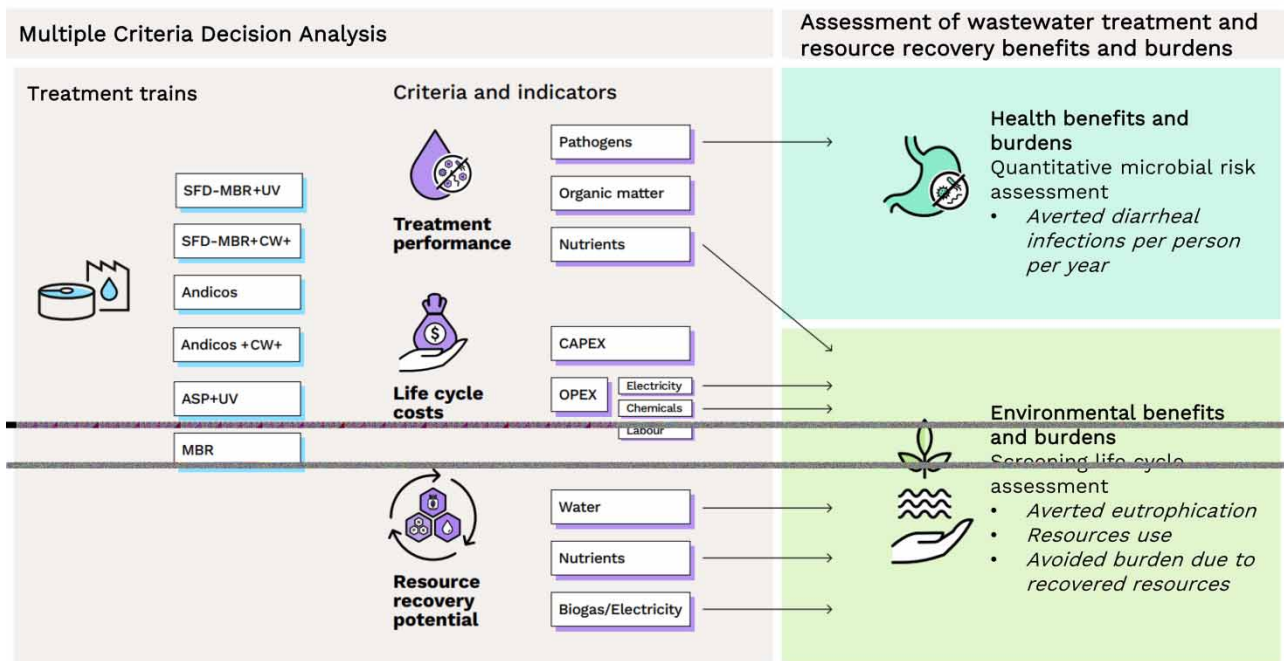
An assessment framework for resource recovery technologies that integrates sustainability and circularity indicators has been emphasized as the basis for developing institutional, policy, and financial instruments that facilitate the transition to treatment and resource recovery schemes in India (Kumar & Goyal 2020; Bassi *et al.* 2022). This study compares three innovative and two reference treatment and resource recovery technologies for Kanpur, India, using an MCDA that considers treatment performance, costs, and resource recovery potential indicators. For the resource recovery potential indicators, the study further evaluates economic benefits using the market values of resources recovered at the treatment plants, such as water, energy, and nutrients. Finally, it estimates the environmental and health benefits and burdens through wastewater treatment and resource recovery for the downstream environment and communities.

## MATERIALS AND METHODS

This study compares wastewater treatment and resource recovery systems by an MCDA. The MCDA is based on independent criteria and indicators considering local decision-making priorities. The criteria include treatment performance, treatment costs, and resource recovery potentials. Based on selected MCDA indicators, the environmental and health benefits and burdens for the downstream environment and communities are further assessed by a screening LCA and QMRA (Figure 1).

### Case study site

Kanpur, located in the northern Indian state of Uttar Pradesh, is one of the largest cities in the state and a major industrial hub, e.g., for the leather tanning industry. It has a population of approximately 3 million as of the latest estimates (Cuadrado-Quesada *et al.* 2020). The city's water supply is primarily sourced from the Ganges River, supplemented by groundwater. The wastewater volume produced is estimated at 340 million litres per day (MLD; 340,000 m<sup>3</sup>/d). While Kanpur has three sewage treatment plants (STPs), the total treatment capacity is still insufficient to treat the generated urban wastewater (Cuadrado-Quesada *et al.* 2020; CPCB 2021). This leads to untreated wastewater being discharged into the Ganges River, contributing to elevated biological oxygen demand (BOD), chemical oxygen demand (COD), heavy metals, and FC levels in the Ganga River, affecting aquatic and public health (CPCB 2016). The current activated sludge process (ASP) at Jajmau STP (130,000 m<sup>3</sup>/d) has an insufficient aeration capacity, reducing the effectiveness of bacterial processes, and making the whole system unstable and highly dependent on the efficiency of the primary clarifiers (Boonen 2023). Jajmau STP effluent is mixed with effluents from a so-called CETP (common effluent treatment plant), an industrial treatment plant treating mainly tannery wastewater. The mixed effluent flows into irrigation channels and is reused in agriculture, which is expected to cause high health risks for the farmers (Babalola *et al.* 2023). The affected peri-urban farming community has around 4,000 members and mainly grows wheat and rice (Breitenmoser *et al.* 2024). Three innovative treatment trains, including Andicos, SFD-MBR, and CW +, were tested at Jajmau STP as alternative treatment and resource recovery systems within the Pavitra Ganga Project (Kanpur – Jajmau Wastewater Treatment Plant 2024).



**Figure 1** | The methodological approach of this study.

### Multiple criteria analysis

The method chosen for the MCDA was the weighted sum model (WSM) for its ease of replicability, its ability to be adapted in studies with low data availability, and its consideration of local decision-making priorities (El Amine Pailhès & Perry 2014).

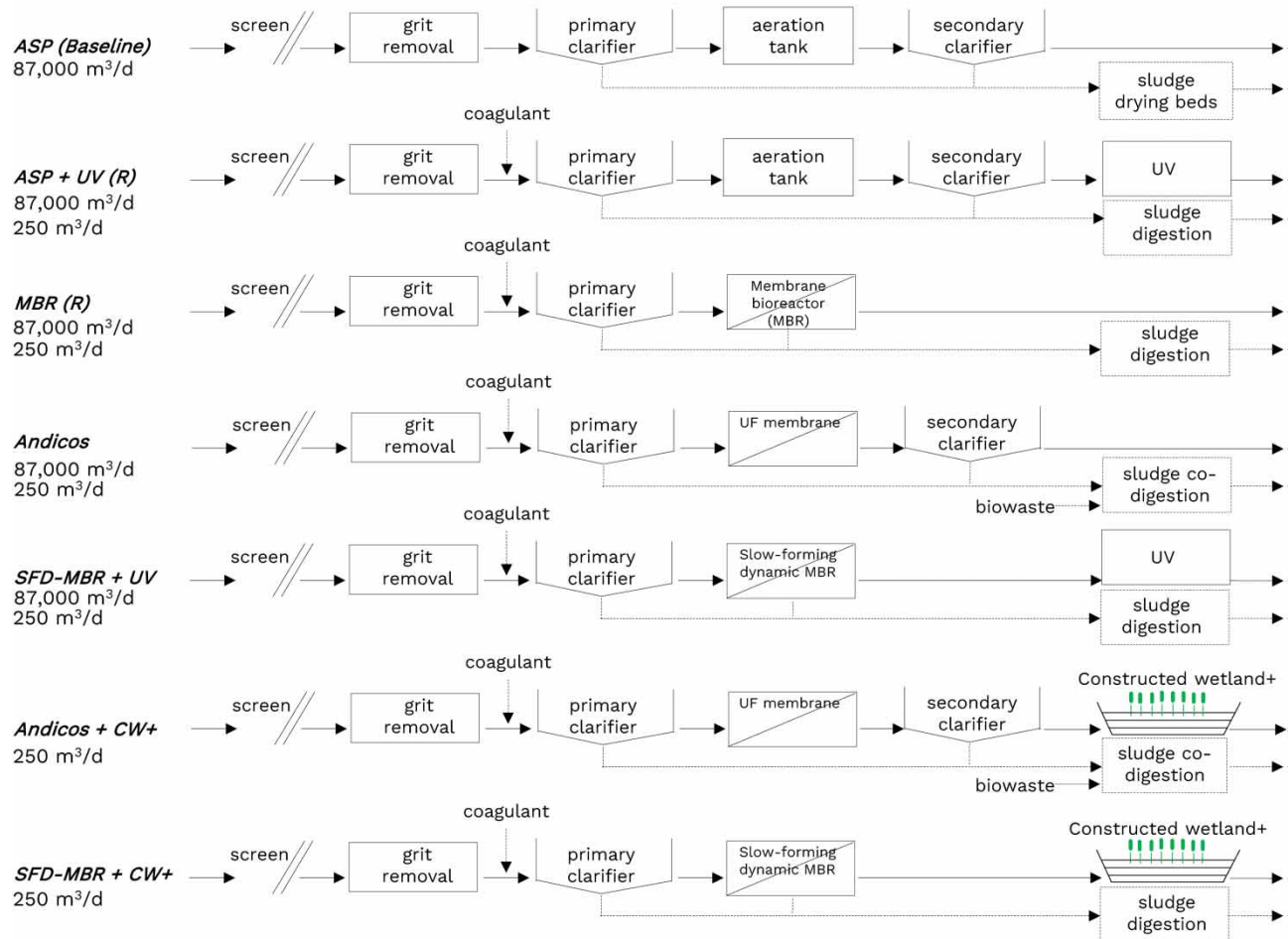
### Treatment trains and scenarios

The technologies were integrated into comparable treatment trains, as illustrated in Figure 2. The treatment trains were designed for three different scenarios ( $S_i$ ), reflecting the gradual transition from discharge to resource recovery systems:

- $S_{\text{discharge}}$ : The treatment trains should meet the NGT (2019) discharge standards' Class 1 City' standards for 87,000 m<sup>3</sup>/d and 'Other' standards for 250 m<sup>3</sup>/d (NGT 2019; Table 1).
- $S_{\text{reuse}}$ : Water and nutrients (N, P) in the effluents are used in agriculture. No nutrient removal process is assumed under this scenario. The treatment trains should meet the recommended norms for water reuse in agriculture (CPCB 2024; Table 1).
- $S_{\text{reuse+energy}}$ : This scenario builds on  $S_{\text{reuse}}$ . The treatment trains also consider anaerobic digestion of sewage sludge for energy recovery.

The existing activated sludge process (*existing ASP*) in Jajmau, Kanpur, served as the baseline treatment train. At the same time, a conventional membrane bioreactor (*MBR*) and an upgraded ASP with state-of-the-art fine bubble aeration followed by ultraviolet disinfection (*upgraded ASP + UV*) were employed as reference treatment trains due to their widespread use in India (CPCB 2021). The treatment trains were designed for large-scale and small-scale capacities, i.e., one operating at a capacity of 87,000 m<sup>3</sup>/d, representing the average flow at the Jajmau STP (80% of the capacity) and another scale at 250 m<sup>3</sup>/d to consider capacity ranges of the CW+ (Figure 2).

The treatment trains differ in their secondary treatment processes. They share the same pre- and primary treatment (fine screen/grit removal followed by primary clarifiers), disinfection (UV) as post-treatment, and sludge treatment processes (thermophilic digesters followed by sludge thickeners and sludge drying beds). To comply with the NGT (2019) discharge standards, P precipitation is part of the treatment trains for  $S_{\text{discharge}}$ , except in the baseline treatment train, which has no P precipitation step and treats sewage sludge solely by thickening and sludge drying beds. Further treatment train modifications are done for the *Andicos* treatment trains, which co-digest sewage sludge with organic wastes and for the



**Figure 2** | Treatment trains and unit processes. Dashed lines indicate variations in the treatment trains depending on scenarios Si.

ultrafiltration-based secondary treatments (i.e., aerobic *MBR* and *Andicos*), which provide sufficient pathogen removal without UV disinfection.

The influent wastewater, primarily of municipal origin, exhibits total suspended solids (TSS) at 1,223 mg/L, biochemical oxygen demand (BOD) at 360 mg/L, COD at 1,366 mg/L, total nitrogen (TN) at 75 mg/L, and total phosphorus (TP) at 24 mg/L. Faecal contamination is significant, with a FC count of  $10^8$  CFU/100 mL (Babalola *et al.* 2023; Boonen 2023). Although industrial effluents are likely contributors to the influent wastewater, industrial pollutants such as chromium were excluded from the scope of this study.

### MCDA indicators

The criteria selection was based on a survey involving 20 stakeholders who are experts in Indian wastewater treatment and reuse management (Rohrer 2024). The survey results indicated that costs (CAPEX and OPEX) and compliance (or treatment performance) of wastewater treatment have the highest priority among Indian decision-makers. The MCDA framework was thus built around three main criteria: performance (% reduction or logarithmic reduction of pollutants), treatment costs ( $\text{INR}/\text{m}^3_{\text{treated}}$ ), and resource recovery potential (water  $\text{m}^3_{\text{irrigation water}}/\text{m}^3_{\text{treated}}$ , nutrients  $\text{kg N}/\text{m}^3_{\text{treated}}$  and  $\text{kg P}/\text{m}^3_{\text{treated}}$ , and energy  $\text{kWh}/\text{m}^3_{\text{treated}}$ ) to include circularity indicators. The main criteria were categorized into eight indicators and 15 sub-indicators (Table 2).

The performance criteria involve indicators and sub-indicators concerning pollution (Table 2) aligned to the Indian wastewater treatment and reuse standards (Table 1). The sub-indicator data were provided from the results of piloting of the

**Table 2** | Criteria, indicators, and weights

Criteria	Indicator	Sub-indicator	Unit	Direction	Weights		
					S <sub>discharge</sub>	S <sub>reuse</sub>	S <sub>reuse+energy</sub>
Treatment performance	Pathogen removal	Faecal coliform (FC)	log reduction	Benefit	0.083	0.17	0.17
		Organic material removal	Total suspended solids (TSS)	% reduction	Benefit	0.083	0
	Nutrient removal	Biological oxygen demand (BOD)	% reduction	Benefit	0.083	0.17	0.17
		Chemical oxygen demand (COD)	% reduction	Benefit	0.083	0	0
		Total phosphorous (TP)	% reduction	Benefit	0.083	0	0
		Total nitrogen (TN)	% reduction	Benefit	0.083	0	0
Treatment costs	CAPEX	Land area	INR/m <sup>3</sup>	Cost	0.1	0.066	0.066
		Civil works, E&M installations	INR/m <sup>3</sup>	Cost	0.1	0.066	0.066
	OPEX	Electricity	INR/m <sup>3</sup>	Cost	0.1	0.066	0.066
		Chemicals	INR/m <sup>3</sup>	Cost	0.1	0.066	0.066
		Maintenance and labour	INR/m <sup>3</sup>	Cost	0.1	0.066	0.066
Resource recovery potential	Water recovery	Treated wastewater for irrigation	m <sup>3</sup> <sub>irrigation water</sub> /m <sup>3</sup> <sub>treated</sub>	Benefit	0	0.11	0.083
	Nutrient recovery	TP	kg P/m <sup>3</sup>	Benefit	0	0.11	0.083
		TN	kg N/m <sup>3</sup>	Benefit	0	0.11	0.083
	Energy recovery	Electricity	kE <sub>el</sub> /m <sup>3</sup>	Benefit	0	0	0.083
Total of weights:					1	1	1

secondary processes in the Pavitra Ganga Project, from literature data (Supplementary Table S1) and information from technology providers.

The treatment cost criteria involve the indicators of capital expenditure (CAPEX, INR/m<sup>3</sup>) and operational expenditure (OPEX, INR/m<sup>3</sup>). CAPEX considers land costs, assuming an average price per plot in Jajmau around 7,500–8,500 INR/m<sup>2</sup> (Property Rates in Kanpur-Real Estate Property Price & Trends in Kanpur 2020), infrastructure civil works and electrical and mechanical installations costs (INR/m<sup>3</sup>). All CAPEX is calculated for a lifetime of 15 years and an average usage of 80% of the treatment capacity. OPEX includes electricity costs, assuming an electricity tariff of 8.6 INR/kWh in Kanpur (U.P. PCL 2023). The electricity demands (kWh/m<sup>3</sup>) were estimated based on data from the pilot technologies, technology providers, and literature (Supplementary Table S2). They were down-scaled with the assumption of a reduced efficiency for the small-scale treatment trains due to economies of scale (Diaz-Elsayed *et al.* 2020). The chemical costs include 0.002–0.005 kg/m<sup>3</sup> polyacrylamide (Boonen 2023) at 108 INR/kg (Polyacrylamide 2024) for sludge thickening, and 0.025 kg/m<sup>3</sup> of ferric chloride (MDE 2014) at 6 INR/kg (Ferric Chloride Chemical 2024) for P precipitation for S<sub>discharge</sub>. The maintenance and labour costs include spare parts, repairs, and human labour (INR/m<sup>3</sup>).

The resource recovery indicators involve the sub-indicators reused treated wastewater (m<sup>3</sup><sub>reused</sub>/m<sup>3</sup><sub>treated</sub>), total P (kg P/m<sup>3</sup>), TN (kg N/m<sup>3</sup>), and produced electricity (kWh/m<sup>3</sup>). They are considered benefits for wastewater treatment plant operators and could be future revenue sources. The volume of recovered water is equivalent to that of treated wastewater, i.e., 1 m<sup>3</sup> of treated water is available as 1 m<sup>3</sup> of irrigation water. In Haryana state, for example, treated wastewater is sold for an estimated price of 4.5 INR/m<sup>3</sup> (HWRA 2022). The amount of recovered nutrients is equivalent to the effluent's total P and total N concentrations. Nutrients in the sewage sludge are not considered further because Indian sewage sludge does not meet the criteria for direct land application (Sude *et al.* 2024). The elemental content of P and N in the effluent could replace the same elements in typical fertilizers used for wheat and rice farming, such as superphosphate (phosphate content of 16%) and urea (elemental N content of 50%) (PAD 2019). It was assumed that the effluent's total phosphorous (TP) is mainly in the form of orthophosphates, which is made up of 32% elemental P (Ruzhitskaya & Gogina 2017). TN is mainly ammonium, comprising 82% elemental N (Mažeikienė & Šarko 2023). Revenues for operators can occur if they sell the nutrients together with the irrigation water to farmers to substitute industrial fertilizers. The assumed selling price is based on market prices for superphosphate, i.e., 8.4 INR/kg and urea fertilizer, i.e., 6.4 INR/kg (TNAU 2013). The amount of energy recovered is calculated

based on the amount of sludge produced ( $\text{kg}/\text{m}^3$ ) per technology and a sludge-to-electricity conversion rate of (0.49–0.59  $\text{kWh}_{\text{el}}/\text{kg}$ ) by thermophilic digesters and gas turbines as calculated in Boonen (2023). Operators could save treatment costs through the electricity demand covered by their own production or generate revenues by selling electricity for 8.6  $\text{INR}/\text{kWh}_{\text{el}}$  (U.P. PCL 2023).

### Weighting

In this study, the weighting was distributed proportionally to the criteria, the indicators, and sub-indicators (Table 2), similar to other WSM studies (Kalbar *et al.* 2012). The different scenarios reflect the decision-making priorities, e.g., under  $S_{\text{discharge}}$ , no weights are distributed to the resource recovery potentials.

### Performance index

For the calculation of the MCDA performance indices (PIs), each sub-indicator was assigned lower and upper benchmarks (shown in Supplementary Table S3). The benchmarks for performance and resource recovery indicators were based on the minimum and maximum observed values for each sub-indicator, ensuring consistent scoring and comparison across technology alternatives. For the treatment cost indicators, the benchmarks were determined using the minimum and maximum observed costs across all sub-indicators. This approach ensures that the value of one  $\text{INR}$  is treated the same across all monetary sub-indicators, enabling fair comparison of their contributions.

The data were then normalized (on a scale from 0 to 1) according to the following min–max normalization formula (Rowley *et al.* 2012):

For benefit indicators:

$$x_{ij} = \frac{r_{ij} - r_{i\text{min}}}{r_{i\text{max}} - r_{i\text{min}}}$$

For cost indicators:

$$x_{ij} = \frac{r_{i\text{max}} - r_{ij}}{r_{i\text{max}} - r_{i\text{min}}}$$

where  $i$  is the indicator;  $j$  is the alternative technology;  $x_{ij}$  is the normalized value of the indicator;  $r_{ij}$  is the value of the alternative for indicator  $i$ ;  $r_{i\text{min}}$  is the lower benchmark value, and  $r_{i\text{max}}$  is the upper benchmark value for indicator  $i$ .

The normalized data were multiplied with the corresponding weights (Table 2) and the performance index  $PI S_j$  was calculated from the sum of the weighted data for each treatment train and scenario  $S$  (Kalbar *et al.* 2012), as follows:

$$PI S_j = \sum_{i=1}^n w_{Si} \times x_{ij}$$

where  $w_{Si}$  is the weight assigned under the scenario  $S$  to the indicator  $i$ .

PIs are calculated using the range of observed sub-indicator data (Supplementary Tables S1 and S2). The resulting PI range, from minimum to maximum, highlights the best- and worst-case scenarios, representing the highest and lowest observed sub-indicator data, respectively. This approach ensures that the results reflect not just a single score but also the potential variability of the PI under varying conditions, such as fluctuating treatment performance.

### Impact assessment

#### Improved hygiene

The number of gastrointestinal infections related to specific pathogens in wastewater is calculated using QMRA. The QMRA method is based on WHO (2016) and case studies conducted in similar low-income contexts by Fuhrmann *et al.* (2016). Supplementary Table S4 summarizes the model assumptions. The pathogens are norovirus, rotavirus, *Campylobacter* spp. *Escherichia coli* O:157, and *Cryptosporidium* spp. *E. coli* is used as an indicator of potential pathogens. *E. coli* concentrations and technologies' log removal rates (Supplementary Table S1) are used to model exposure scenarios. The exposure route is through accidental ingestion during irrigation. It is assumed to be between 1 and 10  $\text{mL}/\text{d}$  (Fuhrmann *et al.* 2016), with 235

exposure days per year in a farming population of 4,000 (Breitenmoser *et al.* 2024). The pathogen dose ingested was calculated and used to obtain the probability of illness (Supplementary Table S4). Monte Carlo simulations are performed for 10,000 iterations using @Risk, version 8.2 (Palisade Corporation; Newfield, NY, USA). One iteration simulates all the exposure events and the associated probability of illness for one person per year. Model outputs show the expected number of gastrointestinal infections per person per year without considering immunity (Fuhrimann *et al.* 2016). A smaller number of gastrointestinal infections is considered an avoided health burden and, thus, an essential benefit of wastewater treatment.

### Reduced water pollution and reduced use of finite resources

The environmental impacts per m<sup>3</sup> of treated wastewater are calculated by a screening LCA conducted with the SimaPro software and the Ecoinvent v3 database. A screening LCA is less detailed than an in-depth LCA study. It focuses on the major drivers for the environmental impacts of a process or product (Remy *et al.* 2015). In wastewater treatment, the major drivers for environmental impacts are related to the operation of the processes: (i) the resources used, such as electricity (kWh/m<sup>3</sup>), land use (m<sup>2</sup>/m<sup>3</sup>/year), and chemicals (kg<sub>chemical</sub>/m<sup>3</sup>), and (ii) the emissions produced, such as effluent (kg<sub>pollutant</sub>/m<sup>3</sup>) and sewage sludge quality (kg<sub>pollutant</sub>/m<sup>3</sup>) (Kalbar *et al.* 2016). Apart from sewage sludge quality, all indicators are considered in the MCDA framework (Table 2). ReCiPe 2016 v1.1, Midpoint egalitarian value choice (Huijbregts *et al.* 2017) method is used to assess the environmental impacts and calculate end- and mid-point impacts in Recipe points (Pt).

The resources used and the treatment plants' emissions are considered to have negative environmental impacts (i.e., burdens). The positive environmental impacts (i.e. benefits), such as reduced emissions, are shown by the averted eutrophication potential per m<sup>3</sup> of treated wastewater. The averted eutrophication potential is calculated as the difference between the eutrophication potential of discharging raw wastewater and the wastewater treated by the reference and innovative treatment trains. Additional environmental benefits of resource recovery, such as the reduced use of non-renewable resources, are calculated using the concept of avoided burden (Chantrain *et al.* 2022). It assumes that recovered materials, such as treated water and nutrients, and energy produced by the wastewater treatment plant can replace freshwater, conventional fertilizer, and grid electricity use. The quantifiable environmental benefits from producing or using freshwater, conventional fertilizer, and conventional electricity are allocated as avoided impacts to the resource recovery treatment trains (Chantrain *et al.* 2022). The LCA model in this study does not consider the level of local water scarcity or the origin of the local water resources.

## RESULTS AND DISCUSSION

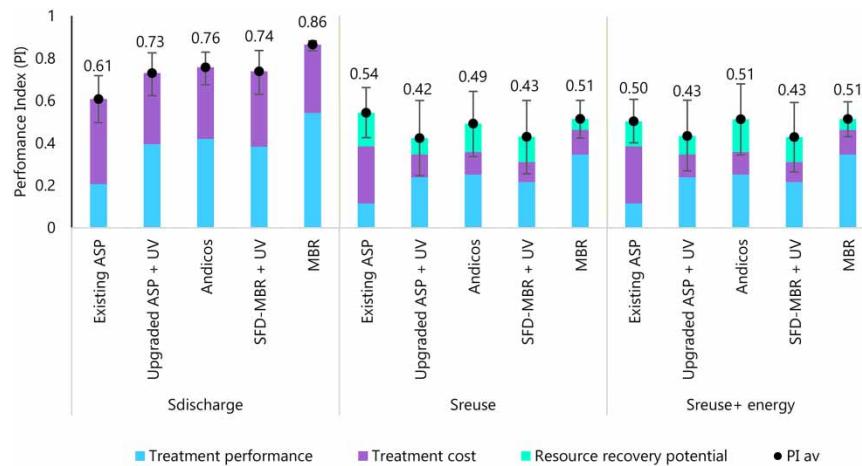
### Comparative assessment of treatment trains

An MCDA was conducted to assess the PI ranges of the treatment trains in three scenarios reflecting the gradual transition from treatment and discharge to resource recovery systems. The PIs for the large-scale treatment trains are presented in Figure 3, and for the small-scale treatment trains in Figure 4. It must be noted that comparisons between treatment train PIs are possible only within individual scenarios.

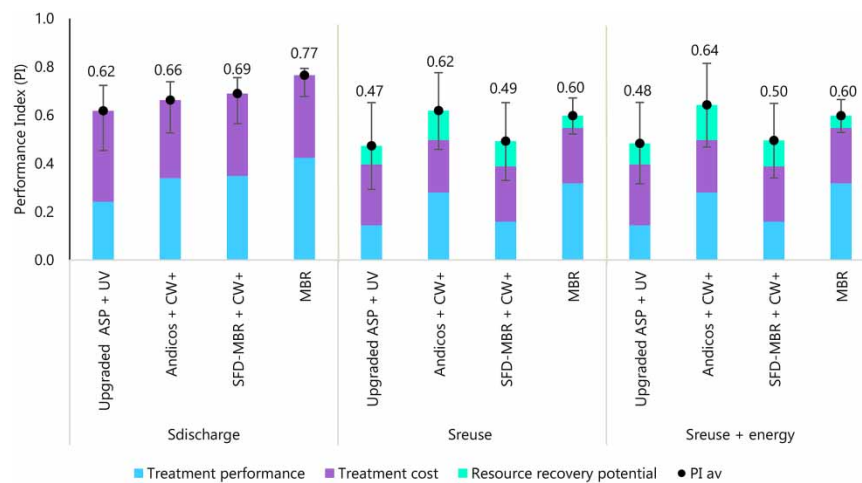
For the discharge scenario (S<sub>discharge</sub>), the large-scale reference treatment train *MBR* (PI range = 0.84–0.88) has a slightly higher PI than the reference *upgraded ASP + UV* (PI = 0.62–0.83) and the *Andicos* (PI = 0.67–0.83) and *SFD-MBR + UV* (PI = 0.63–0.84) (Figure 3). This is due to the better treatment performance of the *MBR* (Supplementary Table S1) for organic materials and nutrients (BOD, COD, and TN). N elimination for *Andicos* is insufficient because, even with a maximum of 75% removal efficiency, it is not compliant with the NGT discharge standards, which would require an 80% reduction considering the influent water quality. The *SFD-MBR + UV* and the *new ASP + UV* likely achieve treated water quality levels that comply with the discharge standards, except for TSS. Compared to the baseline (*existing ASP*, PI = 0.50–0.72), the large-scale reference and innovative treatment trains perform better because the *existing ASP* does not comply with any of the discharge standards.

Among the small-scale treatment trains, under S<sub>discharge</sub>, *MBR* has the highest PI (0.68–0.80), followed by the *upgraded ASP + UV* (PI = 0.46–0.73), the *SFD-MBR + CW +* (PI = 0.57–0.76) and *Andicos + CW +* (PI = 0.53–0.74) (Figure 4). All reference and innovative treatment trains are compliant, assuming the maximum removal rates, but the *MBR* has the highest removal efficiency.

Total treatment costs are similar between the technologies (between 15 and 28 INR/m<sup>3</sup> for large-scale and 28 and 41 INR/m<sup>3</sup> for small-scale treatment trains; Figure 5), with electricity demand being the main cost driver (shown in Supplementary Table S2).



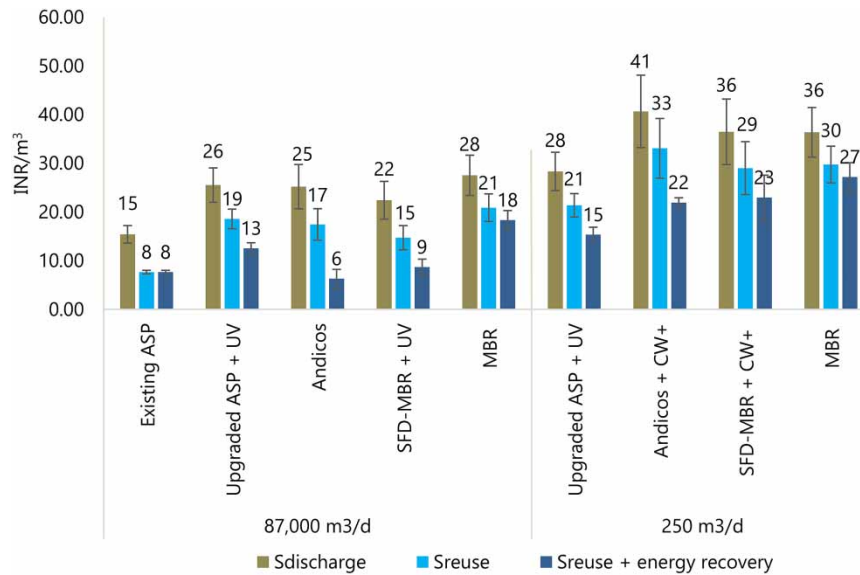
**Figure 3** | Performance criteria and indices of the large-scale treatment trains (87,000 m<sup>3</sup>/d) under scenarios S<sub>i</sub>. The PIs are presented as min–max range, while the average PI (black dots and data value) offers an estimate of typical performance. Comparisons between treatment train PIs are possible only within individual scenarios.



**Figure 4** | Performance criteria and indices of the small-scale treatment trains (250 m<sup>3</sup>/d) under different scenarios S<sub>i</sub>. PIs are presented as min–max range, while the average PI (PI av, black dots, and data value) offers an estimate of typical performance.

These results correlate with the MCDA by Kalbar *et al.* (2012), where MBR also achieved the highest performance compared to ASP and sequence batch reactors mainly due to its lower land use in dense urban areas. In another MCDA study, the MBR was only preferable when economic criteria were given a lower weight, given its higher treatment costs than ASP (Bertanza *et al.* 2017).

Under S<sub>reuse</sub> (Figure 3), the large-scale MBR treatment train has a similar PI (0.42–0.60) than the *upgraded ASP + UV* (PI = 0.25–0.60), *Andicos* (PI = 0.34–0.64), and *SFD-MBR + UV* (PI = 0.26–0.60). There are some differences in treatment performance and resource recovery potential between the treatment trains. The *upgraded ASP + UV* and *SFD-MBR + UV* eliminate only up to 6 log FC compared to the required 7 logs based on the influent quality. *Andicos* and *SFD-MBR + UV* remove up to 95% of BOD compared to the required 98% (Supplementary Table S1). On the other hand, the resource recovery potential is higher for those treatment trains which have a lower nutrient removal from the wastewater, i.e., *Andicos* and *SFD-MBR + UV*. The *existing ASP*, although not compliant with the 2024 draft water reuse norms, has the highest resource recovery potential because effluents contain the highest nutrient levels (i.e., 0.06 kg N/m<sup>3</sup> and 0.014 kg P/m<sup>3</sup>). The resource recovery potential for irrigation water is the same for all the large-scale and small-scale treatment trains (i.e., 1 m<sup>3</sup><sub>irrigation water</sub>/m<sup>3</sup><sub>treated</sub>). For the small-scale treatment trains (Figure 4), the *Andicos + CW+* and *MBR* show the highest PIs (0.46–0.78 and



**Figure 5** | Total treatment costs (INR/m<sup>3</sup>) of the treatment trains for different capacities and scenarios. The treatment costs are presented as mean values and their min–max range.

0.52–0.67). *Andicos + CW +* has a higher estimated FC log removal capacity of 8 logs compared to 7 logs of the *MBR*, but the total treatment costs are slightly higher ( $33 \pm 6$  INR/m<sup>3</sup>) than those of the *MBR* ( $30 \pm 4$  INR/m<sup>3</sup>; Figure 5).

Under  $S_{\text{reuse+energy}}$ , the *Andicos* and the *MBR* have the highest PIs (0.34–0.68 and 0.43–0.59, respectively) among the large-scale treatment trains (Figure 3), followed by the *upgraded ASP + UV* and *SFD-MBR*. Among the small-scale treatment trains (Figure 4), *Andicos + CW +* (PI = 0.47–0.82) and the *MBR* (PI = 0.53–0.67) show the best PIs. The energy recovery potential of *Andicos* is 2–6 times the energy recovery potential of the other membrane systems (i.e., *SFD-MBR* and *MBR*) due to the co-digestion of organic wastes with sewage sludge. Differences between the *MBR* PIs of the large-scale and small-scale treatment trains are due to the economies of scale causing increased energy use at a small scale and the values assigned as lower and upper benchmarks (see Supplementary Tables S2 and S3).

### Financial benefits from resource recovery

The financial benefits, i.e., the expected additional revenues from selling recovered resources, were calculated for all treatment trains and scenarios. The additional revenues are assumed to reduce the net treatment costs and thus directly benefit the plant operators (Figure 5; Supplementary Table S2). Additional costs arising from resource recovery systems, such as pipes and pumps to distribute treated wastewater to agricultural fields or gas turbines for electricity conversion are not considered in this study but are important for future cost-benefit assessments.

Total resource recovery (water + nutrients + energy) could compensate between 60% (*SFD-MBR + CW +*) and 86% (*Andicos*) of estimated treatment costs. Some cost-savings for plant operators occur due to lower treatment costs for nutrient removal (i.e., fewer chemical costs as P precipitation is no longer required). The chemical costs comprise 8–12% of the total treatment costs under  $S_{\text{discharge}}$  (Supplementary Table S2). The savings on P precipitation chemicals (1.5 INR/m<sup>3</sup>) under the reuse scenarios would reduce the costs for chemicals by 75–80% (Supplementary Table S2).

Additional revenues through selling water, energy, and nutrients sum up to 7–18 INR/m<sup>3</sup> (Supplementary Table S2). They are highest for the *Andicos* treatment trains due to the higher biogas production from the co-digestion process. Revenues occur mainly through selling irrigation water and energy (80–90% of the total revenues), while selling nutrients in the irrigation water is less relevant (0.4–1.8 INR/m<sup>3</sup>). This is because nutrient concentrations in effluents are low (TN: 0.004–0.019 kg/m<sup>3</sup>; TP: 0.004–0.016 kg/m<sup>3</sup>). Nutrient concentrations are likely higher in the sewage sludge and should be considered for recovery in future studies. Gowd *et al.* (2022) argue that 4% of total imported fertilizer, worth 110 million USD/yr, can be substituted by nutrients from sewage sludge. While selling nutrients from the sewage sludge could bring substantial additional revenues for the plant operators, public and environmental health must be assured. Considering the high

chromium concentrations in the sewage sludge at Kanpur's case study site (Cedeño Villarreal 2023), its direct agricultural application is not permissible. The feasibility of specific nutrient recovery processes should be further investigated.

While the innovative treatment trains have a slightly lower expected removal efficiency than the reference treatment trains under the  $S_{\text{discharge}}$  (Figures 3 and 4), they could be promising resource recovery systems if FC standards are met. Among the large-scale treatment trains, *SFD-MBR + UV* has a significantly lower electricity demand than conventional *MBRs*, higher effluent nutrient contents, and more sludge production for further biogas and electricity production. This could reduce net costs for *SFD-MBR + UV* to  $9 \pm 2$  INR/m<sup>3</sup> compared to  $18 \pm 2$  INR/m<sup>3</sup> for *MBR* under  $S_{\text{reuse+energy}}$ . *Andicos* has even lower net costs ( $6 \pm 2$  INR/m<sup>3</sup>) because biogas production is highest due to co-digestion with biowastes. The *SFD-MBR + CW +* ( $23 \pm 5$  INR/m<sup>3</sup>) and the *Andicos + CW +* ( $22 \pm 1$  INR/m<sup>3</sup>) small-scale treatment trains both have lower net costs than the *MBR* ( $27 \pm 3$  INR/m<sup>3</sup>) under  $S_{\text{reuse+energy}}$ . However, the *upgraded ASP + UV* ( $15 \pm 2$  INR/m<sup>3</sup>) has the lowest net costs due to its lower electricity consumption compared to the membrane technologies (Supplementary Table S2).

## Impacts of wastewater treatment and resource recovery

### Improved hygiene

The number of gastrointestinal infections per year for a farmer using irrigation canal water with an *E. coli* concentration between  $10^5$  and  $10^6$  CFU/100 mL (Babalola *et al.* 2023) is 0.65. This results in up to 2,600 gastrointestinal infections per year for the downstream farming population of 4,000 in this case study. The existing ASP system is thus not providing safe irrigation water. For the downstream farmers and communities, the present irrigation water quality poses high health risks (Babalola *et al.* 2023).

Upgrading the wastewater treatment and reuse plants can thus manifest in up to 2,600 reduced gastrointestinal infections among downstream farmers per year and thereby in reduced economic burdens, i.e., health and healthcare-related costs for Indian households, where diarrheal episodes are a significant out-of-pocket expenditure (Kastor & Mohanty 2018). The mean expenditure for treating one episode of diarrheal illness among children under five years in Odisha, India, is assumed to be between 1,186 INR for episodes without hospitalization and 6,385 INR for episodes with hospitalization (i.e., 13–72 EUR, Pradhan *et al.* 2020). Assuming that 85% of the gastrointestinal infections are mild without hospitalization (Fuhrmann *et al.* 2016) and 15% are moderate to severe with hospitalization, an averted diarrheal illness, on average, saves 1,966 INR (i.e., 22 EUR). This is a considerable share of the average per capita monthly household consumption expenditure, with 3,773 INR (52%) in rural and 6,459 INR (30%) in urban India (Pradhan *et al.* 2020). With 2,600 averted infections in the downstream farmer population annually, up to 5 million INR/yr (ca. 50,000 EUR/yr) on health expenditure could be saved yearly among the 4,000 farmers.

The 2024 draft water reuse norm foresees an FC concentration of  $\leq 5$  MPN/100 mL (corresponding to *E. coli*  $\leq 3$  CFU/100 mL (Leydecker 2008)) for crops eaten cooked, which would result in no gastrointestinal infections for the consumers of wheat and rice nor for the farmers using the irrigation water. The 2024 draft water reuse norms are very stringent, and a multiple-barrier approach (WHO 2006) is required to achieve the necessary irrigation water quality. Influent water quality to the treatment plants contains around  $10^8$  CFU FC/100 mL; thus, an 8-log reduction is needed to achieve the permissible FC levels of  $\leq 5$  MPN/100 mL. The reference and innovative treatment trains as the technical barriers are expected to reach 6 logs (*SFD-MBR + UV*, *SFD-MBR + CW +*, and *upgraded ASP + UV*), 7 logs (*MBR* and *Andicos*) and 8 logs (*Andicos + CW +*). Additional barriers are die-off (2 logs) and washing of the produce (1 log) before cooking (WHO 2006). It is to be discussed whether the very stringent FC norms should be better aligned with the WHO norms of *E. coli*  $10^3$ – $10^4$  CFU/100 mL for irrigation water used for crops being cooked. Allowing concentrations of *E. coli*  $10^4$  CFU/100 mL in the irrigation water would result in only one expected infection in the Kanpur farming population per year (i.e.,  $2.5 \times 10^{-4}$  infections per individual farmer). The definition of health-based targets (e.g.,  $10^{-6}$  disability-adjusted life years (DALY) per person per year as set by the WHO related to the reuse of treated wastewater is recommended before adopting the 2024 draft water reuse norms into state reuse standards. This would advantage the Pavitra Ganga innovative wastewater treatment and reuse treatment and better align to an integrated approach that addresses urban sustainability challenges while encouraging resource recovery and reuse (Schellenberg *et al.* 2020).

### Reduced water pollution and reduced use of finite resources

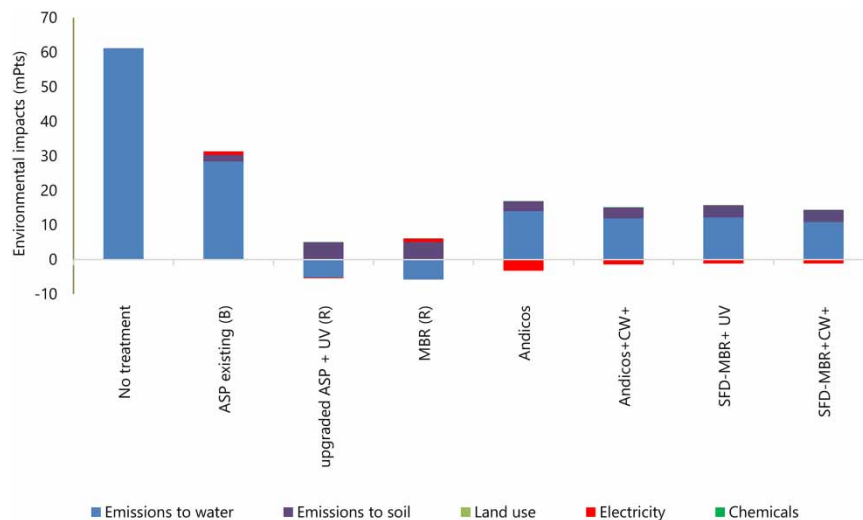
Environmental burdens of the wastewater treatment trains are allocated to the resources used, i.e., electricity demand (kWh/m<sup>3</sup>), land use (m<sup>2</sup>/m<sup>3</sup>/year), and chemicals (kg<sub>chemical</sub>/m<sup>3</sup>), as well as the direct emissions to water and soil from

pollutants in the effluent ( $\text{kg}_{\text{pollutant}}/\text{m}^3$ ) and in sewage sludge ( $\text{kg}_{\text{pollutant}}/\text{m}^3$ ), respectively. The environmental burdens of the wastewater treatment trains for these sub-indicators were calculated (Supplementary Table S5), and the cumulative environmental impacts in mPts are summarized for  $S_{\text{reuse+energy}}$  (Figure 6). No uncertainty analysis was conducted in this study; however, the cumulative environmental impacts are expected to vary by  $\pm 20\%$  (Remy *et al.* 2015).

The discharge of untreated wastewater in Kanpur, containing  $0.024 \text{ kg P}/\text{m}^3$ ,  $0.075 \text{ kg N}/\text{m}^3$ ,  $1.223 \text{ kg TSS}/\text{m}^3$ ,  $0.360 \text{ kg BOD}/\text{m}^3$ , and  $1.366 \text{ kg COD}/\text{m}^3$ , would lead to an environmental burden of  $61.2 \text{ mPts}/\text{m}^3$  (Figure 6; no treatment). Over 91% of this impact is due to freshwater eutrophication (primarily from phosphorus), while marine eutrophication (mainly from nitrogen) contributes 8%. If effluents were treated to meet the NGT (2019) standards ( $0.001 \text{ kg P}/\text{m}^3$ ,  $0.015 \text{ kg N}/\text{m}^3$ ), the environmental burden would drop to  $3.8 \text{ mPts}/\text{m}^3$  according to the screening LCA, thus avoiding  $57.4 \text{ mPts}$  per  $\text{m}^3$  of treated wastewater; equivalent to a 94% reduction in impact (Supplementary Table S5). The *upgraded ASP + UV* and *MBR* treatment trains could avert up to 99% of the environmental burdens from water emissions due to their superior nutrient removal efficiency. In contrast, the innovative treatment trains, with lower nutrient removal performance, could still achieve a 77–82% reduction, while the *existing ASP* system achieves only a 53% reduction of the environmental burdens compared to the discharge of untreated wastewater. The avoided environmental burdens can be considered as positive indirect financial benefits of wastewater treatment, as demonstrated by the upper Yahara watershed study in the USA (Sampat *et al.* 2021). The authors concluded that every kg of excess P emitted to the environment results in an economic loss of 74.5 USD due to reduced ecosystem functions, such as lost recreational activities. In Kanpur, the effluent from the *existing ASP* has a concentration of  $0.014 \text{ kg P}/\text{m}^3$ , thus an excess of  $0.013 \text{ kg}/\text{m}^3$  compared to the NGT (2019) discharge standards of  $0.001 \text{ kg P}/\text{m}^3$ . The current system would, hence, generate an estimated economic loss of up to  $0.96 \text{ USD}/\text{m}^3$  ( $80 \text{ INR}/\text{m}^3$ ).

The environmental burdens from nutrient emissions to the soil via sewage sludge ( $1.9\text{--}2.0 \text{ mPts}/\text{m}^3$  of treated wastewater) are substantially lower than those from emissions to water ( $6.1\text{--}25.9 \text{ mPts}/\text{m}^3$  of treated wastewater, Figure 6; Supplementary Table S5). Therefore, reusing nutrient-rich effluents on soil, such as for agricultural irrigation, would lead to reduced environmental impacts compared to discharging them into water bodies. For instance, the screening LCA results indicate that reusing an effluent with  $0.001 \text{ kg P}/\text{m}^3$  and  $0.015 \text{ kg N}/\text{m}^3$  on soil can reduce environmental burdens by 50%, from  $3.8 \text{ mPts}$  (if emitted to water) to  $1.9 \text{ mPts}$ . The model does not consider additional eutrophication potential reduction through the uptake of P by the plants.

The avoided burden of reduced use of synthetic single superphosphate by replacing with  $1 \text{ kg P}$  from the effluent is  $0.003 \text{ mPts}$ . Considering a P content between  $0.003\text{--}15 \text{ kg}/\text{m}^3$  (arising without P precipitation), the environmental benefit ranges from  $0.01\text{--}0.05 \text{ mPts}/\text{m}^3$  between the treatment trains and could reduce their cumulative environmental impacts by another 1–2%. Thus, the P content in wastewater is too low to provide significant additional environmental benefits, as Maesele & Roux (2021) also found. P recovery from sewage sludge and expected environmental benefits and burdens should be explored



**Figure 6** | Cumulative environmental impacts of wastewater treatment trains per  $1 \text{ m}^3$  of treated wastewater (in mPts) under  $S_{\text{reuse+energy}}$  and compared to environmental impacts of  $1 \text{ m}^3$  of untreated wastewater discharged to the river.

in additional studies. Reusing treated wastewater instead of freshwater has the highest avoided burden in the model, with 11.9 mPts/m<sup>3</sup>. As a result, the *upgraded ASP + UV* and *MBR* treatment trains, which have minimal environmental impacts due to their low nutrient emissions and the added benefit of providing an alternative to freshwater, exhibit marginal cumulative environmental impacts of -0.4 and 0.3 mPts/m<sup>3</sup>, respectively (Figure 6). However, the LCA model does not consider the level of local water scarcity or the origin of the local water resources. The avoided burden is likely higher as Kanpur will experience increasing water shortages, a decline in the groundwater table, and inadequate rainfall in the future (Cuadrado-Quesada *et al.* 2020). Incorporating this consideration into the model would further enhance the environmental performance of the innovative treatment trains under the reuse scenarios.

Electricity requirements show higher environmental burdens (0.8–1.9 mPts/m<sup>3</sup>) than land use and chemical requirements in the treatment processes, which have negligible impacts (0.02–0.03 mPts/m<sup>3</sup>; Figure 6; Supplementary Table S5). Using 1 kWh of electricity from the Northern Indian grid has an environmental burden of 2.8 mPts, mainly due to human carcinogenic toxicity, fossil resource scarcity, and GWP. This is primarily due to the mix of energy resources in the Northern Indian grid, which consists of >60% coal, which leads to harmful air pollution and greenhouse gases when fired in the power stations (Hossain 2016; Delanka-Pedige *et al.* 2021). Consequently, producing 1 kWh of renewable electricity from sewage sludge can avoid some of these environmental burdens. For this study, the environmental impacts of electricity-producing infrastructure have been neglected; hence, a theoretical avoided impact calculation was performed.

Treatment trains with high electricity demands, such as those including *MBR* (0.5–0.7 kWh<sub>el</sub>/m<sup>3</sup>) will generate a higher environmental impact compared to unit processes with a moderate or low electricity demand such as the *upgraded ASP + UV* (0.3–0.4 kWh<sub>el</sub>/m<sup>3</sup>), *Andicos* (0.35–0.55 kWh<sub>el</sub>/m<sup>3</sup>), *SFD-MBR* (0.3–0.5 kWh<sub>el</sub>/m<sup>3</sup>), and *CW +* (0.1 kWh<sub>el</sub>/m<sup>3</sup> respectively). Under  $S_{\text{reuse+energy}}$ , the energy recovery potential from sludge is estimated to be 0.6–0.8 kWh<sub>el</sub>/m<sup>3</sup> for the *upgraded ASP + UV* and *SFD-MBR* treatment trains. For *Andicos* treatment trains, due to the co-digestion of sewage sludge with organic wastes, the energy recovery potential is higher with 0.7–1.9 kWh<sub>el</sub>/m<sup>3</sup>, while for the *MBR*, it is 0.2–0.4 kWh<sub>el</sub>/m<sup>3</sup> due to the lower sludge quantity generated from the treatment trains (roughly two third less, Boonen 2023). Environmental benefits are thus expected from the innovative and *upgraded ASP + UV* treatment trains, which theoretically produce more electricity from anaerobically digested sludge than they consume (Figure 6). The avoided burdens of electricity use from the Northern Indian grid would be between 0.7 and 3.2 mPts/m<sup>3</sup> with higher environmental benefits for more renewable electricity production (such as for the *Andicos* treatment trains).

## Limitations

Within the MCDA framework, the data on removal efficiencies were mainly provided by literature for the reference treatment trains and from the short-term piloting of the innovative treatment trains. Using reliable data from long-term piloting is crucial to inform technology selection. Therefore, the comparative MCDA results must be read carefully since the treatment trains, so far, rely on theoretical assumptions regarding their long-term removal efficiencies.

The WSM method was utilized for decision-making; its reliance on subjective weighting factors may introduce bias into the results, and its lack of consideration for human error and inconsistency in data could create a setback in comparison with other MCDA methods like the analytical hierarchy process (El Amine Pailhès & Perry 2014). A sensitivity analysis of the MCDA results was not performed, but it would be needed once reliable long-term data are generated and used in the model. The sensitivity analysis should evaluate how variations in key parameters (i.e., weights, criteria scores, and normalization methods) impact the PIs of the technology alternatives. Further, an indicator of the ‘reliability’ of the technology (the process robustness concerning normal and future operational variations) could be included in the model (Kalbar *et al.* 2012; Bertanza *et al.* 2017). This would influence the PIs of the studied treatment trains, as the piloting phase indicated that *SFD-MBR* and *CW +* are more reliable than *Andicos* due to its complexity of operating. Furthermore, additional removal efficiencies have not been considered as, for example, *CW +* have been shown to effectively remove heavy metals and micro-pollutants (Ofiera *et al.* 2024), which are water quality parameters of emerging concern.

The price of reused water was assumed to be 4.5–7 INR/m<sup>3</sup> as set in Haryana State. However, other states in India distribute treated wastewater for irrigation free of charge since the willingness to pay among the farmers is low (Breitenmoser *et al.* 2022). In Kanpur, the economic value of treated wastewater might be low as water stress is not immediate (Cuadrado-Quesada *et al.* 2020). The calculation of nutrient contents in treated wastewater and fertilizer is based on the elemental content of P and N. It is assumed that all phosphorus is in the form of orthophosphates and all N is in the form of ammonium,

disregarding other potential forms of P and N in wastewater. It was also assumed that all nutrients are readily available as fertilizer to plants, which may not be the case in practice.

In the screening LCA, polyacrylamide was assumed to be the polymer used for sludge dewatering due to a lack of information on the actual sludge process in Kanpur. Furthermore, replacement materials such as granular activated carbon, zeolites, gravel, and biochar in CW+ and additional infrastructure, e.g., gas turbines or water supply pipes, were not considered, thus disregarding the environmental burden of substrate replacements.

In the QMRA, acquired immunity due to repeated gastrointestinal infections was not modelled, thus lowering the theoretical impact potentials in Kanpur.

## CONCLUSIONS

The circularity and sustainability assessments of wastewater treatment and resource recovery systems in Kanpur, India, using MCDA, screening LCA, and QMRA, offer several key learnings. First, by assessing the treatment performance, costs, and resource recovery potential, the study found that *MBR* systems perform best in pollutant removal, with the *Andicos* and *SFD-MBR* systems offering 1.3 to 2 times higher revenues from selling water, nutrients, and energy. Among small-scale systems, *Andicos + CW +* treatment trains excelled due to energy recovery and efficient FC removal. Second, the study quantified significant environmental and health benefits of compliant wastewater treatment and resource recovery treatment trains. These include a mitigation of up to 2,600 gastrointestinal infections per year among downstream farmers and a reduced eutrophication potential of 94% compared to the discharge of untreated wastewater. Third, compliance with the 2024 draft water reuse norms may require additional treatment processes, especially for stringent FC standards. Aligning the stringent FC draft norms with WHO standards, based on health-based targets like DALY, would support sustainable wastewater reuse practices while ensuring public health and resource recovery. Finally, the findings highlight the benefits of transitioning from traditional wastewater treatment to resource recovery systems, advancing the circular economy in India. The sustainability and circularity assessment framework presented in this study offers a basis for informed technology selection.

## AUTHOR CONTRIBUTIONS

Conceptualization, L.B. and K.R.; methodology, L.B., K.R., and C.H.; validation: L.B. and C.H.; formal analysis, L.B. and K.R.; writing – original draft preparation, L.B.; writing – review and editing, L.B., K.R., C.M.H., M.D.K., P.C., A., C.K., and C.H.; visualization, L.B. and K.R.; supervision, C.H., C.M.H., and C.K.; funding acquisition, P.C., C.K., C.M.H., and A. All authors have read and agreed to the published version of the manuscript.

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## DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

## CONFLICT OF INTEREST

The authors declare there is no conflict.

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