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Phosphorus recovery from Indian sewage sludge by acidification and precipitation

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Phosphorus (P) recovery from sewage sludge offers potential for nutrient recycling in agriculture and is supported by India's 2023 Draft National Policy on Fertilizer Management. This study investigates P recovery from five sewage sludge samples collected from sewage treatment plants in Kanpur and Delhi, with P concentrations ranging from 2.34 ± 0.03 to 15.80 ± 2.05 g P/kg dry matter. However, heavy metal concentrations, particularly cadmium (Cd) and chromium (Cr), exceeded Indian compost regulations, making direct land application unsuitable without further treatment. To assess recovery potential, sludge samples underwent 1-hour acidification. Between 17 and 48% of P was released at pH 3.5–4.5, considered optimal for minimizing chemical input. However, Cd, nickel (Ni), and zinc (Zn) were solubilized below pH 5, and Cr, copper (Cu), and lead (Pb) below pH 3. Subsequent precipitation from pH 3 leachates achieved 80–88% P recovery, but the final products exceeded international limits for Cr, Cd, arsenic (As), Ni, and Zn, even after citric acid treatment for heavy metal complexation. While the process demonstrates technical feasibility, as established in European contexts, the lower P concentrations in Indian sludge and the co-leaching of heavy metals present major challenges. With chemical costs estimated at 37–99$/kg of recovered P, the process is not yet economically viable compared to subsidized synthetic fertilizers at 0.76 $/kg$_P$. Additionally, the absence of regulatory standards for mineral recycling fertilizers in India further limits the potential for scaling, underscoring the need for clear guidelines to foster product safety and market acceptance.

Keywords Phosphorus recovery, Sewage sludge, Heavy metals, Acidification and precipitation, Circular economy, India

Sewage sludge in India is typically disposed of in landfills, discharged into water bodies, or directly applied to soils without adequate treatment[1]. Although some sewage treatment plants (STPs) use drying beds, centrifuges or belt filter presses for sludge dewatering, it often receives no further stabilization or hygienization[2]. This inadequate management of a growing waste stream contributes to releasing heavy metals, pathogens, and greenhouse gases, posing environmental and public health risks[3]. With an average of 144 kg of sludge dry matter (kg$_{DM}$) produced per one MLD (million litres per day) of sewage treated[2] and considering that only 37% of the 72,368 MLD of sewage generated nationwide is treated[4], India produces an estimated 1.41 million tons (t) of sludge dry matter annually. Current sludge valorisation strategies focus mainly on energy recovery, such as biogas production or co-incineration[2,5], while the opportunity to recover valuable nutrients remains untapped. Yet, sewage sludge contains valuable nutrients and organic matter that can support circular economies if repurposed as agricultural fertilizer.

Estimates suggest that 0.38 million t of struvite, a crystallized mineral fertilizer composed of magnesium, ammonium, and phosphate, could be recovered annually from Indian sewage, depending on recovery efficiency and methodology[6], replacing up to 4% of yearly P fertilizer imports. As an agriculture-based country, India imports nearly 90% of its rock phosphate as raw material for mineral phosphorus (P) fertilizers, making it heavily reliant on global markets[7]. Reducing this dependence is critical to achieving 'self-reliance' in fertilizer production[8]. Organic and organo-mineral fertilizers are promising alternatives to the mineral (also known as inorganic or synthetic) fertilizers. Organic and organo-mineral fertilizers, derived from plant or animal material,

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the latter enriched with mineral nutrients, offer slow to moderate nutrient release and contribute to soil health, in contrast to highly soluble mineral fertilizers like urea or superphosphate.

Considering the growing awareness of P resource scarcity, many countries have introduced policies to promote P recycling from wastewater[9]. The National Policy on Fertilizer Management 2023 was introduced to foster nutrient recycling from organic waste streams, such as urban biowaste or sewage sludge, thereby reducing the environmental impacts of producing and using mineral fertilizers[10]. Complementing this, the Policy on the Promotion of Organic Fertilizers (2023) provides subsidies of up to ₹1,500 per t of organic fertilizer (∼17$ per t), to incentivize the production and marketing of organic fertilizers, aiming to build a viable market for recycled nutrient sources[11]. However, using sewage sludge in agriculture requires caution, as its composition depends heavily on the treatment process and influent sources. In addition to valuable nutrients, such as P, nitrogen (N), and potassium (K), sewage sludge can contain heavy metals and pathogens, which require proper management before land application. Recent studies assessed sewage sludge from Indian STPs, highlighting both its fertilising potential and contamination risks. Sludge from industrial catchments showed elevated levels of heavy metals, especially cadmium (Cd), nickel (Ni), and chromium (Cr), posing significant environmental and health concerns[12,13]. Furthermore, helminth eggs and high vector attraction indicated a need for further hygienization through co-composting or anaerobic digestion[14]. To address these risks, regulatory frameworks have evolved to control contaminant levels in organic and organo-mineral fertilizers (Table 1). In India, the Fertilizer Control (Amendment) Order (FCO[15], specifies maximum allowable concentrations of heavy metals in organic composts and P-enriched organic manures, the latter referring to organo-mineral products. While the FCO (2013) requires only 1.75 g P/kg_{DM} for organic compost, the newer IS 18146:2023 standard for P-enriched organic manure specifies a substantially higher minimum of 46 g P/kg_{DM}[15].

Since this study was conducted within the EU–India Horizon 2020 project *Pavitra Ganga*, we compare findings with EU and Swiss regulatory frameworks to benchmark recovery performance and product quality against mature, widely adopted standards relevant for policy transfer. The EU Fertilizing Products Regulation[16] provides a comprehensive framework for fertilizers containing organic carbon and nutrients. It includes strict limits for both heavy metals (Table 1) and pathogens (i.e. *Salmonella* spp, *E.coli*, Enterococcaceae) to ensure safe use in agriculture. As a result, the direct application of untreated sewage sludge as organic fertilizer to soils has been banned in many European countries to prevent heavy metal accumulation and protect long-term soil fertility[18]. Instead, P recovery from sewage sludge and its incorporation into controlled fertilizer products offer a safer and more sustainable alternative.

P recovery technologies vary in approach and efficiency, with some already in full-scale operation and others still under development[19]. Among these, struvite ($MgNH_4PO_4 \cdot 6\ H_2O$) precipitation has received considerable attention. The process involves solubilizing phosphate from sewage and sewage sludge via acidification, followed by precipitation with magnesium and ammonium to form struvite[20]. Struvite is a slow-release, plant-available P fertilizer with crop performance comparable to conventional mineral fertilizers like triple superphosphate[21]. However, the quality of struvite recovered from sewage sludge can be affected by the presence of heavy metals, such as cadmium (Cd), lead (Pb), and chromium (Cr), especially when sourced from industrial catchments or when pre-treatment is insufficient[22]. These contaminants can accumulate in the final product, potentially limiting its safe use in agriculture if not properly managed. Recognizing these challenges, Switzerland has proposed specific contaminant thresholds for mineral recycling fertilizers building on the Chemical Risk Reduction Ordinance[23] and the Ordinance on the Avoidance and Disposal of Waste[17,24]. Due to the wide range of phosphorus content in mineral recycling fertilizers (60–200 g P/kg), Swiss regulations express heavy metal thresholds per kilogram

	Indian standards for organic compost and P-rich organic manure[15]	**EU - Organic fertilizer containing organic carbon and nutrients**[16][a]	**Switzerland – mineral recycling fertilizer**[17]
	[mg/kg_{DM}]	**[mg/kg_{DM}]**	**[mg/kg_{P}]**
Arsenic (As)	10	40	100
Cadmium (Cd)	5	1.5	25
Chromium (Cr)	50	(Cr VI) 2	1,000
Copper (Cu)	300	300	3,000
Mercury (Hg)	0.15	1	2
Nickel (Ni)	50	50	500
Lead (Pb)	100	120	500
Zinc (Zn)	1000	800	10,000

Table 1. Maximum heavy metal concentrations in organic, organo-mineral and mineral recycling fertilizers according to different standards*. Notes: Indian and EU limit values are expressed per kg dry matter (mg/kg_{DM}), whereas Swiss limit values are expressed per kg phosphorus (mg/kg_{P}). * Organic fertilizers contain organic matter along with nutrients typically bound in organic compounds, that must decompose to become plant-available (such as compost, manure, digestate or sewage sludge). Mineral recycling fertilizers are typically derived from chemical or physical processes and contain nutrients in mineral forms (such as phosphate salts), which are easily soluble and available to plants. [a]Limit values according to Annex 1 Part II section PFC 1(A).

of phosphorus (mg/kg$_P$) instead of per kilogram of dry matter (Table 1). By setting limits per kg P, Switzerland ensures that the same quantity of heavy metals per hectare is applied, regardless of the product used.

Although India currently lacks a dedicated regulatory framework for mineral recycling fertilizers, struvite precipitation has been identified as a promising method for P recovery. Recovery efficiencies for dissolved P in Indian sewage streams have been estimated between 60 and 90%[6,22,25]. Only a limited number of experimental or pilot-scale studies have been conducted in India to date. Issac et al.[26] achieved an 85% recovery of dissolved P as struvite from household wastewater, while Srivastava et al.[27] reported 70–85% recovery of P contained in sewage sludge in Rajasthan, with heavy metal concentrations in the recovered struvite remaining within acceptable limits for agricultural use. Depending on the matrix studied, these recovery efficiencies are not directly comparable, as they refer to different phosphorus pools, i.e. dissolved P in wastewater and P bound in sewage sludge.

This study explores the technical feasibility and chemicals' cost implications of P recovery from five sewage sludge through the laboratory-scale acidification and precipitation experiments. In addition, the study examines heavy metal solubilization during acidification and the resulting contaminant levels in the precipitated product to assess its suitability as a mineral recycling fertilizer. Finally, it presents context-specific implications for adapting India's sewage treatment strategies to support phosphorus recovery and outlines key directions for future research to enhance sustainable sludge management.

To our knowledge, this study provides the first comparative assessment of phosphorus recovery potential and heavy-metal behavior across multiple Indian STPs under standardized laboratory conditions, offering preliminary insights into the technical feasibility and regulatory readiness of sludge-derived fertilizers in the Indian context.

Materials and methods

Sewage sludge samples

Five sewage sludge samples were collected from four STPs in Kanpur and Delhi (Table 2) between August and September 2023. One sample was secondary sludge from the self-forming dynamic membrane bioreactor (SFD-MBR) pilot plant at Jajmau STP, an innovative alternative to the conventional activated sludge process[28]. The Jajmau STP receives municipal wastewater and, very likely, some fraction of industrial wastewater from nearby tannery industries. A separate common effluent treatment plant is constructed to treat the tannery wastewater[18]. Solid-liquid separation in the SFD-MBR is achieved by a self-forming cake layer that develops on a supporting surface. Excess, non-digested sludge was sampled from the pilot plant.

At Bingawan STP, non-digested sewage sludge was sampled from the UASB reactor prior to the thickening stage. At Sajari STP, which operates an activated sludge process followed by anaerobic digestion of secondary sludge, two samples were collected—one secondary sludge before digestion and one digested sludge (digestate) sampled prior to the sludge thickening stage. In Delhi, sewage sludge was sampled from the anaerobic digesters at Okhla STP.

The selected sludges represent common treatment configurations used across Indian municipal STPs, i.e. UASB-based, activated sludge, and anaerobic digestion systems, covering both digested and non-digested sludge types[29]. This diversity was intentionally chosen to capture typical variations in phosphorus and heavy-metal composition and to provide a representative basis for assessing P recovery potential under different treatment conditions.

Sludge samples were collected as grab samples from representative sampling points of the treatment process, as indicated above. Samples were transferred into clean, sealed containers and transported to the laboratory on the same day. To preserve the samples for subsequent analyses and international shipment, they were centrifuged to remove excess water and dried at 105 °C. This procedure ensured stability and prevented compositional changes during storage and transport, although drying may slightly alter sludge characteristics compared to fresh samples.

If data was available, the STP operators provided P concentrations in the influent and effluents. None of the STPs applied biological or chemical P precipitation.

Sewage sludge analysis

Sewage sludge samples from Bingawan and Sajari STPs were allowed to settle, and the supernatant was discarded. pH was determined immediately after sampling using a pH meter. Sewage sludge was centrifuged at 10,000 g for 10 min at 25 °C and then dried at 105 °C for 48 h to determine the dry matter (DM) content. Okhla sewage sludge was dried at 105 °C for 48 h without prior centrifugation. Dried sewage sludge samples were homogenized

Sewage treatment plant (STP)	Treatment Design	Treatment Capacity [m^3/d][d]	P influent [mg/L][d]	P effluent [mg/L][d]	Type of Sludge[e]
Pavitra Ganga pilot, Jajmau, Kanpur	SFD-MBR[a]	120	3.5	2.3	Non-digested (Secondary)
Okhla, Delhi	ASP[b]	136,000	2.0–4.0	0.8	Digested (Primary + Secondary)
Bingawan, Kanpur	UASB[c]	210,000	n.a.	n.a.	Non-digested
Sajari, Kanpur	ASP[b]	42,000	n.a.	n.a.	Non-digested and digested (Primary + Secondary)

Table 2. Overview of the investigated treatment plants and their sewage sludges. [a] Self-Forming Dynamic Membrane Bio-Reactor, [b] Activated sludge process, [c] Upflow Anaerobic Sludge Blanket, [d] Average values provided by the STP operators, [e] Digestion status ('digested' or 'non-digested') was reported by STP plant operators without specific details on digestion parameters.

at 30 Hz using a ball mill for 1 min. Sewage sludge characteristics, such as P, metals, heavy metals, total organic carbon (TOC) and ammonium (NH_4^+), were determined in triplicate. For microwave digestion (CEM Mars 6, United States), 100 mg of dried sludge was mixed with 4 mL of aqua regia. The temperature and power were ramped to 175 °C and 1600 W over 20 min and then maintained at these conditions for a further 15 min before cooling to room temperature. 1.0 mL aliquots were centrifuged at approx. 2,000 g (6,000 rpm, IKA Mini G) for 1 min and filtered through a 0.45 µm PTFE stirring filter. The filtrate was diluted with 3% nitric acid to 1:100 and 1:1,000 before analysis with inductively coupled plasma mass spectrometry (ICP-MS, Agilent 8800 Triple Quadrupole, United States). To ensure quality assurance in ICP-MS measurements, a calibration curve spanning 1–500 ppb was generated using a multi-element standard (Periodic Table Mix 1, Sigma-Aldrich, in 3% nitric acid) and measured at the beginning of each measurement. $^{103}\mathrm{Rh}$ was used as an internal standard to account for matrix effects and to monitor instrument stability. The quantification of $^{52}\mathrm{Cr}^+$, $^{55}\mathrm{Mn}^+$, $^{56}\mathrm{Fe}^+$, $^{60}\mathrm{Ni}^+$, $^{63}\mathrm{Cu}^+$, $^{66}\mathrm{Zn}^+$, $^{101}\mathrm{Ru}^+$, $^{111}\mathrm{Cd}^+$, and $^{206}\mathrm{Pb}^+$ was performed in single-quadrupole mode using helium as the collision gas, while $^{24}\mathrm{Mg}^+$, $^{31}\mathrm{P}^+$, and $^{75}\mathrm{As}^+$ were quantified in triple-quadrupole mass-shift mode with O_2 as the reaction gas. Isotope selection for each element considered natural abundance and minimization of spectral interferences typical in sludge matrices. For example, $^{52}\mathrm{Cr}^+$, $^{60}\mathrm{Ni}^+$, and $^{63}\mathrm{Cu}^+$ were selected as the most abundant and least interfered isotopes under He collision mode, while $^{75}\mathrm{As}^+$ was measured in O_2 mass-shift mode to eliminate the $^{40}\mathrm{Ar}^{35}\mathrm{Cl}^+$ interference. The selected isotopes provided optimal sensitivity and accuracy across the analyte suite. Correlation coefficients ($R^2 > 0.999$), limit of detection (LOD), and limit of quantification (LOQ) were calculated for each element, along with recovery rates from positive samples and blank sample controls (Tables S.1 – S.7 Supplementary materials). Two types of blanks were used for quality control: a reagent blank prepared with 3% nitric acid to account for background from the acid matrix, and an instrument blank prepared with millipore water to detect possible contamination from vessels, filters, or the measurement system. This dual blank approach ensured that both reagent-related and procedural interferences were identified and minimized.

Total organic carbon (TOC) was measured using the solid sample module (SHIMAZU - SSM-5000 A, Japan) and analysed with the TOC-L (SHIMADZU - Ver. 1.10.10, Japan). The ammonium (NH_4^+) concentration was analysed in the suspension (with 3% DM) of the sewage sludges before acidification using the HACH Lange test kit (HACH, Switzerland) and the ultraviolet-visible (UV-VIS) spectrometer (HACH, Switzerland).

Acidification of sludge

The experimental batch setup of the acidification followed by P precipitation is shown in Fig. 1.

A 3% (w/w) suspension of dried sludge and millipore water was prepared in a 500 mL Erlenmeyer flask with a magnetic stir bar. The flask was covered with foil to prevent evaporation. The suspension was stirred at 500 rpm for 1 h, then acidified gradually to various pH levels (8 to 1) using 95% sulphuric acid (Sigma Aldrich, United States). Sulphuric acid was selected as the leaching agent because it is commonly used for phosphate solubilization in P-recovery processes such as the Stuttgart process, offering effective P release with minimal interference in struvite precipitation[20,30]. After acid addition, stirring continued for 1 h. The final pH was measured after 1 h and the leachate was sampled for further analysis (i.e., P, metals and heavy metals) as described above.

To quantify the release of P, metals, and heavy metals, the following equation was used:

$$X\ release\ [\%] = \frac{X_{leachate}}{X_{total}} \times 100 \tag{1}$$

where X is the element being quantified (i.e., P, metals, heavy metals); $X_{leachate}$ is the concentration of X in the leachate [mg/L], and X_{total} is the concentration of total X in the acidified sewage sludge sample [mg/L] (Fig. 1).

Phosphorus, metal and heavy metal precipitation

In a second experiment, dried sludge samples from the Jajmau pilot and Okhla STP were suspended and acidified to pH 3, as described before (section Acidification of Sludge). This setpoint was chosen as the literature-guided lower bound of the reported optimal range (pH 3–5) that balances high phosphate solubilization with reasonable acid demand[20]. The suspension was centrifuged at approx. 2,800 g (4,000 rpm, Eppendorf 5810 R with A-4–44 rotor) for 10 min, and the supernatant was filtered through a 5 µm filter using a vacuum pump. The filtered

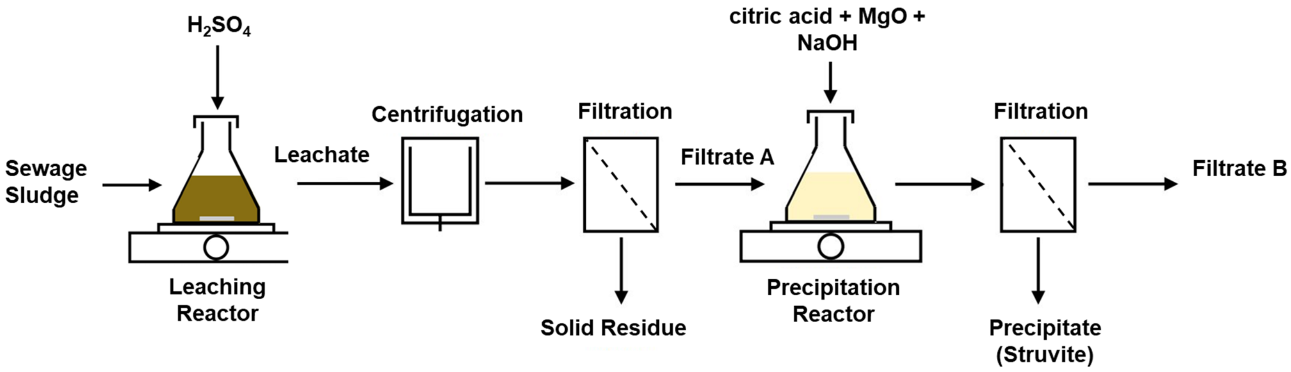

Fig. 1. Experimental setup for sludge acidification, filtration and P precipitation.

leachate was transferred to a 500 mL Erlenmeyer flask with a magnetic stirrer. The flask was covered with foil to prevent evaporation. Ammonium chloride was added to achieve an NH_4^+ concentration of 1.5 g/L, matching typical levels in dewatered sewage sludge[31]. The solution was stirred for 30 min at 500 rpm. Citric acid, for metal complexation[20], was then added in a 1:1 stoichiometric ratio to predominant metals (Fe, Al, Ca, Mg) and stirred for another 30 min. Magnesium oxide was added in a 1.5:1 Mg ratio for P precipitation, and the solution was stirred for 30 min. The pH was adjusted to pH 8 with 5 M sodium hydroxide, and the solution was stirred for 2 h before being filtered through a 5 µm filter at 20 mbar. Filtrates A and B (Fig. 1) were sampled for further analysis using ICP-MS.

To quantify the P, metal and heavy metal recovery, the following equation was used:

$$X\ recovery\ [\%] = \frac{X_{filtrate\ A} - X_{filtrate\ B}}{X_{total}} \times 100 \tag{2}$$

where X is the element being quantified (i.e., P, metals, heavy metals); $X_{filtrate\ A}$ is the concentration of X in the filtrate A [mg/L]; $X_{filtrate\ B}$ is the concentration of X in the filtrate B [mg/L]; and X_{total} is the total concentration of X in the acidified sewage sludge sample [mg/L].

Because the precipitate mass obtained in bench tests was < 1 g and could not be analyzed directly, we estimated precipitate composition by partial mass balance. Specifically, the mass of P captured in the solid (per unit of sludge dry matter, DM) was divided by a literature-based precipitate yield of 120 g precipitate per kg sludge DM[6] to obtain precipitate P concentration (g P/kg precipitate). Metals and heavy metals were expressed as mg metal per kg P (i.e., metal captured ÷ P captured), aligning with fertilizer quality limits defined per kg of P[17].

Illustrative example (with units): if X_{total} for P is 100 mg/L, $X_{filtrate\ A}$ = 80 mg/L, and $X_{filtrate\ B}$=20 mg/L, then P recovery is according to formula (2): $\left(80\frac{mg}{L} - 20\frac{mg}{L}\right) \div 100\frac{mg}{L} = 60\%$.

This means that 60% of the total P originally present in the sludge was transferred from the liquid phase into the solid precipitate. If this corresponds to 2.0 g P/kg_{DM} captured, and assuming a precipitate yield of 120 g per kg_{DM}, the estimated P content of the precipitate is: $2.0\frac{g\ P}{kg\ DM} \div 0.120\frac{kg\ precipitate}{kg\ DM} = 16.7\frac{g\ P}{kg\ precipitate}$. Metal concentrations are expressed as mg metal per kg P using the same mass-balance approach.

Cost analysis

Literature indicates that chemical costs dominate the Stuttgart process[20,32]. We calculated the chemical costs for acidifying sewage sludge and precipitating P from Jajmau pilot and Okhla STP for an initial cost analysis. Chemical prices [\$/kg] were sourced from an online retailer in India[33]. Average prices were used to calculate the chemical costs per kg of recovered P. The costs [\$/kg_P] were then compared with literature values for recycling fertilizers from the Stuttgart process[20] and current P fertilizer prices in India[34].

Results and discussion

Sewage sludge analysis

Dry matter and phosphorous levels in sewage sludges

DM, TOC and P concentrations of the five sewage sludges are shown in Table 3. As expected, the highest dry matter and P concentrations were found in sludge from Jajmau and Okhla STPs, reflecting the combined effects of higher solids content and, in the case of Okhla, anaerobic digestion, which concentrates P in the remaining solids.

DM contents of the sewage sludges are within the expected ranges of dewatered sewage sludge from activated sludge treatment plants (2.6–3.2%[20]. DM contents of the SFD-MBR pilot were lower since this sample was not dewatered. TOC values ranged from 12.8 ± 0.1% to 33.0 ± 0.2%, with the highest in Jajmau STP, followed by Okhla STP. These values align with typical Indian sewage sludges ranging from 12% to 42%[14]. The minor TOC differences between non-digested and digested sludge at Sajari STP may be due to fluctuating sludge compositions or suboptimal digestion conditions, which did not lower organic contents. NH_4^+ concentrations in the 3% (w/w) dried sludge suspension ranged from 3.8 mg/L (Jajmau pilot STP) to 14.8 mg/L (Sajari 1 STP), significantly below the typical 0.5–2.0 g/L for dewatered sludge[31]. This is likely because the sludge sample was dewatered, centrifuged, decanted, and dried before preparing the suspension, removing NH_4^+ via the liquid phase. Since NH_4^+ concentration influences the efficiency of struvite precipitation[35], ammonium chloride was added for the precipitation experiments, as described above.

P concentrations in sewage sludge from Jajmau, Bingawan, and Sajari (1&2) STPs fall within the expected range for Indian sewage sludges, between 1.9 and 12.4 gP/kg_{DM}[14]. Differences are consistent with treatment and

STP	Type of Sewage Sludge	pH	DM [% of sludge]		TOC [% of DM]		P [g/kg_{DM}]^a
Jajmau	Non-digested (secondary from SFD-MBR pilot)	7.5	0.4	± 0.0	33.0	± 0.2	12.2 ± 0.1
Okhla	Digested (primary + secondary)	6.5–8.0^a	3^a		24.2	± 0.2	15.8 ± 2.0
Bingawan	Non-digested	6.5	4.1	± 0.0	14.0	± 0.2	2.3 ± 0.0
Sajari 1	Non-digested (primary + secondary)	7.5	3^a		14.0	± 0.1	3.8 ± 0.2
Sajari 2	Digested (primary + secondary)	7.0	3.2	± 0.0	12.8	± 0.1	3.2 ± 0.1

Table 3. pH, dry matter, TOC and P shares of sewage sludges (mean ± standard deviation). ^{a}Average values reported by the STP operators.

influent composition: the Okhla sample (digestate) shows higher P, reflecting concentration during anaerobic digestion and effective solids capture, while the Jajmau sample (secondary sludge from an SFD-MBR co-treating municipal and tannery wastewater) is comparatively lower in P, consistent with the absence of digestion/primary concentration and a lower-P industrial co-load.

In contrast, P concentrations in sewage sludges from European STPs, where P is often chemically precipitated, are 2 to 15 times higher than in Indian sewage sludges. European sewage sludges have P concentrations of 26 to 34 g/kg_{DM}[32,36]. This disparity may be due to lower initial P content in Indian sewage and the absence of P removal processes in Indian STPs. In Europe, average P concentrations in municipal wastewater are between 6 and 20 mg/L and about 95% of the P is retained in the sludge[32]. In contrast, Okhla STP retains 60–80% of the P in the sludge, while the SFD-MBR pilot only retains 34% (Table 3). P contents in Indian municipal wastewater ('sewage') seem lower than in Europe (e.g., 7 mg/L[27], likely due to the lower sewage network coverage[37], less meat and less processed food consumption[38] and the lower use of phosphate-based detergents[39].

Metals and heavy metals in sewage sludges

The sewage sludges' metal and heavy metal concentrations in the DM were analysed (Fig. 2). The metal concentrations in sewage sludge from India generally align with those reported in the literature for dried sewage sludge from STPs in Europe, i.e., Al: 5.9–14.1 g/kg_{DM}, Ca: 14.8–51.1 g/kg_{DM}, Fe: 16.3–72.6 g/kg_{DM}, Mg: 3.9–7.68 g/kg_{DM}[32]. Heavy metal concentrations were found to be similar to those reported by Sude et al.[14] for Indian dewatered sewage sludges, i.e., As: 0.00–0.02 g/kg_{DM}, Cd: 0.00–0.02 g/kg_{DM}, Cr 0.00–0.11 g/kg_{DM}, Cu: 0.00–0.68 g/kg_{DM}, Ni: 0.00–0.07 g/kg_{DM}, Pb: 0.00–0.03 g/kg_{DM} and Zn: 0.00–0.72 g/kg_{DM}. Compared to European sewage sludges, those from Kanpur and Delhi generally had lower heavy metal concentrations, except for Cd and Cr[3,9]. Cd levels were 3–530 times higher, while Cr levels were 1–350 times higher than those reported for Europe. The elevated Cd in Kanpur suggests nearby industrial activity. The exceptionally high Cr in Jajmau STP likely results from nearby tanneries discharging Cr-rich wastewater into the municipal system.

The P concentrations in all the sludge samples meet the minimum concentration for organic compost (i.e. 4 g P_2O_5/kg_{DM} or 1.75 g P/kg_{DM}; Table 3). Based on Fig. 2, most sludges show heavy metal concentrations exceeding the Indian limits[15]. In particular, Cd, Ni and As exceed or are close to the permissible thresholds in nearly all samples, while Pb, Cr and Zn exceed limits in individual cases. Only Cu remains largely within acceptable ranges. Direct application of the untreated sewage sludge is, therefore, not suitable, as has been found in other studies[12–14]. For the Okhla sewage sludge, which only slightly exceeds the Cr level, co-composting with other biowastes, such as the organic fraction of municipal solid waste, could be explored as a strategy to achieve heavy metal concentrations within permissible limits, ensuring the final product is suitable as a fertilizer. To increase the P contents of composted sewage sludge and other biowastes, the new standard IS18146:2023[15] recommends co-composting with unprocessed rock phosphate to achieve the minimum desirable level of 105 g $P_2O_5/kg_{DM,}$ i.e. 46 g P/kg_{DM}. Compared with the relatively low P requirement for organic compost under the FCO (2013), this much higher target implies that most of the P in such P-enriched products would need to be supplied by added rock phosphate rather than by the sewage sludge itself. This needs to be further explored and the final product compared against the permissible heavy metal concentrations in the IS 18146:2023[15] standards, since rock phosphate can also contain heavy metals such as cadmium, lead and arsenic.

Acidification of sludge

Release of phosphorus during acidification

P bound in the sludge was increasingly solubilised as pH decreased, resulting in higher concentrations of dissolved P (Fig. 3, left). This is consistent with previous studies attributing this to the dissolution of inorganic P as ortho-phosphate[33,40,41]. Initially (pH 6.51–7.49), dissolution rates for all sewage sludge samples were similar (2–10%). At the lowest pH (0.89–1.01), except for Jajmau STP (53%), dissolution rates remained comparable (63–70%). Okhla STP exhibited the highest P release rates throughout acidification (70%).

Dissolution rates increased between pH 6–4.5 and 2.5–1 (Fig. 3). Meyer et al.[20] also observed differences in P release rates across various pH ranges (Table 4). Their study of European sewage sludges from STPs using Fe and Al salts for P removal found lower P release rates in Al-precipitated sludge compared to Fe-precipitated sludge, as Fe phosphates dissolve more readily in sulfuric acid.

At pH > 4.5, Okhla STP's P release aligns with literature values, while Sajari sewage sludges (1&2) are slightly lower than values for Al salts. Jajmau and Bingawan STPs fall below the literature range. A similar trend is seen at pH 4.5–3.5, where Okhla matches literature values, and Bingawan and Sajari align with Al-salt values. P release from Jajmau remains below the expected range for both Al and Fe salts.

At pH < 3.5, all Indian STP sludges fall within the literature range for Al salts (0.5) but below Fe salt values (0.8). Acidification thus enhanced P release from all sludges, but the extent differed between samples. Compared with the digested European Fe/Al-precipitated sludges studied by Meyer et al.[20], where Fe/Al-bound inorganic phosphates dominate and are readily dissolved by acid[32,41], the Indian sludges showed lower P-release efficiencies, consistent with their low Fe and Al contents and the absence of chemical P removal. Consequently, the limited Fe/Al-P pool likely represents the main constraint on the acid-extractable P fraction.

Acid consumption per g of P released varies between sludges (Fig. 3, right). Okhla STP requires the least acid, followed by Jajmau and Sajari 1, while Sajari 2 and Bingawan have the highest demand. At pH 3, Okhla needs one-fifth, and Jajmau half, the acid required by Bingawan per g of P released.

Okhla's results are consistent with the literature (0.33–0.54 mol H_2SO_4 per g P released[32], but Kanpur sludges required more acid, likely due to lower P concentrations, indicating higher chemical costs for P recovery. About one-quarter of the total acid was used to reduce pH to 2.5, while the remaining three-quarters was needed

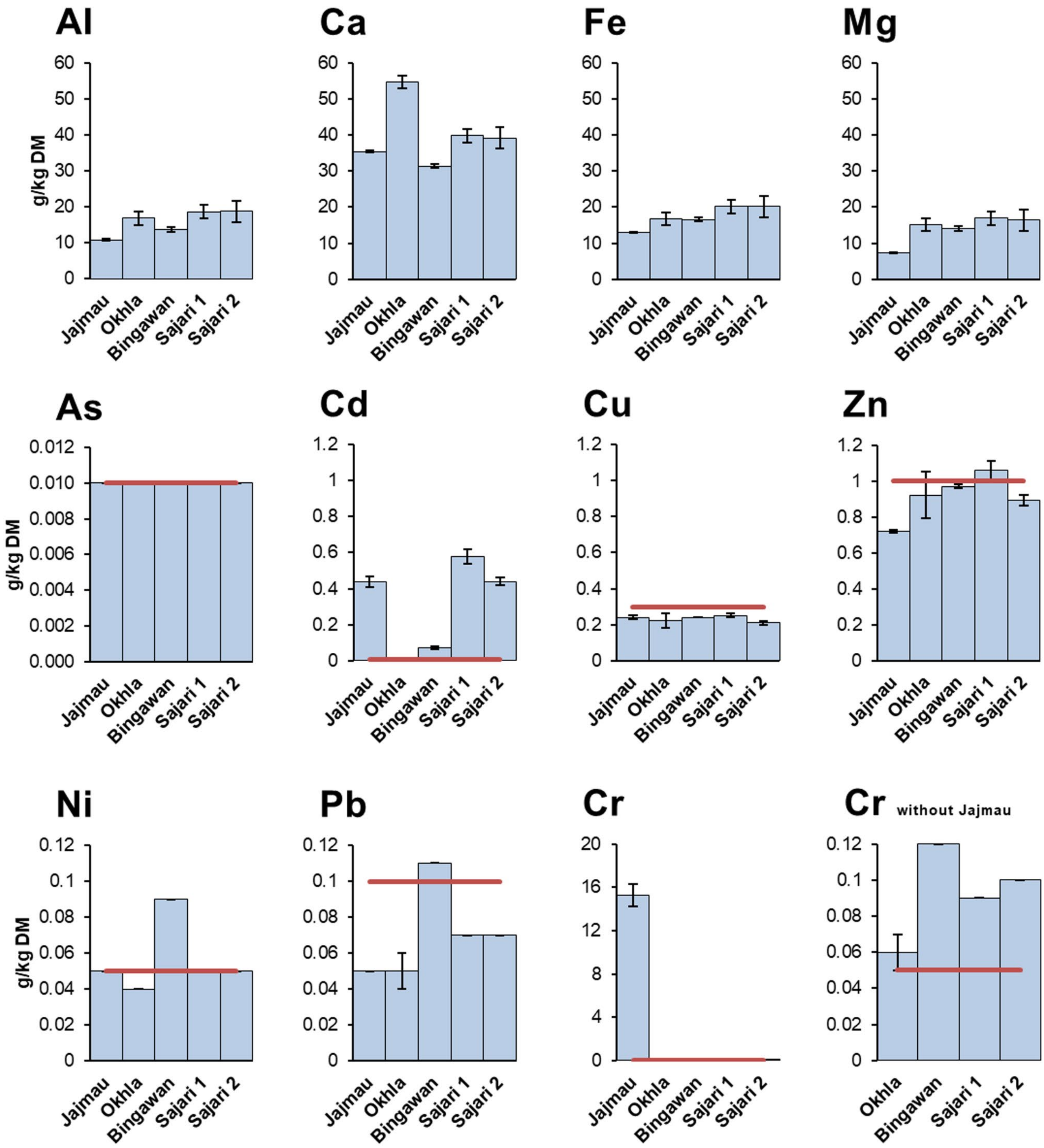

Fig. 2. Metals and heavy metals in sewage sludges from five STPs. Bars show mean ± standard deviation (n = 3) on a dry-matter basis (g/kg$_{DM}$). Red horizontal lines indicate the Indian standard limits for As, Cd, Cr, Cu, Ni, Pb, Zn in organic and P-rich organic fertilizers[15].

to reach pH 1. Acidification should, therefore, not exceed pH < 2.5 to be a viable process, as shown in other studies[20].

Quist-Jensen et al.[32] reported higher acid consumption for digested sludge than non-digested which was explained by the high amounts of carbonates and bicarbonates produced during the anaerobic digestion process increasing the sludges' buffer capacity. In this study no significant difference was found between digested and non-digested sludges. Since sludge samples were centrifuged and dried in this study some of the buffering capacity was likely lost. The acid consumption and carbonate/bicarbonate concentrations should therefore be re-investigated with wet sludge samples to understand the buffering dynamics.

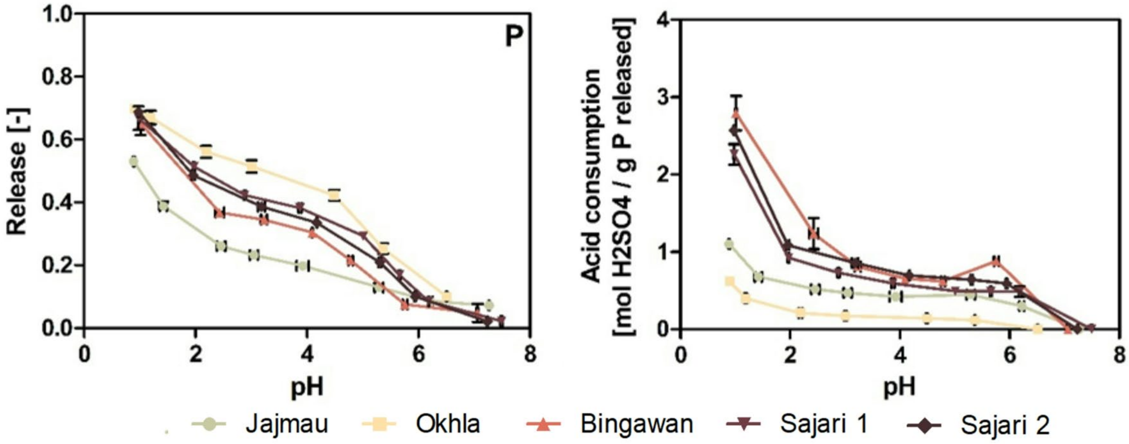

Fig. 3. P release during acidification (*left figure*) and acid consumption during the acidification (*right figure*). Error bars represent the standard deviation of the reaction triplicates ($n = 3$).

Leaching pH	Chemical P removal in STP		Without chemical P removal in STP				
	With Fe salts[20]	With Al salts [20]	Jajmau	Okhla	Bingawan	Sajari 1	Sajari 2
> 4.5	0.36–0.55	0.28–0.49	0.07–0.17	0.10–0.42	0.04–0.25	0.02–0.33	0.02–0.30
3.5–4.5	0.40–0.70	0.24–0.47	0.17–0.21	0.42–0.48	0.25–0.33	0.33–0.39	0.30–0.37
< 3.5	0.80	0.50	0.21–0.53	0.48–0.70	0.33–0.63	0.39–0.67	0.37–0.67

Table 4. Comparison of P release rates during leaching at different pH ranges between Indian sewage sludge and literature values.

Release of heavy metals during acidification

Heavy metal release during acidification (Fig. 4) was found to vary:

- Increased release rate at pH < 5: Cd, Ni, Zn.
- Increased release rate at pH < 3: Cr, Cu, Pb.
- No clear trend: As.

In some cases, such as with As and Pb, heavy metal concentrations were below the LOQ or LOD, preventing the determination of release at all pH levels (Tables S.8 – S.12 Supplementary materials). At pH 5, Cd, Ni, and Zn releases ranged from 6 to 35%, with rates increasing at lower pH values. At pH 1, Cd, Ni, and Zn releases reached 58–100%. The highest release rates for Cd, Ni, and Zn were found in Bingawan STP and the lowest in Jajmau STP and Okhla STP. Cr, Cu, and Pb showed minimal release above pH 3, but at pH 1, their release increased, ranging from 22 to 76%. The lowest release rates were found for sewage sludge from Okhla STP (Cr, Pb) and Sajari STP (Cu). As showed no consistent pattern and was measurable only in Bingawan and Sajari 2 STPs, with releases of 26–75%.

Heavy metal release from sewage sludge during acidification complicates fertilizer production, as metals mobilised into the leachate can co-precipitate with P and cause the recovered product to exceed permissible limits or increase treatment costs if left in the liquid phase[32]. However, this mobilisation can also enable targeted extraction and stabilisation of heavy metals prior to P precipitation, facilitating safer removal[42].

Phosphorus precipitation

Recovery of released phosphorus through precipitation

Almost all P released during acidification was successfully precipitated (Fig. 5). At pH 3, 22% of P was released from Jajmau STP sewage sludge and 48% from Okhla STP sewage sludge. Following precipitation at pH 8, 17% of P from Jajmau and 42% from Okhla sewage sludge was recovered, corresponding to recovery efficiencies of 80% and 88% of dissolved P from filtrate A, respectively (Fig. 5 left). Similar recovery rates were found for sewage sludge in Rajasthan in a recent study[27]. This indicates that the P recovery rate strongly depends on P release during acidification, with the precipitation step not being the limiting factor, as also found by[20].

According to the literature, P recovery rates from sewage sludge typically range between 33 and 67%, with recoverable amounts of 7.8–16 g P/kg$_{DM}$ under optimized conditions (pH < 3.5 for acidification and pH ~ 8 for precipitation)[9,20]; Fig. 5 right). In this study, both the recovery rates and absolute amounts were lower, with 6.65 ± 0.52 g P/kg$_{DM}$ for Okhla and 2.11 ± 0.09 g P/kg$_{DM}$ for Jajmau, likely due to lower initial P concentrations

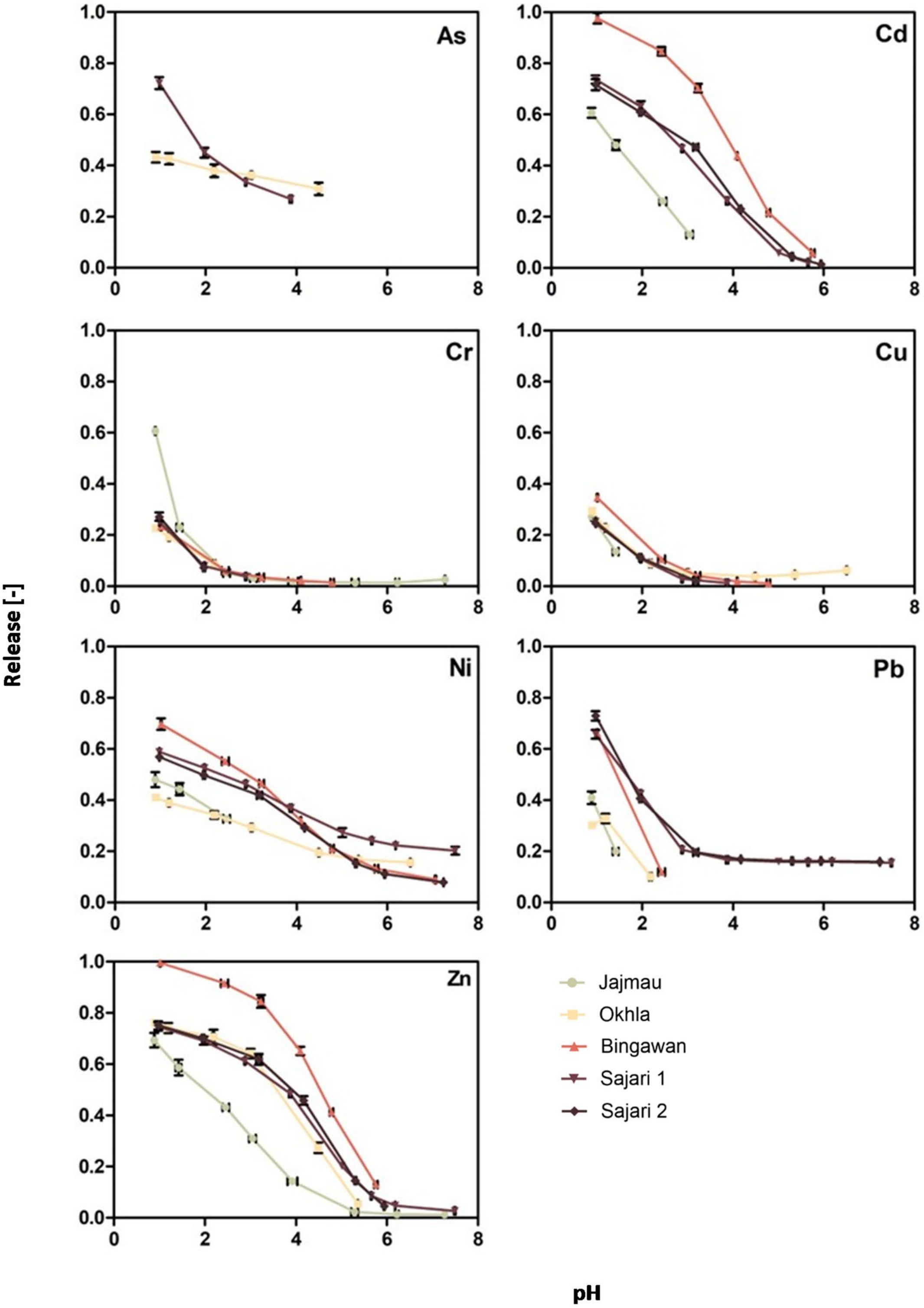

Fig. 4. Heavy metal release during acidification reaction at different pH values. Error bars represent the standard deviation of the reaction triplicates ($n = 3$).

in the raw sludges. Based on an assumed precipitate yield of 120 g/kg$_{DM}$[6], the resulting P concentrations in the precipitates were 55.4 g P/kg for Okhla and 17.6 g P/kg for Jajmau, falling below the typical range for technical-grade struvite (100–120 g P/kg[9]. As the P content in the final product is critical for agronomic effectiveness and marketability, these results suggest limited suitability for use as fertilizer-grade mineral products. While P recovery appears technically feasible at both sites, efficiency remains lower than in comparable European settings, potentially increasing chemical demand and reducing economic viability. Further research is needed to

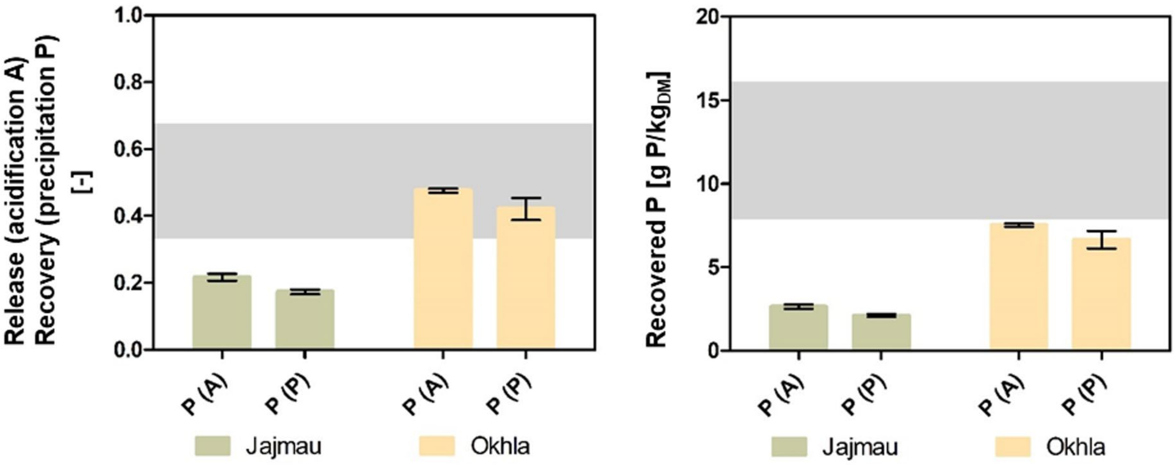

Fig. 5. P release after acidification (A) at pH 3 and P recovery after precipitation (P) from Jajmau pilot STP and Okhla STP sewage sludges (*left figure*). Amount of recovered P in g P/kg$_{DM}$ of sludge after acidification (A) and after precipitation (P) (*right figure*). The shaded area indicates the range of values found in the literature[19]. Error bars represent the standard deviation of the reaction triplicates ($n = 3$).

evaluate the recovered products' composition, consistency, and fertilizer value and determine their compliance with quality standards in target markets.

Precipitation of metals and heavy metals

Although citric acid was used in the precipitation experiment to complex metals and prevent their presence[20] in the final product, it was only partially effective. For instance, only 10% of released Al from Jajmau pilot STP and 18% from Okhla STP sewage sludge were precipitated, while 17% and 45% of released Ca and 37% and 64% of released Fe were precipitated, respectively. Thus, P may have precipitated as metal phosphates rather than struvite due to the presence of those metals. Despite this, the Mg concentration remained nearly unchanged in Leachate A compared to Leachate B (Fig. 1), although additional MgO was added in the precipitation phase, suggesting that some P likely precipitated as struvite. An X-ray diffraction analysis should be conducted to confirm struvite formation.

While acidification to pH 3 effectively retains many heavy metals in the filter cake (Fig. 4), some still appear in the final precipitate (Fig. 6). Studies suggest that less than 3.5% of the heavy metals released during acidification should be in the precipitate[20]. However, this study found higher percentages: 10–16% for As, Cu, and Ni, and 50–92% for Cd, Cr, Pb, and Zn. Similar results were noted by[43], who found that heavy metal concentrations in struvite vary based on metal concentrations, wastewater composition, reaction parameters, and interactions among metal species.

Heavy metals in the Jajmau STP sewage sludge precipitate were significantly higher than in Okhla sewage sludge, with Cd and Cr exceeding Swiss limit values 180 to 430 times (Table 1). While the Okhla STP precipitate would meet some limits, Cd and Zn would exceed the allowed Swiss thresholds. Additional treatment processes should be explored to meet standards as a suitable recycling fertilizer. For Okhla STP sewage sludge, for example, ultrafiltration after acidification could further reduce heavy metal concentrations before P precipitation[20]. For Jajmau STP sewage sludge, treatment options like pyrolysis or nanofiltration should be considered, as pyrolysis immobilizes heavy metals while recovering P[44], and nanofiltration has been shown to effectively reduce heavy metal concentrations[45]. Recent work also shows that a two-stage static–dynamic struvite crystallisation system can physically separate Cu- and Zn-rich fines from struvite and thus improve product purity and P recovery efficiency, providing a promising direction for producing higher-purity struvite from metal-rich sludges[46].

Cost analysis

Only chemical costs were considered in this assessment, as they form the bulk of the process costs[9]. Overall, the estimated chemical costs per recovered P are 2.6 times higher for Jajmau STP sewage sludge than for Okhla STP sewage sludge, showing that lower P concentrations and recovery rates increase costs significantly (Table 5).

Recovering P from sewage sludge via the Stuttgart process costs 9–17$/kg$_P$[9]. Chemical costs for P recovery at Jajmau STP are 6 to 11 times higher (99$/kg$_P$), and at Okhla STP, 2 to 4 times higher (38$/kg$_P$). This difference is mainly attributed to the lower P concentrations in the sewage sludge. While the amount of magnesium oxide used is directly proportional to the P concentration, the consumption of other chemicals does not decrease proportionally at low P concentrations. Therefore, chemical costs per recovered P increase with lower P concentrations in the sewage sludge.

Recycling fertilizers must compete with conventional fertilizers in the Indian market, where government subsidies significantly influence prices. Under the Nutrient Based Subsidy (NBS) Scheme, fixed subsidies are provided for individual nutrients, including nitrogen (N), phosphorus (P), potassium (K), and sulphur (S). As

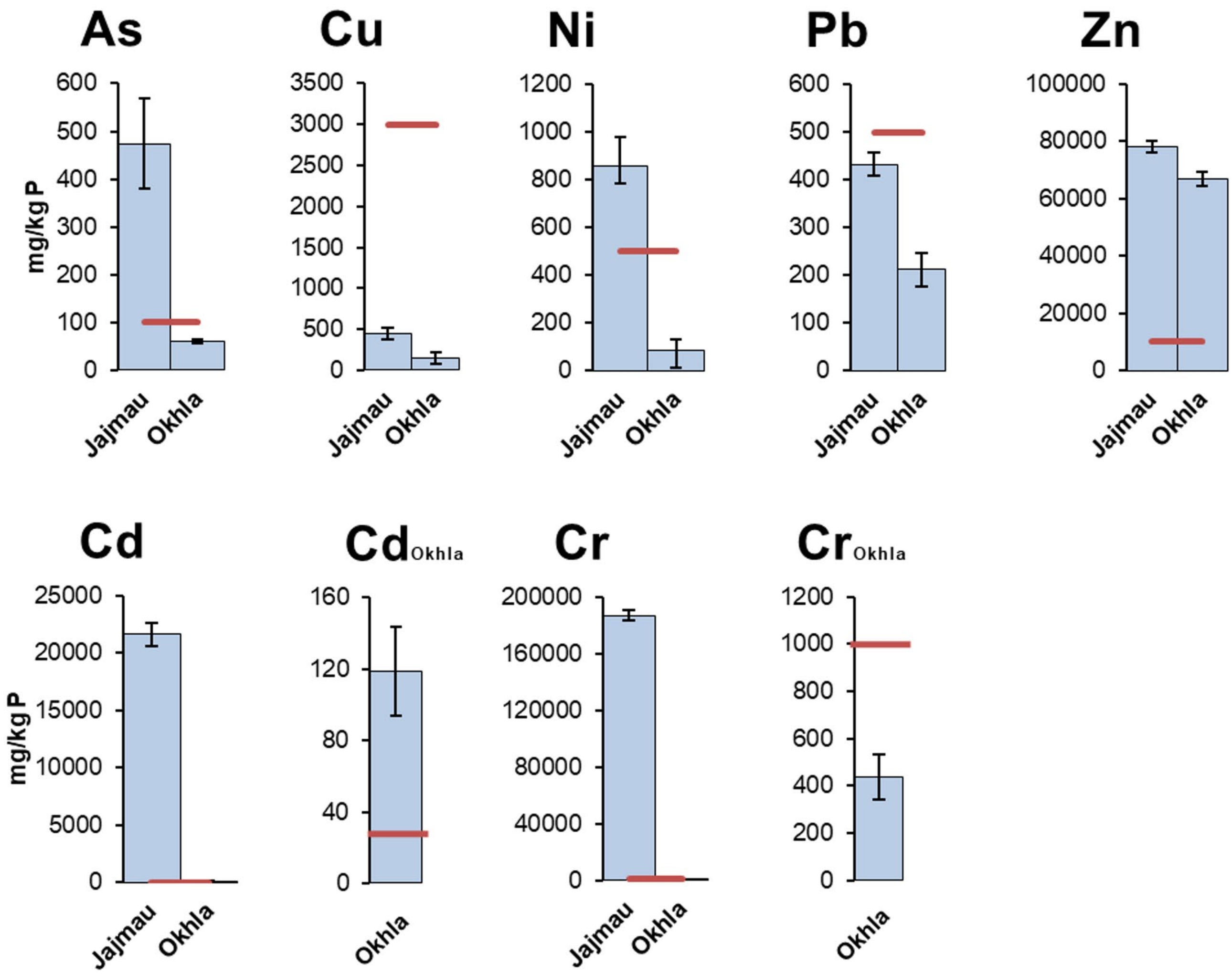

Fig. 6. Heavy metal concentrations in P precipitates from Jajmau pilot STP and Okhla STP, estimated via partial mass balance from triplicate leaching–precipitation experiments (mean ± standard deviation, *n* = 3). Concentrations are expressed as mg/kg$_P$ to allow comparison with fertilizer quality limits. Red horizontal lines indicate the maximum permissible concentrations according to the Swiss Ordinance on Mineral Recycling Fertilizers[17].

Chemical	Chemicals' Costs [\$/kg][32]		Consumption per P [kg/kg$_P$][a]		Cost per P recovered [\$/kg$_P$]	
	Range	Average	Jajmau STP	Okhla STP	Jajmau STP	Okhla STP
Sulfuric acid	0.1–0.6	0.4	46.3	17.4	17.2	6.5
Citric acid	0.7–1.0	0.8	42.5	18.3	35.7	15.4
Magnesium oxide	0.1–0.6	0.4	1.9	2.1	0.7	0.8
Sodium Hydroxide	0.6–1.0	0.8	58.3	19.2	45.5	15.0
Total costs					**99.1**	**37.7**

Table 5. Chemicals' costs and consumption for acidification and P precipitation for sewage sludge from the Jajmau and Okhla STPs. [a] Consumption calculated for acidification until pH 3 and precipitation at pH 8. The average price of the chemicals was used for the calculations.

of 2024, the subsidy for P is approximately 67₹ per kg P (~0.80\$/kg$_P$). Consequently, the subsidized retail price of superphosphate is around 0.76\$/kg$_P$[47], more than 50% lower than the unsubsidized market price. In contrast, organic and P-enriched fertilizers, are eligible for subsidies of up to 1,500₹ per t (~17\$ per t), irrespective of their nutrient content[10,11]. However, mineral recycling fertilizers, such as struvite, do not currently receive subsidy support and also lack quality standards. This regulatory gap severely limits high-purity recycled P products' competitiveness and adoption potential.

Economic assessments indicate that the cost of recycling fertilizers from the Jajmau and Okhla STPs would currently exceed the market price of conventional fertilizers by factors of 63 and 22, respectively. This is mainly due to the high costs associated with sludge acidification and P precipitation, coupled with relatively low P concentrations in the source sludge, which limit yield and purity. Even with European assumptions of 9–17 $\$/kg_P$, the prices of the recycling fertilizers still exceed the market price by factors of 6 to 11. Under current conditions and assumed chemical costs, P recovery seems not economically viable without policy, regulatory and financial support.

To overcome these challenges and unlock the potential of P recycling, several measures have been proposed. These include subsidizing P recovery technologies, offering financial incentives to farmers using recycling mineral fertilizers, and introducing regulatory mandates for P recovery from wastewater[48]. The recently launched National Policy on Fertilizer Management 2023[10] provides an important policy framework. However, further implementation and standardization are required to improve economic feasibility, ensure product quality, and promote market acceptance of recycling P fertilizers in India.

Conclusion

This study shows that sewage sludges from Okhla and Jajmau STPs, with relatively high P concentrations (12–15 g/kg_{DM}) and low acid consumption, are technically suitable for P recovery via struvite precipitation at pH 3. However, elevated levels of heavy metals, particularly Cd and Cr, pose regulatory and environmental challenges that may limit the acceptability of the recovered products. Compared to European sludges, lower P concentrations in Indian sludges lead to higher recovery costs and lower economic efficiency.

Despite the technical feasibility, the absence of nutrient-based subsidies and quality standards for mineral recycling fertilizers and subsidized conventional fertilizers in India hinder the market viability of products like struvite. Given India's high dependency on imported P, establishing policy and financial support for domestic recovery could improve cost-effectiveness and support the goals outlined in the Draft National Policy on Fertilizer Management 2023.

Limitations of this study include the use of a single sludge sample per STP, pre-dried before acidification, and incomplete data on digestion parameters. Drying was necessary to allow safe transport and storage but may have altered the sludge characteristics, for example by changing how P is bound or the availability of certain ions, which could influence leaching and precipitation behaviour. Future research should incorporate seasonal sampling, direct acidification of raw sludge, and detailed operational data to assess variability and process performance better. This includes coordinated influent–effluent–sludge sampling to enable complete P mass balances and more robust normalization of acid demand and recovery performance.

Product quality should also be evaluated under varying process conditions, including struvite purity and heavy metal content. Options like ultrafiltration may help reduce contaminants, though they may also generate more concentrated hazardous waste streams.

Improving the P-to-heavy metal ratio through optimized sewage management, increased separation or pre-treatment of industrial effluents, and enhanced treatment strategies could improve both recovery potential and marketability. Despite current limitations, advancing sustainable P recovery technologies remains essential for promoting resource efficiency and supporting India's transition to a circular economy.

Data availability

Data is provided within the manuscript or supplementary information files.

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Declarations

Competing interests

The authors declare no competing interests.

Additional information

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