Research Article

Phosphorus Recovery Potential from Decentralised Wastewater Treatment Systems in India: A Constrained Mass-Balance Study of Auroville

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Decentralised Wastewater Treatment Systems (DEWATS) are widely implemented across India to address sanitation gaps in peri-urban and semi-urban regions. However, these systems are primarily designed for pollution control rather than resource recovery, resulting in the dissipation of valuable phosphorus into sludge and receiving environments. This study evaluates the phosphorus recovery potential of an operational DEWATS serving the Auroville Residential Zone, Tamil Nadu, using a constrained mass-balance approach suited to data-limited, low-energy sanitation systems. Influent and effluent monitoring data were combined with literature-derived partitioning coefficients to reconstruct internal phosphorus pathways and quantify recoverable fractions without intrusive internal sampling. Three magnesium-based recovery scenarios were assessed: pre-primary dosing, pre-secondary (vortex) dosing, and sludge-line processing. Results indicate that pre-primary dosing offers the highest theoretical phosphorus recovery but introduces substantial operational complexity. Pre-secondary dosing provides the most balanced outcome, achieving improved effluent phosphorus reduction and operational stability with modest recovery yields and minimal infrastructure modification. Sludge-line recovery generates a higher-purity product but requires significantly greater capital investment. The findings also highlight a distinct tropical advantage, where elevated temperatures enhance phosphorus bioavailability and recovery efficiency compared with temperate systems. Despite technical feasibility, current fertiliser subsidy structures limit economic competitiveness. The study concludes that nutrient recovery in Indian DEWATS should prioritise effluent quality improvement and system resilience over maximum recovery yields, and that targeted policy support is required to enable decentralised circular phosphorus management.

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1. Introduction: From Liability to Asset

The global wastewater sector is currently undergoing a paradigm shift, moving beyond treatment processes designed solely for pollutant removal towards resource recovery, in which wastewater is reframed not as a public health liability but as a reservoir of valuable materials. While nutrient recovery technologies such as struvite crystallisation are operationally mature in centralised, high-income wastewater utilities, a critical disconnect persists in the Global South. In these contexts, rapid urbanisation is predominantly serviced by decentralised wastewater treatment systems (DEWATS), which are engineered for passive pathogen control, robustness, and low energy demand rather than nutrient circularity.

Within this transition, phosphorus (P) is emblematic. As a non-substitutable macronutrient essential for global food production, phosphorus is derived primarily from finite phosphate rock reserves subject to geopolitical concentration and price volatility. At the same time, the discharge of residual phosphorus into receiving waters contributes to eutrophication and harmful algal blooms. Closing the phosphorus loop, therefore, represents not only a technological opportunity but a geo-economic necessity. This challenge is particularly acute in India, which remains heavily dependent on imported phosphate fertilisers while simultaneously discharging substantial quantities of nutrient-rich wastewater into environmentally sensitive catchments.

India's sanitation strategy relies extensively on DEWATS modular treatment trains typically comprising settlers, anaerobic baffled reactors (ABRs), and planted gravel filters. These systems prioritise gravity-driven hydraulics, operational simplicity, and resilience under variable loading conditions. While DEWATS have demonstrated reliable performance in reducing organic loading and suspended solids, they operate within a fundamentally linear *treat-and-dispose* paradigm. Nitrogen is often lost to the atmosphere through denitrification, while phosphorus is predominantly partitioned into diffuse sludge deposits that are periodically removed and discarded rather than recovered. As a result, decentralised sanitation infrastructure continues to function primarily as a pollution control mechanism, rather than as a platform for resource recovery.

This design philosophy gives rise to a persistent empirical gap. Routine monitoring of DEWATS is generally limited to influent and effluent points, with minimal process control and little or no sampling of intermediate treatment units. Consequently, while operators can quantify what enters and exits the system, there is limited understanding of where potentially recoverable nutrients accumulate within the treatment train, whether in primary settler sludge, anaerobic biofilms, or liquid supernatant phases. Without this internal mass-balance information, DEWATS cannot be meaningfully evaluated as productive assets, reinforcing a disposal-oriented sanitation model that conflicts with India's emerging circular economy ambitions.

Addressing this empirical gap requires analytical approaches that are compatible with data-limited, low-infrastructure sanitation systems. Recognising that comprehensive internal sampling is often logistically and operationally infeasible in decentralised contexts, this study adopts a constrained mass-balance approach. The methodology integrates accessible influent and effluent monitoring data with literature-derived partitioning coefficients to infer the internal distribution of phosphorus across liquid and solid phases. By constraining the system with known inputs and outputs, it becomes possible to reconstruct internal phosphorus pathways without intrusive sampling or sophisticated instrumentation. This approach is particularly well-suited to such systems in low-resource settings, where monitoring capacity and operational flexibility are inherently constrained.

The analysis focuses on an operational DEWATS serving the Auroville Residential Zone in Tamil Nadu, India, and evaluates its potential to function as a decentralised nutrient recovery node. Although such systems were not originally designed for resource recovery, it is examined whether targeted retrofitting can enable phosphorus capture without undermining the low-energy, low-maintenance ethos of DEWATS. Three magnesium-based recovery strategies are examined, representing increasing levels of intervention complexity. These include magnesium dosing at the system inlet to promote phosphorus precipitation within primary sludge; targeted dosing prior to the vortex aeration stage to enhance effluent quality and operational stability; and sludge-line processing of high-concentration liquors generated during desludging to produce a higher-purity recovered product.

Against this background, the study evaluates whether passive DEWATS in semi-urban India can be transformed into operationally viable phosphorus recovery systems using data-constrained analytical methods. Using a constrained mass-balance framework applied to the Auroville case study, internal phosphorus pathways are reconstructed from influent and effluent monitoring data and literature-informed assumptions. The relative performance of the three recovery strategies is assessed in terms of phosphorus recovery potential, effluent quality improvement, operational practicality, and economic context relevant to Indian sanitation systems. By moving beyond the binary question of whether phosphorus recovery is possible, the study seeks to determine how recovery strategies can be operationalised within decentralised wastewater infrastructure in a manner consistent with India's environmental, economic, and institutional constraints.

2. Methodology

2.1. Overview and Research Design

This chapter outlines the methodological framework employed to quantify the nitrogen (N) and phosphorus (P) recovery potential within decentralised wastewater treatment systems (DEWATS) in Auroville, Tamil Nadu. A key challenge in assessing decentralised sanitation infrastructure in the Global South is the persistent *empirical void*, characterised by the absence of high-resolution internal monitoring data due to financial, institutional, and logistical constraints[1]. In contrast to centralised wastewater utilities equipped with supervisory control and data acquisition (SCADA) systems and continuous inline instrumentation, DEWATS typically operate with limited process control and rely primarily on periodic inlet and outlet monitoring[2]. To address this limitation without introducing prohibitively complex or costly instrumentation, this research adopts a constrained mass-balance approach, in which the treatment train is conceptualised as a series of interconnected control volumes. Internal nutrient transformations and accumulations are inferred by triangulating available primary monitoring data, specifically influent and effluent concentrations, with literature-derived nitrogen and phosphorus partitioning coefficients[3]. The research design proceeds through a sequential methodology encompassing spatial delineation of the hydraulic catchment using GIS, site-specific wastewater sampling and accredited laboratory analysis adapted for tropical operating conditions, computational reconstruction of baseline nutrient flows and sludge-phase accumulation, formulation of three magnesium-based retrofitting scenarios (Scenarios A, B, and C), and a techno-economic assessment incorporating local cost structures and sensitivity analysis. Collectively, this methodology ensures that the estimated nutrient recovery potentials are not purely theoretical constructs but are firmly grounded in the hydraulic, operational, and institutional realities of the Auroville DEWATS network[4].

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2.2. Study Area and Spatial Context

2.2.1. Site Selection and System Configuration

The investigation focuses on the Residential Zone Sectors 1 and 2 (Phase 1) DEWATS in Auroville township, Villupuram district, Tamil Nadu. This specific facility was selected based on its representativeness of the 'Auroville Model' of sanitation: a gravity-driven, modular system integrating anaerobic digestion and ecological polishing[1]. The system serves a mixed residential and institutional catchment and possesses a documented history of stable operation, which is a prerequisite for a valid baseline assessment[5].

The treatment train comprises a primary settler for solids separation, a balancing tank for flow equalisation, an Anaerobic Baffled Reactor (ABR) serving as the biological core, an Anaerobic Filter (AF) for fixed-film polishing, and dual vortex sumps for aeration prior to final storage. This configuration covers the full spectrum of hydraulic environments from quiescent settling to turbulent aeration necessary to evaluate different nutrient recovery interventions[6].

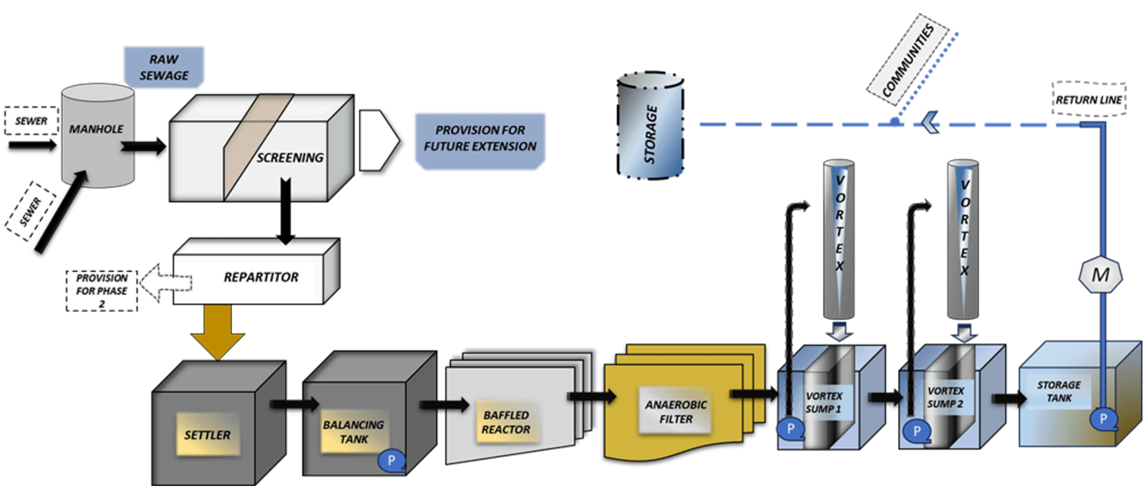

Figure 1. *Process flow diagram of the Auroville Residential Zone DEWATS, showing the treatment train from raw sewage through primary settling, anaerobic treatment, and vortex polishing units. (Author's Own)*

2.2.2. GIS Catchment Analysis

To rigorously define the system's hydraulic boundary, a Geographic Information System (GIS) analysis was conducted using ArcGIS Pro (WGS 84 / UTM Zone 44N). A 30-metre Shuttle Radar Topography

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Mission (SRTM) digital elevation model was conditioned via sink filling to ensure hydrological continuity. Standard D8 algorithms were applied to generate flow direction and accumulation rasters, allowing for the precise delineation of the micro-catchment contributing to the DEWATS[7][8].

This spatial analysis confirmed the hydraulic convergence of wastewater from eleven distinct community clusters, validating the assumption that the influent can be treated as a homogenised domestic stream without significant industrial or commercial inputs[9]. Furthermore, land-use proximity analysis (using 100 m, 250 m, and 500 m buffers) was used to contextualise the potential for local reuse of recovered water and fertiliser products.

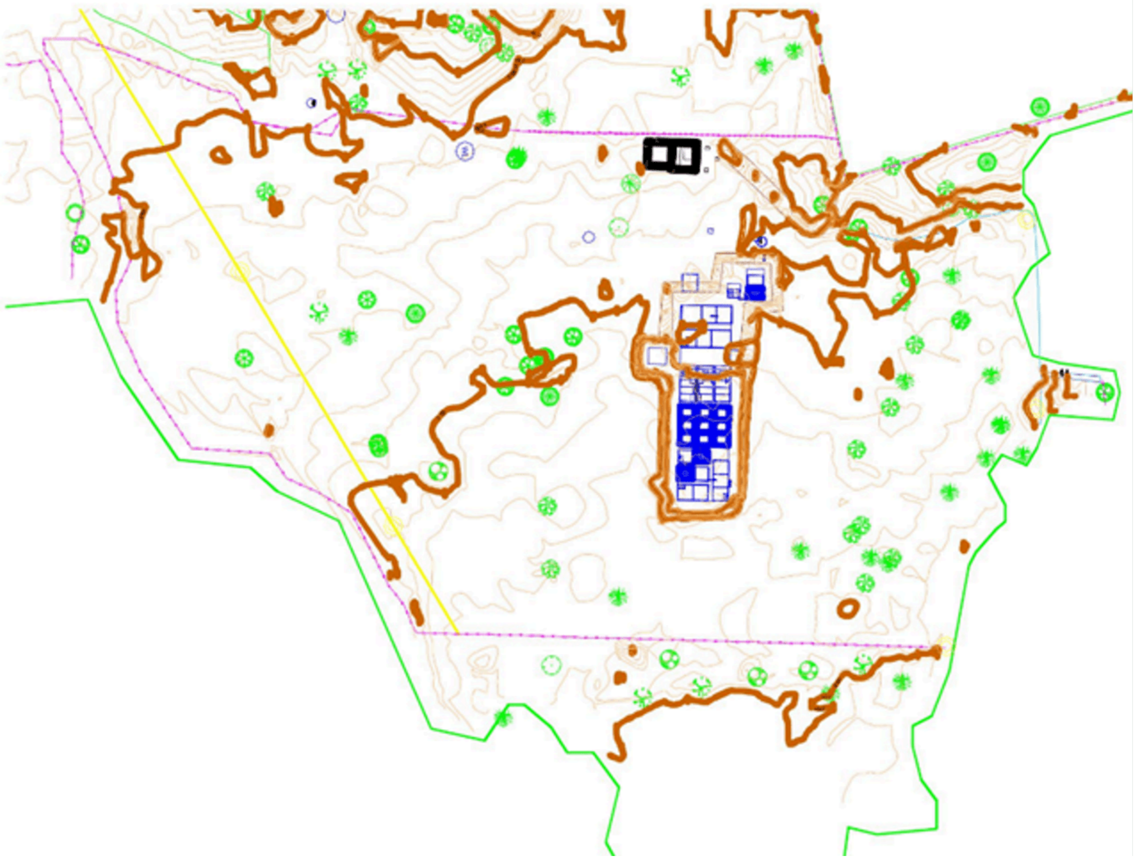

Figure 2. *GIS-derived catchment boundary and topographic context of the Auroville Residential Zone DEWATS, showing natural drainage pathways, built infrastructure, and hydraulic convergence toward the decentralised treatment system.*

2.3. Data Collection and Analytical Protocols

2.3.1. Sampling Strategy and Temporal Scope

The data collection strategy employed a hybrid approach, synthesising secondary institutional records with primary field measurements. Secondary data, including flow rates (Q) and routine maintenance logs, were extracted from Auroville Water Service (AWS) archives and Centre for Scientific Research (CSR) O&M manuals to establish the operational baseline[5][10].

Primary sampling was conducted during the dry season (April, November, July) to exclude stormwater dilution effects and isolate the sanitary wastewater fraction. Samples were collected at four critical control points: (i) the balancing tank inlet (post-screening), (ii) the ABR outlet, (iii) the vortex sump, and (iv) the final reuse reservoir[11][12]. Due to the lack of automated sampling infrastructure and safety constraints regarding confined space entry, grab sampling was utilised. To mitigate the limitations of grab sampling, collections were timed to coincide with peak morning flow periods identified by system operators, and samples were taken in duplicate to ensure analytical reproducibility[13].

2.3.2. Laboratory Analysis and Tropical Modifications

All physicochemical analyses were performed in accordance with Standard Methods for the Examination of Water and Wastewater[13]. Key parameters included pH, electrical conductivity (EC), Total Suspended Solids (TSS), Chemical Oxygen Demand (COD), Total Kjeldahl Nitrogen (TKN), and Total Phosphorus (TP).

A critical methodological modification was applied to the Biochemical Oxygen Demand (BOD) assay. Standard protocols typically prescribe incubation at 20°C. However, to reflect accurately the biological kinetics of the tropical Indian environment, BOD measurements were conducted at 27°C $(BOD_3, 27^\circ C)$. This modification aligns with Bureau of Indian Standards (BIS) recommendations and ensures that the biodegradation rates used in the model reflect the actual 'tropical advantage' regarding hydrolysis and nutrient release rates observed in the field[14].

2.4. Computational Mass-Balance Framework

2.4.1. Governing Equations

The core analytical tool is a steady-state mass-balance model. The DEWATS is conceptualised as a series of linked control volumes $(Settler \rightarrow ABR \rightarrow AF \rightarrow Vortex)$. For any conservative substance or nutrient species (i), the mass balance across the system boundary is defined by the governing equation:

$$Load_{in,i} = Load_{out,i} + \sum Accumulation_i + \sum Losses_i$$

Where the nutrient load (L) is calculated as the product of the volumetric flow rate (Q) and the concentration (C) of the nutrient species:

$$L_i(\frac{kg}{d}) = \frac{Q(\frac{m^3}{d}) \times C_i(\frac{mg}{L})}{1000}$$

This framework allows for the quantification of nutrient mass fluxes in kilograms per day $(\frac{kg}{d})$, which is essential for assessing resource recovery potential, rather than relying solely on concentration reductions $(\frac{mg}{L})$, which can be misleading owing to dilution or evaporation effects[15].

2.4.2. The Constrained Partitioning Approach

A major challenge in DEWATS analysis is the inability to sample deep anaerobic zones or sludge layers without disrupting operations. To address this, the model utilises a Constrained Partitioning Approach. Internal nutrient flows were not measured directly but were inferred by constraining the model with the empirically measured inlet and outlet loads.

Literature-derived partitioning coefficients were applied to distribute the removed load between 'sludge accumulation' (settleable solids), 'biofilm uptake', and 'gaseous losses' (specifically for nitrogen via denitrification). For example, phosphorus removal to sludge in the ABR was constrained to the $20 - 40\%$ range based on established performance data for tropical anaerobic reactors[3]. These coefficients were iteratively adjusted within their literature-defined bounds until the cumulative calculated removal matched the empirically observed effluent concentrations recorded by the certified laboratory[12]. This method turns the 'black box' of the DEWATS into a 'grey box', revealing the hidden sinks of phosphorus in the primary and secondary sludges without requiring invasive core sampling.

2.5. Definition of Nutrient Recovery Scenarios

To operationalise the move from 'treatment' to 'recovery', three distinct retrofitting scenarios were modelled. These scenarios are based on the principle of magnesium-induced crystallisation, where magnesium is added to the wastewater to precipitate soluble orthophosphate (PO_4^{3-}) and ammonium

(NH_4^+) as struvite (magnesium ammonium phosphate hexahydrate). The stoichiometric reaction governing this process is:

$$Mg^{2+} + NH_4^+ + PO_4^{3-} + 6H_2O \rightarrow MgNH_4PO_4 \bullet 6H_2O$$

Scenario A: Pre-Primary Dosing (Sludge Enrichment) This scenario models the injection of magnesium salts immediately upstream of the primary settler. The rationale is to exploit the high influent phosphorus concentrations $(\frac{88mg}{L})$ to maximise precipitation kinetics. The model assumes a precipitation efficiency of 75% and a $Mg : PO_4$ molar ratio of 1.3:1[16][17]. The objective here is *mass maximisation*: capturing the highest possible quantity of phosphorus within the primary sludge, which is then harvested during routine desludging.

Scenario B: Pre-Secondary / Vortex Dosing (Effluent Polishing) This scenario targets the liquid stream at the inlet of the vortex aeration units. At this stage, anaerobic digestion in the ABR has hydrolysed organic phosphorus into soluble orthophosphate, increasing bioavailability. The vortex unit provides high-energy mixing and aeration, which naturally raises pH by stripping carbon dioxide (CO_2), creating ideal conditions for struvite nucleation. The model assumes an 80% precipitation efficiency owing to these favourable hydraulic conditions[18][19]. The primary objective of Scenario B is effluent quality improvement and operational simplicity, rather than yield maximisation.

Scenario C: Sludge-Line Processing (High-Purity Recovery) This scenario focuses on the 'hidden sink' identified by the mass balance: the sludge itself. It models a separate side-stream process where thickened sludge is digested to release bound phosphorus, followed by magnesium dosing. While the total recoverable mass is lower owing to the smaller volume of the side-stream, the model assumes this produces a higher purity product free from wastewater pathogens. Owing to the high presence of competing ions in sludge liquor, a conservative precipitation efficiency of 65% was applied[20].

2.6. Techno-Economic and Sensitivity Assessment

2.6.1. Cost Estimation Framework

The feasibility of the proposed scenarios was evaluated using a comparative techno-economic analysis. Capital Expenditure $(CapEx)$ was estimated based on Indian market quotations for essential components (polyethylene tanks, peristaltic dosing pumps, pH probes) and civil works rates relevant to ferrocement construction[10]. Operational Expenditure $(OpEx)$ was calculated based on stoichiometric chemical consumption rates and current local pricing $(125\, INR/kg\ for\ magnesium\ hydroxide)$, alongside estimates for additional labour and electricity[21].

The economic efficiency of each scenario was defined by the metric Cost per Unit Phosphorus Recovered (C_{rec}), calculated as:

$$C_{rec}(\frac{INR}{kgP}) = \frac{Annual\ OpEx + Annualised\ CapEX}{Annual\ Mass\ Of\ P\ Recovered(kg)}$$

This metric allows for direct comparison between the scenarios and against commercial fertiliser prices[22].

2.6.2. Uncertainty and Sensitivity Analysis Protocol

Recognising the limitations inherent in using snapshot sampling data and literature-derived coefficients, a One-at-a-Time (OAT) sensitivity analysis was performed. Key parameters, specifically influent phosphorus concentration, soluble phosphate fraction, and precipitation efficiency, were varied by $\pm 15\%$ from their baseline values[16]. The objective was not to produce precise error margins but to test the ranking stability of the scenarios. If Scenario B remains the most cost-effective option for effluent polishing even under adverse parameter variations, the strategic recommendation is considered robust.

2.7. Quality Assurance and Research Governance

Research ethics complied with the University of Surrey's Self-Assessment for Governance and Ethics (SAGE) protocol. As the study involved environmental sampling of existing infrastructure without human subjects, it was classified as low risk. Permission was formally granted by Auroville Water Service and the Centre for Scientific Research. Data management followed strict quality control procedures, including chain-of-custody logging and the use of unique site identifiers (SITE_ID) to integrate spatial and analytical datasets. Analytical precision was monitored using field duplicates, with a Relative Percent Difference (RPD) threshold of $< 15\%$ maintained to ensure data reliability[13].

3. Results

3.1. Spatial Characterisation and Hydraulic Boundary Conditions

The reliability of mass-balance modelling in decentralised infrastructure depends on rigorously defining the hydraulic boundary. The GIS catchment analysis confirmed that the Auroville Residential Zone

DEWATS receives a hydraulically convergent wastewater stream from eleven distinct community clusters, with no significant industrial or commercial inputs[9]. Topographic analysis using conditioned SRTM data established a clear pour point at the DEWATS inlet, validating the assumption that the influent represents a homogenised domestic stream characterised by high organic loading and nutrient concentrations typical of residential blackwater and greywater mixing[10].

Based on long-term volumetric monitoring, the system operates at a steady-state flow of approximately $60\,m^3/d$. This flow rate was adopted as the design baseline for all subsequent load calculations, smoothing out diurnal fluctuations to represent the long-term operational reality of the catchment[5].

3.2. Baseline Treatment Performance and Nutrient Partitioning

Accredited monitoring campaigns conducted in April and November 2024, and July 2025, established the baseline performance of the treatment train. The system demonstrates high efficacy in organic matter removal, with biochemical oxygen demand (BOD) and chemical oxygen demand (COD) reductions consistently ranging between 78% and 91% [11][12]. This confirms that the anaerobic baffled reactor (ABR) and planted filter units are biologically active and functioning according to design specifications for organic pollution control.

However, nutrient pathways reveal a fundamental disconnect between 'removal' and 'recovery'. Total Kjeldahl Nitrogen (TKN) concentrations decreased from a mean influent value of $145\ mg/L$ to an effluent concentration of $37\ mg/L$, representing a removal efficiency of roughly 74.5% [12]. While this reduces the immediate nitrogen load to receiving waters, the absence of a capture mechanism implies that the removed nitrogen is largely lost to the atmosphere via denitrification or sequestered in sludge.

The distinction is even more pronounced for phosphorus. Total Phosphorus (TP) concentrations were reduced from an influent mean of $88\ mg/L$ to a final effluent concentration of $7.3\ mg/L$, achieving an apparent removal efficiency of 91.7% [12]. Mass-balance reconstruction reveals that this removal is driven by phase transfer rather than elimination. Of the daily influent load of $5.28\,kg\,P/d$, only $0.44\,kg\,P/d$ leaves the system in the treated effluent. The remaining $4.84\,kg\,P/d$ (approx. 92%) is partitioned into the settler sludge, anaerobic biofilms, and filter media[3]. Under current operational protocols, this phosphorus-rich sludge is periodically extracted and disposed of without targeted recovery, effectively converting a finite resource into a waste management liability[5].

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3.3. Evaluation of Magnesium-Based Recovery Scenarios

To transform this passive sequestration into active recovery, three magnesium-dosing scenarios were modelled. These scenarios reconfigure the internal phosphorus pathways by inducing the precipitation of struvite ($MgNH_4PO_4 \bullet 6H_2O$) at specific control points.

3.3.1. Scenario A: Pre-Primary Dosing (Yield Maximisation)

Scenario A modelled the injection of magnesium salts immediately upstream of the primary settler. This configuration exploits the high influent phosphorus concentration ($88\ mg/L$) to maximise precipitation kinetics before organic hydrolysis occurs. Results indicate that this approach yields the highest theoretical recovery.

By assuming a precipitation efficiency of 75% consistent with high-strength influent conditions reported in the literature, Scenario A is projected to recover approximately $2.57\ k\ P/d$ [16][17]. This corresponds to an annual recovery of nearly $940\ kg$ of phosphorus, or approximately 7.46 tonnes of struvite product per year. In terms of effluent quality, the co-precipitation of phosphate reduces the final effluent TP concentration to $3.2\ mg/L$, a 56% improvement over the baseline[12]. However, the recovery mechanism embeds the struvite crystals within the primary sewage sludge. While this maximises the capture of phosphorus mass, it necessitates downstream processing to separate the mineral fertiliser from the organic faecal sludge, adding operational complexity to the sludge management chain.

3.3.2. Scenario B: Pre-Secondary Vortex Dosing (Effluent Polishing)

Scenario B targeted the liquid stream at the inlet of the vortex aeration units, located downstream of the anaerobic reactors. At this stage, biological digestion has mineralised a significant fraction of organic phosphorus into soluble orthophosphate (PO_4^{3-}). The modelling assumed that elevated ambient temperatures ($27^\circ C$) in the ABR enhance this hydrolysis, creating a 'tropical advantage' regarding bioavailability[20].

Under this scenario, the turbulent, aerated conditions of the vortex unit facilitate struvite nucleation. The model indicates a daily recovery of $0.52\ kg\ P/d$ ($189\ kg\ P/year$), significantly lower than Scenario A. However, the strategic advantage of Scenario B lies in effluent quality and product purity. Because the precipitation occurs in the liquid phase after solids separation, the resulting struvite accumulates in the vortex sump as a relatively clean, granular product[19]. Furthermore, this scenario achieves the highest level of effluent polishing, reducing final TP concentrations to $2.7\,mg/L$ [18]. This represents a 63% reduction relative to the baseline, rendering the treated water highly suitable for unrestricted irrigation or non-potable reuse within the Auroville township.

3.3.3. Scenario C: Sludge-Line Processing (Niche Recovery)

Scenario C addressed the 'hidden sink' of phosphorus identified in the baseline mass balance by modelling a side-stream process for thickened sludge liquor. Despite targeting the most concentrated nutrient pool, the recoverable volume proved operationally marginal.

The analysis indicates a recovery potential of only $0.013\,kg\,P/d$ or roughly $4.7\,kg$ of phosphorus per year[20]. This low yield is attributed to the relatively small volume of sludge liquor generated daily compared to the main hydraulic flow. While this scenario produces the highest-purity struvite product, free from the pathogens present in the main line, it has a negligible impact on the facility's overall effluent quality, leaving discharge concentrations unchanged at $7.3\,mg/L$. Consequently, this approach appears ill-suited for the specific hydraulic scale of the Auroville Residential Zone DEWATS, though it may hold validity for larger, centralised sludge-handling facilities.

3.4. Comparative Analysis of Recovery Performance

Comparing the three interventions reveals a distinct trade-off between mass recovery and system integration.

Yield: Scenario A recovers approximately five times more phosphorus than Scenario B and two orders of magnitude more than Scenario C. If the primary objective is to maximise the quantity of fertiliser produced, pre-primary dosing is the superior technical option[16].

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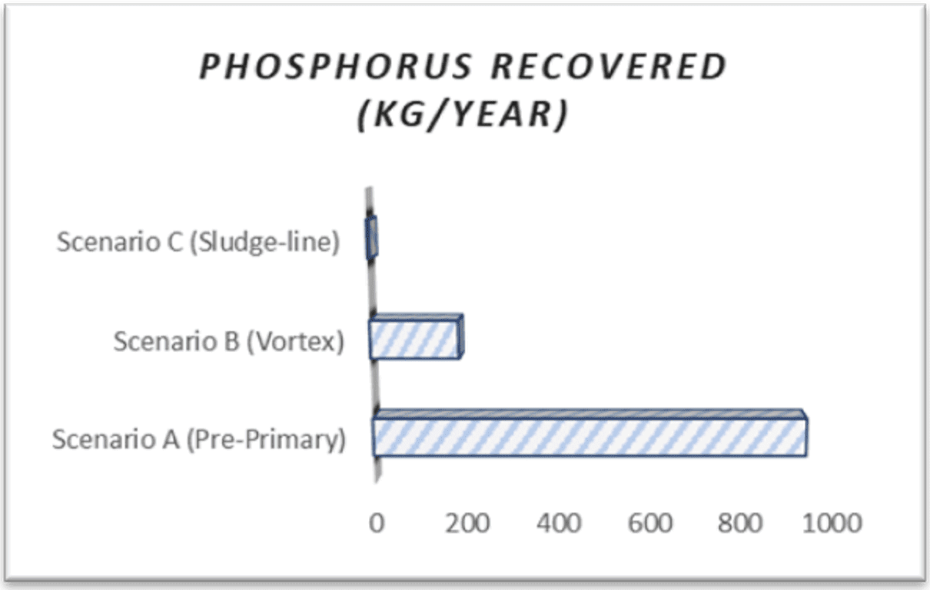

Figure 3. *Compares the annual phosphorus recovery potential of the three magnesium dosing scenarios evaluated in this study. Scenario A achieves the highest absolute recovery, while Scenarios B and C exhibit substantially lower yields. (Author's own)*

Quality: Scenario B outperforms all other options in terms of environmental compliance. By reducing effluent TP to 2.7 mg/L and TKN to 33 mg/L, it transforms the DEWATS from a disposal unit into a source of high-quality reclaimed water[18].

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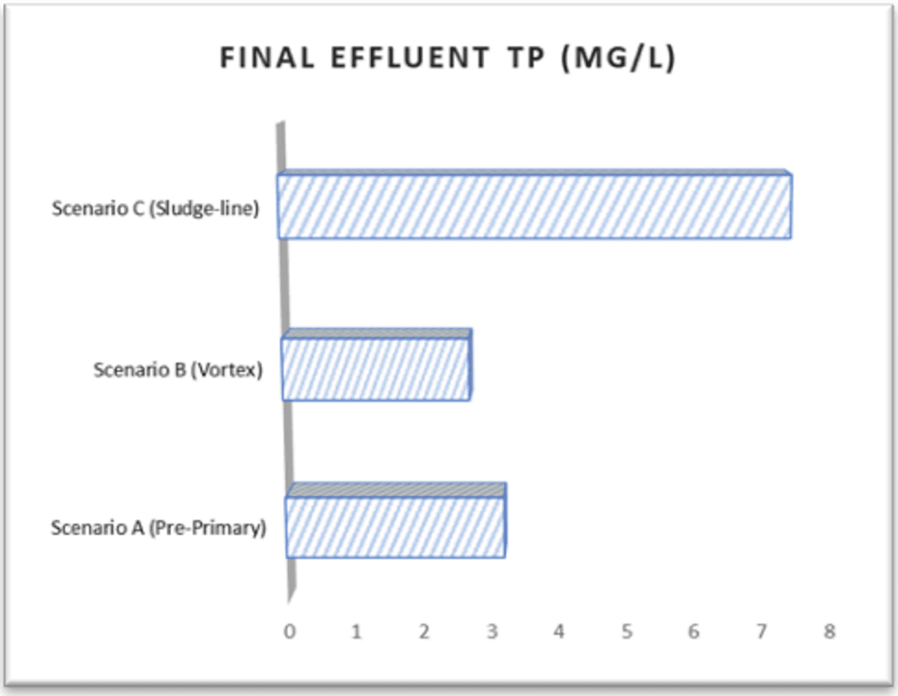

Figure 4.*Modelled final effluent total phosphorus concentrations under the three nutrient recovery scenarios. Scenario B (Vortex dosing) achieves the lowest effluent TP concentration, while Scenario C (sludge-line recovery) exhibits performance comparable to baseline conditions. (Author's own)*

Operation: Scenario B also offers the most seamless operational integration. Unlike Scenario A, which requires managing precipitate-laden primary sludge, or Scenario C, which demands a separate side-stream reactor, Scenario B utilises the existing vortex infrastructure for crystal settling, requiring only the addition of a dosing pump and a simplified collection schedule[17].

3.5. Techno-Economic Feasibility Assessment

The feasibility of these engineering scenarios was stress-tested against the economic realities of the Indian context. Capital Expenditure ($CapEx$) and Operational Expenditure ($OpEx$) were estimated using local supplier quotations and normalised to the metric of Cost per kg of Phosphorus Recovered[10][21].

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3.5.1. Capital Investment

Scenarios A and B represent low-cost retrofits, requiring incremental investments of approximately $INR\,73,000$ ($\sim USD\,880$) and $INR\,72,000$ ($\sim USD\,870$), respectively. These costs cover polyethylene storage tanks, peristaltic pumps, and pH probes, fitting well within the typical maintenance budgets of decentralised community assets. In stark contrast, Scenario C requires a $CapEx$ of approximately $INR\,324,000$ ($\sim USD\,3,900$) due to the need for dedicated sludge thickening and digestion tanks. This 4.5-fold increase in capital cost renders Scenario C financially disproportionate to its limited recovery yield.

3.5.2. Operational Costs and the Viability Gap

The operational cost analysis exposes a critical economic barrier. The chemical cost for magnesium hydroxide $(Mg(OH)_2)$ is stoichiometrically fixed at approximately $INR\,305\,per\ kg$ of P recovered across all scenarios[21]. When labour and maintenance are included, the total production cost rises to between $INR\,348$ and $INR\,438\,per\ kg\ P$ for Scenarios A and B.

This production cost is significantly higher than the market price of commercial phosphate fertilisers in India, which are heavily subsidised. Consequently, there is a clear 'viability gap': the market value of the recovered struvite alone does not cover the input costs of magnesium and labour. However, Scenario B offers a secondary economic value proposition by reducing the operational costs associated with downstream polishing and potential fines for nutrient discharge[10]. If the economic analysis is expanded to include the 'shadow price' of improved water reuse potential, Scenario B approaches financial viability, whereas Scenario A remains dependent on the creation of a premium organic fertiliser market to offset its higher sludge-handling costs.

3.6. Sensitivity and Robustness Analysis

To ensure these findings are not artefacts of specific assumptions, a One-at-a-Time (OAT) sensitivity analysis was conducted. Key parameters, including influent phosphorus concentration $(79 - 97\ mg/L)$, soluble phosphate fraction $(50 - 70\%)$, and precipitation efficiency $(65 - 85\%)$ were varied by $\pm 15\%$ from baseline values[16]. The analysis confirmed the stability of the scenario rankings.

Yield Stability: Even under the most conservative assumptions (lowest influent concentration and precipitation efficiency), Scenario A consistently recovered significantly more phosphorus mass

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$(> 2.2\ kg\ P/d)$ than Scenario B $(< 0.6\ kg\ P/d)$.

Performance Stability: Scenario B consistently achieved the lowest effluent TP concentrations across all parameter variations, maintaining its status as the optimal choice for water quality improvement.

This robustness validates the conclusion that while exact recovery figures may fluctuate with seasonal loads, the strategic hierarchy remains unchanged: Scenario A is the choice for mass maximisation, while Scenario B is the optimal choice for system integration and effluent polishing[20].

3.7. Summary of Results

Scenario	Estimated P Recovery	Effluent TP (mg L^{-1})	Primary Advantage	Primary Limitation
A- Pre-Primary Dosing	2.574 kg P d^{-1}	≈ 3.2	Highest total P recovery; produces enriched primary sludge	Requires pH control and modifications at the settler inlet
B- Pre-Secondary / Vortex	0.518 kg P d^{-1}	≈ 2.7	Vigorous effluent polishing; technically simple retrofit	Lower absolute recovery than Scenario A
C- Sludge-Line Dosing	≈ 4.71 kg P $year^{-1}$	≈ 7.3 (minimal change)	Targets accumulated sludge-bound P; generates high-value struvite product	Highest CAPEX; negligible impact on effluent TP

Source: Calculations based on EMS Laboratory[12], Auroville Centre for Scientific Research[5], and literature-derived precipitation efficiencies[16][18][20][19][17].

The empirical and modelling data demonstrate that the Auroville DEWATS acts as a highly effective phosphorus sink, retaining over 90% of the influent phosphorus load, primarily in sludge. The proposed retrofitting interventions function by unlocking this sink. While Pre-Primary Dosing (Scenario A) offers the highest theoretical yield, it introduces complexity that challenges the low-maintenance ethos of DEWATS. Conversely, Pre-Secondary Dosing (Scenario B) leverages the system's hydraulic design and the region's tropical temperatures to deliver a balanced outcome: recovering a modest but clean fertiliser

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product while significantly upgrading the quality of the treated water for local reuse. The economic analysis indicates that while direct profitability is constrained by subsidy distortions, the low capital cost of retrofitting makes Scenario B a feasible intervention for enhancing the resilience and circularity of India's decentralised sanitation infrastructure.

4. Discussion

The Paradox of Performance: Efficiency without Circularity. The empirical analysis of the Auroville Residential Zone DEWATS reveals a fundamental paradox in Indian decentralised sanitation: the system is simultaneously highly effective and structurally inefficient. Baseline monitoring confirms that the facility achieves an apparent phosphorus removal efficiency exceeding 90 per cent, reducing influent loads to a residual effluent concentration of approximately 7.3 mg/L[12]. By the standards of conventional pollution control, the system is performing according to its design specification, successfully protecting receiving waters from acute nutrient loading.

However, the mass-balance reconstruction exposes the limitations of evaluating DEWATS solely through the lens of liquid-phase compliance. The observed removal is achieved almost entirely through the translocation of phosphorus into settler sludges, anaerobic biofilms and filter media, rather than through elimination or recovery. The system functions as a highly efficient 'resource sink', converting dissolved nutrients into deferred sludge-management liabilities[5]. This confirms the critical gap identified in the literature: while European decentralised systems are increasingly engineered for nutrient circularity, their Indian counterparts remain locked into a linear 'treat-and-dispose' paradigm[1][23].

This distinction between removal (sequestration) and recovery (valorisation) is not merely semantic but defines the operational reality of the facility. Under current protocols, the 4.8 kg of phosphorus removed daily accumulates in the sludge bed, only to be extracted during annual maintenance and typically disposed of without agricultural reuse[4]. Consequently, the high removal efficiency cited in operational reports conceals a systemic failure in resource use. The DEWATS acts as a barrier to pollution but also as a barrier to recirculation, effectively destroying the economic value of the nutrients it captures.

The Tropical Advantage: Climate as a Process Intensifier A critical theoretical insight emerging from this study is the identification of a distinct 'tropical advantage' in decentralised nutrient recovery. Much of the existing literature on struvite crystallisation is derived from temperate contexts, where low ambient temperatures often necessitate energy-intensive heating or biological enhancements to release phosphorus from organic matter[24]. In contrast, the Auroville system operates at ambient wastewater temperatures averaging 27°C[12].

The modelling results for Scenario B (Pre-Secondary Dosing) demonstrate that this elevated temperature regime actively accelerates anaerobic hydrolysis within the baffled reactor. This biological activity converts particulate and organically bound phosphorus into soluble orthophosphate at rates significantly higher than those predicted for temperate systems[20]. Effectively, the climate functions as a passive process intensifier, pre-conditioning the wastewater for downstream physicochemical recovery.

This has profound implications for technology transfer. It suggests that complex, capital-heavy hydrolysis units required in Northern Europe may be redundant in Southern India. Instead, the ambient heat drives the necessary chemical transformations naturally. This validates the hypothesis that passive, low-tech recovery strategies such as the simple magnesium dosing modelled here can succeed in tropical DEWATS where they might fail in colder climates[25]. The tropical context substitutes for infrastructure complexity, lowering the barrier to entry for circular sanitation.

Strategic Trade-offs: Maximisation versus Resilience The comparative evaluation of the three recovery scenarios challenges the assumption that the goal of resource recovery is simply to maximise yield. Instead, the data reveal a complex hierarchy of trade-offs between mass recovery, effluent quality and operational resilience.

Scenario A (Pre-Primary Dosing) represents the logic of maximisation. By intercepting the influent stream, it achieves the highest theoretical yield, approximately 2.6 kg P/day (Appendix A). However, this yield comes at the cost of significant operational disruption. Inducing precipitation within the primary settler embeds the recovered struvite within the faecal sludge matrix. Recovering this product requires the extraction and processing of the entire sludge volume, entangling the resource (fertiliser) with the waste (pathogenic solids). While technically efficient in terms of mass capture, Scenario A contradicts the low-maintenance ethos of DEWATS by demanding complex downstream separation infrastructure[16].

In contrast, Scenario B (Pre-Secondary Vortex Dosing) represents the logic of *optimisation*. Although its yield is significantly lower (approx. 0.52 kg P/day), it outperforms all other options in terms of system integration. By exploiting the high-energy mixing of the existing vortex units and the soluble orthophosphate released by the ‘tropical advantage’, Scenario B precipitates struvite in a relatively clean liquid stream[18]. Crucially, this scenario achieves the lowest final effluent phosphorus concentration (2.7 mg/L), effectively upgrading the DEWATS from a disposal unit to a source of irrigation-quality water.

Scenario C (Sludge-Line Processing) serves as a cautionary example of *technological mismatch*. While it targets the largest nutrient pool (the sludge) and produces the highest-purity product, the capital requirement is disproportionate to the recovery volume[20]. The analysis shows that Scenario C is economically irrational for community-scale systems, requiring nearly 4.5 times the capital investment of the inline scenarios (Section 4.8.1).

Consequently, Scenario B emerges as the superior intervention for the Indian context. It prioritises the resilience of the water cycle over the absolute mass of fertiliser produced. In a region facing acute water stress, the value of upgrading effluent for local reuse arguably exceeds the value of the marginal phosphorus recovered in Scenario A[26].

The Economic Viability Gap. The techno-economic assessment identifies a structural ‘viability gap’ that limits the adoption of these technologies. The analysis indicates that the chemical cost of recovery is stoichiometrically fixed at approximately INR 305 per kg of phosphorus recovered[21]. When labour and maintenance are included, the total production cost rises to between INR 348 and INR 438 per kg P.

This production cost is significantly higher than the market price of commercial phosphate fertilisers in India, which are heavily subsidised to ensure food security[27]. This price distortion means that recovered struvite cannot compete purely as a commodity fertiliser. As long as the external costs of linear disposal (eutrophication, sludge management, water scarcity) remain unpriced, the economics of circularity will remain unfavourable.

Therefore, nutrient recovery in Indian DEWATS cannot be justified by revenue generation alone. It must be framed through the lens of *avoided costs*. Scenario B becomes financially viable if the economic model accounts for the reduced fouling of downstream filters, the extended lifespan of infiltration beds, and the potential revenue from high-quality irrigation water[10]. Policy support is required to monetise these benefits, potentially through performance-based viability gap funding for decentralised operators who demonstrate nutrient diversion.

Synthesis: Re-valuing the Decentralised Asset: The findings of this study align with broader global sustainability agendas, particularly SDG 6 (Clean Water and Sanitation) and SDG 12 (Responsible Consumption). By demonstrating that recovery is technically feasible using simple chemical interventions, the research refutes the perception that DEWATS are ‘too small to matter’ in the national resource equation[28].

The Auroville case study serves as a microcosm of the wider Indian sanitation landscape. It demonstrates that the infrastructure for circularity already exists; it is merely operating under a linear logic. The 'sink' function of the settler and ABR is not a flaw but a latent asset. The transition to recovery does not require the replacement of these systems with high-tech alternatives but rather their strategic retrofitting.

The constrained mass-balance approach adopted here proved robust in identifying these opportunities despite data limitations[3]. It offers a replicable methodology for other data-poor municipalities to assess their own 'hidden' nutrient reserves. Ultimately, this study argues for a shift in perspective: from viewing DEWATS as passive safeguards against disease to recognising them as active chemical reactors capable of securing local nutrient and water cycles. The technology is available, and the climate is favourable; the remaining hurdle is the economic architecture required to make resilience profitable.

5. Conclusions and Future Work

5.1. Conclusions: From Dissipation to Resilience

This research interrogated the potential of decentralised wastewater treatment systems (DEWATS) in India to transition from passive pollution control to active resource recovery. By applying a constrained mass-balance framework to the Auroville Residential Zone DEWATS, the study has empirically demonstrated that the primary barrier to circularity in this context is not technical capability but the structural design intent of the infrastructure.

The baseline analysis confirms that Indian DEWATS currently function as highly efficient nutrient sinks. While the system achieves an apparent phosphorus removal efficiency exceeding 90%, this is accomplished through sequestration in sludge rather than recovery[12]. This validates the critical distinction identified in the literature: the system effectively protects receiving waters from immediate nutrient loading but dissipates the resource value of phosphorus into an unmanaged solid waste stream[5].

A pivotal finding of this work is the quantification of a distinct 'tropical advantage'. The study identified that elevated ambient wastewater temperatures $(\approx 27^{\circ}C)$ within the anaerobic baffled reactor naturally accelerate hydrolysis. This climatic factor preconditions the wastewater by converting organic phosphorus into soluble orthophosphate without the energy-intensive heating required in temperate climates[20]. This suggests that the Global South possesses a latent thermodynamic asset that renders low-tech chemical recovery more feasible than previously assumed.

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The comparative modelling of magnesium-dosing scenarios provides a clear strategic hierarchy. While Scenario A (Pre-Primary Dosing) offers the highest theoretical mass yield ($> 2.5\ kg\ P/d$), it contradicts the operational ethos of DEWATS by producing a contaminated sludge matrix that requires complex downstream processing. In contrast, Scenario B (Pre-Secondary/Vortex Dosing) emerges as the optimal intervention. By leveraging the existing hydraulic turbulence of the vortex units, Scenario B recovers a cleaner product while simultaneously delivering the highest effluent quality ($\approx 2.7\ mg/L\ TP$) [18]. This finding argues that the goal of decentralised recovery should shift from 'yield maximisation' to 'system resilience', prioritising water reuse potential over raw fertiliser volume.

However, the techno-economic assessment exposes a persistent 'viability gap'. With a production cost of approximately $INR\ 305 - 438\ per\ kg$ of phosphorus recovered, struvite precipitation cannot currently compete with subsidised synthetic fertilisers on price alone[21]. Consequently, the study concludes that nutrient recovery in Indian DEWATS must be framed not as a profit centre but as a mechanism for avoided costs, specifically through reduced eutrophication, lower sludge handling burdens, and the creation of superior-quality irrigation water.

5.2. Recommendations for Future Research

While this dissertation establishes the techno-economic feasibility of retrofitting DEWATS for phosphorus recovery, several critical avenues for future research remain to translate these findings from modelling to full-scale implementation.

Empirical Validation of Internal Partitioning: The current study utilised a constrained mass-balance approach to infer internal nutrient distribution due to the 'black box' nature of standard monitoring. Future research should prioritise the physical validation of these inferred pathways. This requires a campaign of vertical core sampling within the primary settler and Anaerobic Baffled Reactor (ABR) to spatially map phosphorus accumulation profiles in the sludge bed. By correlating observed sludge phosphorus fractions with the model's predicted coefficients, researchers can refine the 'partitioning constants' for tropical DEWATS, creating a more accurate predictive tool for operators across India[13].

Pathogen Safety and Product Certification: A critical prerequisite for agricultural reuse is the biological safety of the recovered precipitate. While Scenario B produces a visually cleaner product than Scenario A, the extent of pathogen carry-over remains unquantified. Future work must rigorously assess the microbiological quality of the vortex-harvested struvite, specifically screening for Escherichia coli, Salmonella spp., and helminth ova[4]. Research should determine whether the high-pH environment of crystallisation provides sufficient pathogen inactivation or if a simplified solar-drying post-treatment step is necessary to meet World Health Organisation guidelines for safe reuse.

Agronomic Trials and Bioavailability: The theoretical value of the recovered product depends on its performance as a fertiliser. Future studies should move beyond chemical stoichiometry to agronomic application. Controlled pot trials and field studies using local soil types (often lateritic in the Auroville region) are essential to compare the release dynamics and crop uptake of DEWATS-derived struvite against commercial Diammonium Phosphate (DAP). Understanding how the recovered magnesium-phosphorus complex behaves in tropical soils will be crucial for validating the 'fertiliser equivalent' assumptions made in this economic analysis[29].

Policy Mechanisms for the 'Viability Gap': Given that the cost of recovery exceeds the market price of subsidised fertiliser, future research must explore the policy instruments necessary to bridge this gap. A detailed Cost-Benefit Analysis (CBA) is required that monetises the 'shadow costs' of linear disposal, including eutrophication damage and pipe scaling. Research should evaluate the feasibility of 'Nutrient Diversion Credits', a performance-based financing model where municipalities pay decentralised operators for every kilogram of phosphorus kept out of water bodies[26]. Investigating these governance mechanisms is as critical as chemical engineering in ensuring the long-term sustainability of circular sanitation in India.

Scalability to Non-Vortex Systems: Finally, since not all Indian DEWATS feature the vortex aeration units central to Scenario B, research is needed to adapt this 'effluent polishing' strategy to standard DEWATS configurations. Design modifications that introduce passive turbulence or simple cascade aeration to mimic the vortex effect should be modelled to generalise the findings of this case study to the wider national infrastructure[2].

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